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Investigation of straightforward impedance eduction in the presence of shear flow

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ABSTRACT

A straightforward impedance eduction method is proposed which combines Prony's method with the Pridmore-Brown equation to obtain the impedance of acoustic liners in the presence of shear flow. Particular attention is paid to the reported inconsistency problems associated with the boundary layer effect in the development of impedance eduction techniques. A kind of flow-insensitive acoustic liner is considered which is placed in a rectangular flow duct containing predominant grazing incidence mode. Three slip or no-slip flow profiles are examined, which are the parabola, the one-seventh power law and the uniform core flow with linear boundary layer. A shear-flow FEM model is also set up to simulate the duct acoustic field. The present impedance eduction method has been tested and validated using both the simulated and the published measured data. It is shown that, despite of their distinct boundary layers, the selected flow profiles lead to essentially the same impedance results. And also, for the impedance eduction the strict consideration of no-slip shear flow is very consistent with the use of the Ingard–Myers' boundary condition with the uniform flow assumption over the test conditions. Although not susceptible to the exact shape of flow profile, the impedance eduction critically depends on the determination of the cross-sectional average Mach number. The usual practice of approximately representing the duct flow with the midspan profile results in a slight overestimation of the average Mach number in the two-dimensional acoustic models, and thus can considerably affect the accuracy of the impedance eduction. To solve this problem, the average flow profile is introduced to account for the actual three-dimensional flow non-uniformity in the rectangular duct. It is further found that the effective Mach number, corresponding to a slightly modified average flow profile, can be used to achieve a considerable collapse of the impedance spectra educed at different Mach numbers. Based on the new evaluation of the influence of boundary layer profile, the FEM simulation using the straightforwardly educed impedance as the boundary condition can achieve an excellent agreement with the benchmark data for the complex sound pressure in the flow duct.

1. Introduction

In the pursuit of developing quieter aircrafts, an accurate knowledge of the impedance behavior of acoustic liners is critical to improving and innovating the acoustic design of aeroengines. In the nacelle and inner passages of an aircraft

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engine or other similar flow ducts such as the silencers of internal engines, ventilations, etc., grazing flow past the liner surface can possibly have significant effects on the liner impedance. And the boundary layer profile is also an important influential factor to this effect. For the widely-used perforated liners, the grazing flow effect is increasingly significant as flow speed increases. The underlying mechanism is due to the flow–acoustic interaction at small perforate orifices, converting the acoustic energy into the motion of the unsteady, turbulent-like shedding vortices. This mechanism has been studied by many authors since 1960s, and more recently various numerical simulations have been carried out to reveal much details of the acoustic-vortical conversion process [1–3]. Actually the grazing flow effect can be utilized to enhance the sound absorption of the acoustic liners. On the other hand, the grazing flow effect becomes minimum for some types of linear acoustic liners, such as the liner with woven-wire facing sheet. The linear acoustic liners have the benefit of maintaining their peak absorption over a wider operational range of the aeroengines [4]. Eventually, the sound attenuation in the flow ducts depends on the wall impedance boundary condition. Thus, it is necessary for an impedance measurement method to fully reflect the grazing flow effect, which can be significant or not, and thus providing the physical and technical basis of the acoustic liner technology. In particular, recently there is an increasing concern of the problem how to incorporate the boundary layer effects into the impedance eduction methods such that the grazing flow effect on the impedance can be assessed on more solid experimental basis.

As we know, both the in-situ method [5] and modified impedance tube [6] have been applied to measure the acoustic impedance in the presence of grazing flow. But the usage of these methods is mainly limited to certain kinds of liner structures, such as a perforated liner with hollow honeycomb structure or just a single orifice. So, in recent years there is an increasing trend to develop the so-called waveguide methods that use the measured sound pressure information to infer or educe the liner impedance in a flow duct. The waveguide methods suit to nearly all kinds of locally-reacting acoustic liners and being able to obtain the global impedance over a finite-size test liner. This category includes the infinite waveguide method, the iterative impedance eduction methods and the more recent straightforward impedance eduction method. The infinite waveguide method, first proposed by Armstrong [7] in 1960s, assumes one single acoustic mode in the waveguide; whereas the other two methods are established for more realistic experimental setup that carries a multi-modal sound field with reflections.

The iterative impedance eduction methods (referred as iterative method for brevity) follow the general strategy of optimization, which obtain the acoustic impedance from minimizing the error between the predicted and the measured sound pressure profile along the flow duct. For such objective, a variety of duct propagation models have been used, such as the finite element [8–14], the finite-difference [15] and the mode matching [16–18] models. A diversified optimization algorithm has also been adopted for searching the target impedance. The iterative methods generally need three acoustic inputs: the axial sound pressure profile, the acoustic boundary conditions on the source and duct exit planes. These input data are acquired with wall-flush mounted microphone arrays in the flow duct. Recent improvements to the iterative methods focused on the convergence and accuracy problems when the objective function becomes flat or the eduction process is sensitive to the acoustic boundary condition of the duct exit. In some occasions, a slight variation in the exit impedance can cause the educed impedance to vary significantly [8]. According to Watson and Jones [10], this sensitivity problem can be somewhat relieved if the exit impedance is replaced with sound pressure boundary condition. Eversman and Gallman [13] have shown another way in which the exit impedance is included as part of the search process. Better agreement with the measured sound pressure is reported, but at the expense of considerably more computations. More recently, a systematic comparative research has been carried out to assess the consistency between different iterative methods [19,20].

The straightforward method (referred as SF method for brevity) is capable of extracting the modal parameters from the measured axial sound pressure profile in a deterministic way, and then using only the wavenumber information of the dominant mode to directly obtain the liner impedance [21]. So, the SF method does not need any iteration in the impedance eduction process. The famous Prony's method is readily employed for the modal extraction, since the axial sound pressure profile can be represented as a sum of complex exponentials. Traditionally Prony's method is applied to process the time signals for their “signal prints” [22], and its application has also been extended to analyze the spatial acoustic modes in waveguides [23,24]. The idea of using Prony's method for impedance eduction was only recently proposed in need of improving the liner measurement tools [21]. The SF method does not require solving the complete acoustic field in the duct, but only calculates the unknown impedance from the transverse eigen-equation. Since neither the axial wavenumbers nor the transverse eigen-equation is subject to the acoustic boundary conditions on the source and exit planes, the SF method is expected to be independent of the two additional boundary conditions. This benefit has been demonstrated in both the numerical simulation and the experiment [21,25]. Besides, by means of the modal extraction strategy, the number of the input sound pressure data can be reduced when there contains a few leading modes in the flow duct (as it usually does). The SF method is also computationally efficient, a normal run only takes less than one minute on a common personal computer.

So far, a vast majority of the impedance eduction results presented in open literature have been based on the uniform flow assumption. However, it has long been recognized that shear flow can affect the duct sound propagation to some extent, depending on flow gradient, wavelength and acoustic mode. Generally speaking, due to the refraction of shear flow, the sound wave can be bent either towards or away from the duct wall when propagating downstream or upstream, respectively. Because the impedance eduction methods rely on the duct propagation models in one way or the other, the shear flow effect may potentially influence the accuracy of the impedance eduction results.