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Indirect acoustic impedance eduction in presence of flow based on an analytical two-port formulation

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ABSTRACT

In order to assess the performance of advanced acoustic absorbing materials the acoustic impedance should be determined with high accuracy, especially, in presence of a grazing flow. This paper presents an analytical methodology for the grazing flow acoustic impedance eduction, based on a two-port representation of an acoustic system. This procedure is dedicated to the frequency range below the cut-on frequency of the transversal duct modes and its major appeal refers to a reduced number of microphones and the experimental rig simplicity. The methodology is verified by comparison with acoustic finite element simulations. Experiments are performed on two liner configurations and the educed impedance is compared with reference results obtained with a different approach at another test rig, and shows good agreement. A sensitivity analysis on the influence of the input parameters is carried out showing the influence of the rigid-/impedance wall transition effects, flow Mach number, number of microphones and microphone positioning accuracy.

1. Introduction

Acoustic absorbing materials are commonly used in many applications, ranging from the automotive industry to the civil constructions. It is, however, in the aeronautical sector that they find the most challenging requirements of robustness, low weight and high performance. In commercial airplanes, the aircraft engine is one of the main noise sources, producing noise levels which can exceed 160 dB. In view of a sustainable and environment friendly civil aviation, engine noise reduction through efficient noise mitigation is required. One of the most common solutions to reduce the far-field engine noise is to line the engine nacelle. The acoustic liner is constructed by a rigid backing plate, covered by a honeycomb structure, which, in turn, is covered by a perforated plate. This construction behaves like a Helmholtz resonator, but, due to the covering perforated plate, construction imperfections and the presence of grazing flows, the acoustic characteristics of these materials change drastically. Direct and indirect impedance measurement techniques have been used to characterize acoustic absorbing materials, but with the development of new high performance and multiple degrees of freedom acoustic liners, improved techniques are required to accurately determine the acoustic impedance including all physical complexities.

The direct methods are still commonly used in engineering and scientific applications. The most basic and commonly used direct methods to determine the acoustic impedance are the two microphone technique and the in-situ method [1,2]. This last methodology, specifically designed for acoustic liners, assumes that for a resonant cavity a unique relationship

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exists between the internal acoustic pressure and the acoustic particle velocity along the perforated plate. This technique is valid under the hypothesis of long wavelengths compared to the cavity cross dimensions and the assumption that the locally measured liner properties are extendable to the full extent of the material surface. The main disadvantages of this methodology are the fact that it is intrusive to the sample, since the microphone is positioned inside the sample, and it requires drill holes in the sample for microphone positioning, which can change the system characteristics and may render the material useless after the experiment.

Opposite to the direct techniques, indirect methods emerged as an alternative to avoid the restrictions of these methods and bring additional advantages. Among several indirect methods the Finite Element techniques have been adopted as a first, and are still relevant [3–7]. This technique consists of solving an eigenvalue problem, where the material impedance is treated as an unknown and the measured acoustic field corresponds to the boundary condition. This technique successfully allows integrating flow velocity gradients along any dimension of the testing section and can cope with materials with acoustic impedance variation along any dimension.

Mode-Matching Techniques [8–10] are a promising alternative for the acoustic impedance eduction. The Mode-Matching Technique is based on a modal decomposition of the acoustic pressure and velocity fields, which can be represented as a set of algebraic equations. This technique allows the computation of characteristic acoustic pressure and velocities of high order modes, with a cost of requiring a large number of microphones. In this way, it is possible to accurately determine the acoustic impedance at small wave numbers compared to the duct dimensions and to directly take into account the rigid/impedance wall transition effects unavoidably present in every test rig [10].

As a trade-off between the Mode-Matching Techniques complexity and good accuracy, two-port methodologies have been presented [11,12]. This alternative permits to adopt a less complex rig and produces results with comparable accuracy to the Mode-Matching Techniques. The two-port technique computes the upstream and the downstream propagating acoustic waves on each side of the duct, where the acoustic sample is located. Supposing acoustic plane wave propagation, it is possible to obtain a unique relationship between the upstream and downstream propagating waves and the acoustic impedance. This technique benefits from the reduced number of microphones required to accurately compute the acoustic impedance, it does not require an anechoic termination and, with the use of a polyharmonic distortion model [13], it is possible to take into account non-linear effects in the two-port transfer matrix.

The present paper studies an analytical indirect method for the acoustic impedance eduction based on a two-port formulation. Under the assumption that acoustic plane wave propagation is occurring, this technique enables the acoustic impedance eduction, under grazing flow conditions, using a minimum of four microphones. Furthermore, the methodology is able to determine the rigid-/impedance-wall transition effects leading to a more accurate acoustic impedance prediction. The adopted technique is theoretically presented and verified by comparison with acoustic finite element simulations. Afterwards, experiments are conducted on two acoustic liner samples which are representative for commercial aircraft nacelles. The educed impedance of these samples is compared with reference values, obtained using a different methodology, on a different test rig, and are found to be in good agreement. Finally, a sensitivity analysis discusses the influence of the input parameters and physical effects which should be taken into account to obtain an accurate impedance eduction using the two-port methodology presented in this paper.

2. Acoustic two-port systems

2.1. The linear acoustic network

A two-port network [14] is defined as an acoustic system located in between two straight ducts where the acoustic plane wave propagation hypothesis is valid. A two-port system is fully characterized by an acoustic transfer matrix (T) which can be written as a relation between the acoustic pressure and velocity fluctuations on both sides of the two-port system. Among the different approaches to write the transfer matrix, this paper adopts two formulations: one which relates the right- and left-running acoustic waves (p^+, p^-), on both sides of the system, the so-called scatter matrix T_s (Eq. (1)), and the other that relates the acoustic pressure and velocities (p, u) on both sides of the two-port systems, also known as the acoustic transfer matrix T (Eq. (2)).

$$\begin{Bmatrix} p_2^+ \\ p_1^- \end{Bmatrix} = [T_s] \begin{Bmatrix} p_1^+ \\ p_2^- \end{Bmatrix} = \begin{bmatrix} T^+ & R^- \\ R^+ & T^- \end{bmatrix} \begin{Bmatrix} p_1^+ \\ p_2^- \end{Bmatrix} \tag{1}$$

$$\begin{Bmatrix} p(l) \\ u_z(l) \end{Bmatrix} = [T] \begin{Bmatrix} p(0) \\ u_z(0) \end{Bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{Bmatrix} p(0) \\ u_z(0) \end{Bmatrix} \tag{2}$$

In Eq. (1), the indices 1 and 2 represent, respectively, the upstream and the downstream part of the two-port system. In Eq. (2), the indices 0 and l respectively represent the plane, upstream and downstream, where the transition rigid-/impedance wall occurs. De Roeck [15] presents a formulation which uniquely relates Eqs. (1) and (2).