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An improved impedance eduction technique based on impedance models and the mode matching method

André M.N. Spillere *, Augusto A. Medeiros, Julio A. Cordioli

Acoustics and Vibration Laboratory, Federal University of Santa Catarina, Florianópolis 88040-900, Brazil

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ABSTRACT

The problem of determining the acoustic impedance of liners used in turbofan engines of commercial aircraft has been a point of interest for the scientific community for decades, especially in the presence of grazing flows, similar to operational conditions. Different techniques have been developed to determine liner acoustic impedance under grazing flow. More recent research have been focused on inverse methods, which consist of two steps: (i) measurement of the acoustic field in a rectangular duct with flow and a liner sample located at one or two walls of the duct and (ii) modelling of the acoustic field and application of an optimization procedure to find the impedance that minimize the difference between experimental and analytic results. The process is usually carried on using optimization techniques and performed at each frequency step, which can lead to discontinuous impedance curves and large computational costs. In this work, the mode matching method is discussed in detail, and a new technique for impedance determination is proposed, which incorporates a mathematical impedance model to the optimization process as a mean to improve the impedance curve, therefore suppressing measurements error and convergence issues at single frequencies. The impedance models considered here are given in the frequency domain and satisfy passivity, reality and causality conditions, which allows the use of the educed impedance in time domain simulations. Three models are considered and compared regarding different liner samples, flow velocities and wave propagation direction. The results show that the impedance models can successfully suppress convergence errors close to the liner resonance frequency.

1. Introduction

There are several noise sources on modern aircraft, including airframe noise (fuselage, wings, flaps, landing gear, etc.) and engine noise (fan, turbine, jet, etc.). In many cases, specially for the phases considered in the certification tests, the engine can be the dominating source [1]. High bypass ratio turbofan engines became largely employed in the civil aviation, mostly because of fuel savings and significant reduction of jet noise. This brought attention to other engine noise sources, like the main fan and the engine core. Since fan noise is characterized by dominating discrete tones associated with blade passage frequencies (BPF), acoustic treatment of the fan ducts is achieved by covering the interior nacelle walls with lining materials tuned to these frequencies.

Most current liners are composed of three different parts: a perforated plate subject to grazing flow, a honeycomb core and a rigid backplate. This design is the best trade-off between weight and noise reduction [2] and can be seen as an array of Helmholtz resonators. Therefore, good sound attenuation is achieved over a narrow frequency band, which can be chosen based on the liner geometry, in order to comprise the critical BPF on a specific flight condition. More complex liner geometries have also been employed when a more broadband noise reduction is desired [3].

Liner performance is generally accounted for by means of its acoustic impedance. However, typical aero-engine liner impedance is known to be dependent on the liner geometry [4], temperature [5], grazing flow [6–9] and sound pressure level [10–12]. Because it is not trivial to measure liner impedance under these conditions, several methods were proposed in the last decades.

A group of methods, usually called impedance eduction methods or inverse methods, have similar procedures. First, the acoustic field in a duct with a liner sample at the wall subject to grazing flow is measured. Then, a numerical or analytical model simulates the acoustic field in the duct, and an optimization routine is applied to find the impedance that minimizes a certain criteria, such as the difference between experimental and simulated results.

* Corresponding author.
E-mail addresses: andre.spillere@lva.ufsc.br (A.M.N. Spillere), Augusto.Medeiros@esi-group.com (A.A. Medeiros), julio.cordioli@ufsc.br (J.A. Cordioli).

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The main difference between the many published methods is how the acoustic field is simulated in the presence of the liner sample and grazing flow. There are methods based on Finite Element Method (FEM) simulations [13], two-port systems [14,15], mode-matching [16], solutions to the convected Helmholtz equation [8], to the linearized Euler equations [17], to the Pridmore-Brown equation [8], among many others. Jing et al. [18] also proposed a method that does not require an optimization in order to find the impedance, but instead calculates it directly from the test data. To simplify their derivation and application, most of these methods assume that only plane-waves propagate in the hard-wall sections of the test ducts, i.e, the highest frequency under analysis is lower then the cut-on frequency of the first transverse mode of the duct.

Researchers at NASA have developed several indirect techniques. One of them, the Pressure Gradient Method (PGM) [13], uses a 2D FEM to model the acoustic propagation along the lined section of a duct for a given impedance value. The impedance guess is varied in an optimization until the calculated pressure gradients in the axial direction at the beginning and ending of the liner sample match the measured ones. This is a very robust method because of the FEM approach. It has since been extended to handle higher order modes cut-on in the hard-wall sections [19]. This configuration, however, requires dozens of microphones in order to decompose the acoustic field, which is rather cumbersome and not available at all laboratories.

The two-port method, first proposed by Roeck and Desmet [20], uses an analytic transfer matrix to describe a lined section of a duct with flow. This matrix is a function of the wavenumbers in the lined section, which are found in an optimization procedure and then used to calculate the liner impedance. It showed promising but unstable results, and was later extended by Santana et al. [14] to better handle the effects of the hard-soft wall transitions, solving most of the instabilities seen in Roeck and Desmet preliminary results.

In the mode matching technique, Elnady et al. [16] used the mode-matching technique to couple the acoustic fields in hard-wall and lined sections of a duct, from which the amplitudes of the propagating modes are found for a given impedance guess. The acoustic field is then calculated and compared to the measured one until the error is minimized by finding a matching impedance.

In the straightforward method proposed by Jing et al. [18], the acoustic field along the section with the liner sample is measured at equally-spaced positions. The well-known Pronys method is used to approximate the acoustic field as a series of complex exponentials, whose exponents give the axial wavenumbers, and thus the liner impedance. This method differs from the two-port method and the mode matching method because it is not iterative; the wavenumbers, and then the impedance, are calculated directly from the acoustic pressure measurements. This approach has the advantages of not requiring an optimization, thus avoiding its potential drawbacks, such as dependence on initial guesses and difficult convergence in certain situations.

Some of the aforementioned methods require a high number of microphones and lead to large computational costs, which is not always available nor desirable. Even so measurement error or bad convergence of the optimization at some frequencies might result in a non-smooth impedance curve, which is not a physical result. It is necessary to include in the eduction technique an impedance model that represents the behaviour of an acoustic liner in order to avoid such discontinuities. Such similar approach has been used by Richter et al. [21] and Busse-Gerstengarbe et al. [22] by including the Extended Helmholtz resonator (EHR) model [23] into an impedance eduction technique based on a time domain computational aeroacoustics method. As a drawback, the overall time for a single impedance eduction is around one day [22].

This work focus on the mode matching technique, which results in a systems of equations to be solved at each frequency and, therefore, an optimum impedance at each frequency is to be found (hereby called the single-frequency mode matching). A modification to the mode matching method is proposed to incorporate an impedance model to the eduction process. Instead of finding the complex impedance at each frequency, the proposed method finds the model parameters, that defines it for all frequencies under analysis (hereby called the multiple-frequency mode matching). This always results in smooth impedance results since the employed function is smooth, and facilitates interpolation and extrapolation to obtain the impedance at other frequencies. Due to the frequency domain nature of this technique, only a few minutes are necessary to obtain an impedance curve.

The impedance models analysed in this work were developed for time domain simulations. In order to guarantee a physical behaviour, these models have to satisfy fundamental conditions in the frequency domain, i.e. causality, reality and passivity conditions. Different mathematical approaches have been investigated to guarantee these conditions, including rational and multipole functions [24,25], and also an extension of the basic Helmholtz resonator model [23]. Each model has its own advantages when translated into the time domain, but this work is focused on finding the model that best represents the educed impedance of acoustics liners, with and without grazing flow. Semi-empirical models based on viscous and radiation effects at small holes and non-liner corrections due to grazing flow [26–28] are not included since it has not been proven that they satisfy the fundamental conditions [23].

This work is divided as following: Section 2 introduces the relevant equations in order to derive the acoustic field in a duct with flow. In Section 2.1 the single-frequency mode matching technique is described in detail [29,16]. Section 2.2 shows how the impedance model can be used in the mode matching method, thus resulting in the multiple-frequency mode matching. Section 3 introduces the impedance models as proposed by Ozyörük and Long [24], Li et al. [25] and Rienstra [23]. Section 4 presents the experimental apparatus available at the Federal University of Santa Catarina, and then Section 5 shows the results obtained using the single-frequency mode matching method and the multiple-frequency mode matching method. The main conclusions are presented in Section 6.

2. Impedance eduction technique

This section will first introduce the basic equations for the acoustic field inside a duct in the presence of a lined section. Then, the specific set of equations for the mode matching method is presented. On the following, the impedance model is coupled in the optimization routine, resulting in the multiple-frequency mode matching method.

The basic geometry is shown in Fig. 1, which shows a rectangular duct with width b and height h and whose walls are rigid except for a section of length L where an impedance Z_w is applied at the wall $x = 0$. The duct can be seen as having three different sections: a hard-wall inlet Section (1), then a lined Section (2), which represents the region with the liner in the experimental configuration, followed by a hard-wall outlet Section (3). Uniform flow in the positive z-direction is assumed in all sections.

In a duct with uniform mean flow in the axial (z) direction, the convected wave equation [30] for linear acoustics is given by

$$\nabla^2 p - \frac{1}{c_0^2}\frac{D^2 p}{Dt^2} = 0, \tag{1}$$

where p is acoustic pressure, c_0 is the speed of sound in the fluid, D/Dt is the material derivative and ∇^2 is the Laplace operator.