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Long Elastic Open Neck Acoustic Resonator for low frequency absorption

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ABSTRACT

Passive acoustic liners, used in aeronautic engine nacelles to reduce radiated fan noise, have a quarter-wavelength behavior, because of perforated sheets backed by honeycombs (with one or two degrees of freedom). However, their acoustic absorption ability is naturally limited to medium and high frequencies because of constraints in thickness. The low ratio "plate thickness/hole diameter" generates impedance levels dependent on the incident sound pressure level and the grazing mean flow (by a mechanism of nonlinear dissipation through vortex shedding), which penalises the optimal design of liners. The aim of this paper is to overcome this problem by a concept called LEONAR ("Long Elastic Open Neck Acoustic Resonator"), in which a perforated plate is coupled with tubes of variable lengths inserted in a limited volume of a back cavity. To do this, experimental and theoretical studies, using different types of liners (material nature, hole diameter, tube length, cavity thickness) are described in this paper. It is shown that the impedance can be precisely determined with an analytical approach based on parallel transfer matrices of tubes coupled to the cavity. Moreover, the introduction of tubes in a cavity of a conventional resonator generates a significant shift in the frequency range of absorption towards lower frequencies or allows a reduction of cavity thickness. The impedance is practically independent of sound pressure level because of a high ratio "tube length/tube hole diameter". Finally, a test led in an aeroacoustic bench suggests that a grazing flow at a bulk Mach number of 0.3 has little impact on the impedance value. These first results allow considering these resonators with linear behavior as an alternative to classical resonators, in particular, as needed for future Ultra High Bypass Ratio engines with shorter and thinner nacelles.

1. Introduction

Locally reacting liners, as those used in aeronautical engine nacelles, are generally "sandwich" resonators with a perforated plate linked to a honeycomb material above a rigid plate. Their absorption behavior can be described approximately with the principle of a Helmholtz resonator. The frequency range of absorption is thus essentially controlled by the thickness of the honeycomb cavity ("quarter-wavelength" behavior). Honeycomb cells are necessary to force wave direction perpendicularly to the perforated plate. It is classical to verify that the cell diameter *d* is lower than the minimal half wavelength. Moreover, the cell layers are supposed to be rigid (no vibration or damping). The small size of the holes (mostly from 0.4 to

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2 mm according to industrial needs), absorbs the energy (through the acoustic boundary layer applied at the internal walls) when a wave is propagated through the resonant cavity [1,2]. The impedance can depend non-linearly on the incident particle velocity level (or sound pressure level) [1]) and on the grazing flow. Acoustic "vortices" of particle velocity can therein occur at the resonator surface, thus modifying impedance. Many studies, since Ingard in the 1950s [3], have tried to determine the influence of various parameters on the impedance and the absorption of holes. Gaeta and Ahuja [4] show in particular that to increase the perimeter of the hole with the same surface allows an increase of the absorption at low magnitudes of particle velocity (<1 ms^{-1}) but has no significant effect for higher velocities. Above a threshold value of the ratio "*vo/v**" (acoustic or particle velocity/friction velocity of the acoustic boundary layer) the hole behavior becomes non-linear [5]. It appears that the nonlinear dissipation mechanism of vortex shedding is crucial for noise levels greater than 120 dB [6], values unfortunately much lower than in an aircraft engine. Chandrasekharan et al. [7] led impedance measurements in a tube and compared results with classical laws of Hersh, Kraft and Candrall & Melling. It is shown that an increase of ratio "l_p/r" (plate thickness/ hole radius) increases the frequency band over which there is linear behavior of the plate with the sound level (between 100 and 150 dB until 6,4 kHz). Boden et al. [8] show that, for a high pressure level noise at different tones, to modify the sound pressure level at one particular frequency can generate a non-linear variation of impedance at other frequencies. Indeed, if the acoustic excitation is periodic with multiple harmonics, the impedance at a given frequency may depend on the particle velocity at other frequencies. It is proven that a simply linear model of the impedance cannot be enough to accurately characterize a material. That is the reason why it can be interesting to determine an impedance model taking into account the non-linearity and to then separate linear and non-linear parts [9]. In Ref. [10] the ratio "*vo/v**" is also introduced as a parameter (similar to what is done in Ref. [5] for a single resonator) to determine a limit of linearity that depends on the Mach Number: 1 for Mach 0.15, 0.3 for Mach 0.3 and 0.1 for Mach 0.51. The grazing flow produces non-linearity phenomena for lower acoustic velocities. In Ref. [11], it is specified that the resistance of several samples (liner diameter 140 mm, liner thickness 1 mm, hole diameter 1.25 mm, porosity 0.42 and 6.79%) increases with the Mach Number (Mach 0–0.1 at 1400 Hz). Jones et al. [12] have tried to identify the influence of hole diameter with a grazing flow ($0 \leq M \leq 0.5$), and with a variation of porosity ($6.4\% \leq \sigma \leq 13.2\%$), plate thickness ($0.51\text{mm} \leq l_p \leq 1.02\text{mm}$), l_p/d ($0.34 \leq l_p/d \leq 0.80$) and cavity length h ($38.1\text{mm} \leq h \leq 76.2\text{mm}$). It appears that l_p/d has no influence on the impedance up to Mach 0.3. Beyond this Mach number, the resistance tends to increase slightly, especially for low values of l_p/d. The resonance frequency decreases obviously as h increases. In Refs. [13,14], in order to reduce the frequency band of the absorption, the concept of a material with straight main pores bearing lateral cavities (dead-ends) is studied. The presence of dead-ends significantly alters the acoustical properties of the material and can significantly increase the absorption at low frequencies, because of a low sound speed in the main pores and thermal losses in the dead-end pores.

Finally, in order to enlarge the frequency range of absorption, different types of one degree of freedom liners can be stacked to constitute two or three degrees of freedom liners. In such cases, the increase of sound pressure level increases their resistance and decreases their reactance [15]. The presence of grazing flow even seems to increase the resistance and to have no influence on the reactance. Furthermore, it would generate strong sound levels for Strouhal Number (defined with regard to the grazing flow) from 0.1 to 0.4. The authors develop a non-linear model of impedance based on Helmholtz formulations, in uniform grazing flow: the non linear terms are only relative to the first cavity. Nevertheless, the physical law of two or three degrees of freedom liners is not suited to an absorption at the lowest frequencies, as needed for future Ultra High Bypass Ratio (UHBR) engines with shorter and thinner nacelles (frequencies around 500 Hz).

A possible approach could be to include, in a Helmholtz resonator, a winding neck extension built at the upper surface for tuning at a low frequency [16], or to link an upper perforated panel with flexible tubes introduced in the cavity, as proposed by Lu et al. [17].

In these configurations, incident acoustic waves are damped in a long resistive and reactive medium (winding neck extension [16] or flexible tubes [17]) before being transmitted in the cavity. The interface with the cavity generates a low resonance frequency by a prolongation of the air column length (end correction of the hole neck). Indeed, the analogy with Helmholtz resonator shows that, in the case of long tubes, the resonance frequency can be governed by the tube length l_{tube} with an effect comparable to cavity thickness h (frequency dependence in $\frac{1}{\sqrt{(l_{\text{neck}}+l_{\text{tube}})h}} \approx \frac{1}{\sqrt{l_{\text{tube}}h}}$, the perforated plate thickness being negligible compared to the tube length).

The interest of this concept has been proven experimentally by these last authors but without any mathematical model to allow for determination of the absorption frequency range according to dimensional parameters.

The aim of this paper is therefore, firstly, to implement a mathematical model without the hypothesis of a short tube, in order to describe a concept of a perforated plate coupled with tubes of variable lengths that fill a limited volume of a cavity (LEONAR for "Long Elastic Open Neck Acoustic Resonator"), then to validate this concept with materials having one or several lengths of flexible tubes within different cavities. The potentialities of additive manufacturing, as shown for example by Setaki et al. for combination of multiple resonators [18], can also be used in order to manufacture plates with tubes and cavity cells in the same process without classical problems of gluing. Indeed, the liner manufacturing is generally carried out in two stages: the process begins firstly by laser drilling of an upper thin plate to generate the desired porosity, and continues secondly by the bonding of this plate on the honeycomb. With this fabrication method, the glue can fill holes that are too close to the honeycomb cells, a problem avoided by 3D printing by additive manufacturing with Selective Laser Sintering or Stereolithography for polymers and Selective laser Melting for metal.