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Thermal effect on the acoustic behavior of an axisymmetric lined duct

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ABSTRACT

This paper deals with the effect of the temperature and the frequency on the acoustic behavior of lined duct partially treated with usual material used in acoustic insulation.

First, the effect of frequencies and temperature on the acoustic impedance of usual materials used in lined duct such as glass or rock wools in order to reduce acoustic level is investigated.

Secondly, the variational formulation of the acoustic duct problem taking into account velocity and temperature effects is established. Then, a numerical model is derived which permits to compute the reflection and the transmission coefficients of such duct for different temperatures and several flow velocities. The acoustic power attenuation is then computed from these coefficients and the effect of the temperature and flow velocities on this energetic quantity is evaluated.

The numerical results are obtained for three configurations of a lined duct treated for different temperature ranges and several velocities. Numerical coefficients of transmission and reflection as well as the acoustic power attenuation show the relative influence of temperature.

1. Introduction

The multimodal scattering matrix presents a powerful tool to characterize the acoustic behavior of duct systems because it presents an intrinsic propriety of the duct element and provides a complete description of the reflection and transmission phenomena of the duct as presented in Abom [1], Leroux et al. [2], Bi et al. [3], Sitel et al. [4] and Taktak et al. [5] and used to evaluate the efficiency of the duct by computing its acoustic power attenuation as presented in Aurégan and Starobinski [6] and Taktak et al. [7].

In a previous work, Taktak et al. [7], the authors developed a numerical method to compute the multimodal scattering matrix of axisymmetric duct without flow. This method was validated by a comparison with analytical solution [8]. Then, this method was improved to incorporate the flow. The effect of this parameter on the acoustic behavior and the acoustic power efficiency of duct systems was studied and discussed in Taktak et al. [5] and Taktak et al. [7,8].

In this paper, the developed numerical method is extended to evaluate the effect of another parameter: the temperature which is present especially in ventilation systems in which the air is propagating with a varying temperature. The aim of the present paper is to evaluate the effect of this parameter used in duct systems lined by a porous material. This later is modeled by its acoustic impedance given by the semi empirical model of Delany and Bazley [9]. According to the document published by Sagartzazua et al. [10], Mechel and Ver differentiate two families of absorbing materials and they consider the normalized frequency parameter E which depends on frequency, flow resistivity and density. This model is a more refined adjustment which is confirmed by Beranek and Ver [11]. Hamet [12,13] and Berengier et al. [14] have introduced, in matching acoustic impedance, two new parameters: porosity and tortuosity of the absorbing material. Moreover, in their model, Hamet and Berengier take into account the thermal and viscous effects of the fluid by introducing the adiabatic constant and the Prandtl number.

In this paper, the studied problem is presented in Section 2. Then the acoustic impedance dependence on temperature and frequency is presented in Section 3. The Section 4 presents the thermal acoustic study of lined duct, the variational formulation and the computation of the reflection and transmission coefficients. Numerical results are presented and discussed in Section 5 to evaluate the influence of temperature and velocities effects on the reflection and transmission coefficients.

2. Description of the physical problem

Ventilation ducts, air conditioning heating are often sources of noise (hiss). These are caused by the flow regime and the flow velocity. It is therefore useful to perform an acoustic duct insula-

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tion to limit the sound level of the noise. The duct is then processed by an insulating material such as rock wool, glass wool, foam or another fibrous material. The acoustic impedance Z_o of the air ($Z_o = \rho_o c_o$) depends on the density ρ_o of the air conditioning and the sound velocity c_o. These depend on the temperature [15]. The density ρ_o decreases with temperature when sound velocity c_o increases with temperature (Figs. 1 and 2).

The air acoustic impedance decreases with temperature. The variation is about 10% for a range of temperature −30 °C to 30 °C (Fig. 3). The studied duct has a constant circular section with unit length. The treated part is arranged to have two wall parts (Fig. 4). However, an impedance discontinuity caused by the liner is modeled by its acoustic impedance Z. Ω is the acoustic domain inside the duct.

The edge of the studied duct is composed of four types: The rigid wall duct part Γ_{WD}, the lined duct part Γ_{LD}, the left transversal boundary Γ_L and the right transversal boundary Γ_R which are characterized by their normal vectors $\vec{n}_{WD}$, $\vec{n}_{LD}$, $\vec{n}_L$ and $\vec{n}_R$. The flow which generates a temperature field T is supposed uniform in the duct. This flow is modeled by the vector $\vec{M}_0$ defined as:

$$\vec{M}_0 = \left(\frac{\vec{U}_0}{c}\right) = \left(\frac{U_0\vec{z}}{c}\right) = M_0\vec{z} \tag{1}$$

where M_0 is the Mach number, U_0 is the flow velocity; c_o is the sound velocity and $\vec{z}$ is the duct axis.

The first objective of this paper is to investigate the effect of frequency and temperature on the acoustic impedance of usual materials used in lined duct such as glass or rock wools in order to reduce acoustic level.

The second objective of this work is to determine the influence of temperature on acoustic behavior of a partially lined duct. The transmission and reflection coefficients will be calculated numerically for a temperature range and several velocities. The attenuation of the acoustic power will be deduced. This is obtained by establishing a variational formulation of acoustic duct problem taking into account velocity and temperature effects based on the use of a multimodal scattering matrix. The methodology of the numerical computation of this matrix is presented in the following sections. A numerical model has been derived allowing calculating variation of the transmission and reflection versus temperature and frequencies.

3. Acoustic impedance dependence

The purpose of acoustic models is to characterize porous material by complex characteristic impedance Z. Sound wave propagation in porous can be described by the acoustic resistance and the acoustic reactance. Most models are based on the following writing:

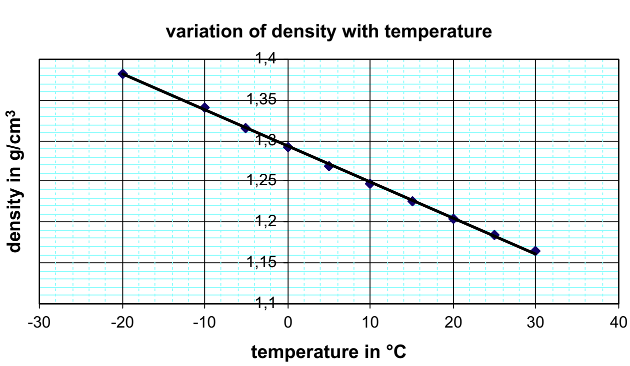

Fig. 1. Density versus temperature.

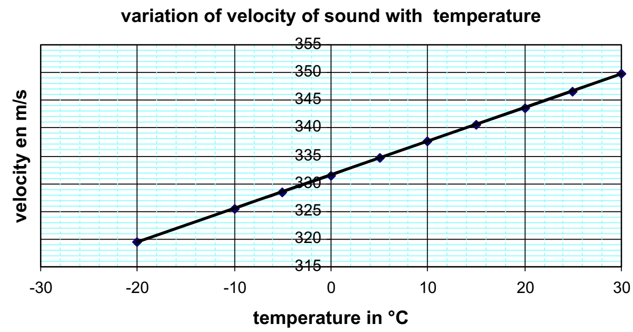

Fig. 2. Velocity versus temperature.

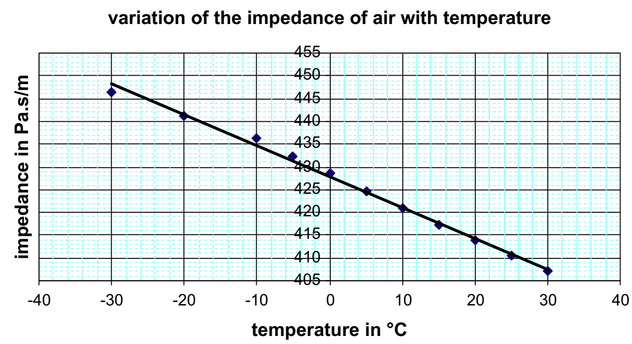

Fig. 3. Impedance of air versus temperature.

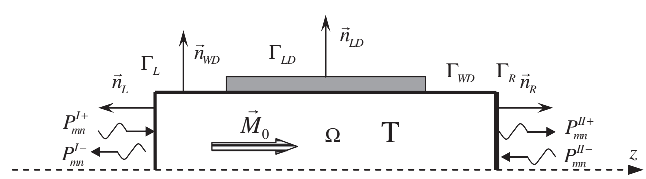

Fig. 4. Axisymmetric modeling of treated duct.

$$Z = Z_0(R' + iR'') \tag{2}$$

where $Z_0 = \rho_0 \cdot c_0$ (Pa s/m) is the characteristic impedance of air, R' is acoustic resistance and R'' is acoustic reactance.

The acoustic impedance depends on the type of material used for duct treatment. Previous studies show that the acoustic impedance depends on fundamental parameters such as flow resistivity, frequency, velocity and density of the air.

The empirical model developed by Delany and Bazley [9] for porous elastic materials is presented as follows:

$$Z = Z_0\left(1 + 9.08\left(\frac{f}{\sigma}\right)^{-0.754} - 11.9.i\left(\frac{f}{\sigma}\right)^{-0.732}\right) \tag{3}$$

where f is the frequency (Hz) and σ is resistivity (cgs Rayls/cm)

This model depend only on the flow resistivity of the liner and its range validity is $10 \leqslant \frac{f}{\sigma} \leqslant 1000$.

If we take into account temperature in velocity and density variation, we obtain acoustic impedance dependency with temperature. For fiber glass material (σ: resistivity is about 2300 N m^{-4} s), acoustic impedance is calculated with this model for frequencies ranging 100–5000 Hz (range of frequencies used in buildings).

Bérengier and Hamet [14] have introduced additionally the tortuosity and the porosity of porous insulating material. The model allows expressing the acoustic impedance from the physical