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Broadband noise reduction by circular multi-cavity mufflers operating in multimodal propagation conditions

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A B S T R A C T

In this study, sound propagation through a circular duct with non-locally lining is investigated both numerically and experimentally. The liner concept is based on perforated screens backed by air cavities. Dimensions of the cavity are chosen to be of the order or bigger than the wavelength so acoustic waves within the liner can propagate parallel to the duct surface. This gives rise to complex scattering mechanisms among duct modes which renders the muffler more effective over a broader frequency range. This work emanates from the Cleansky European HEXENOR project which aim is to identify the best multi-cavity muffler configuration for reduction of exhaust noise from helicopter turboshaft engines. Here, design parameters are the cavity dimensions in both longitudinal and azimuthal directions. The best cavity configuration must in addition fit weight specifications which implies that the number of walls separating each cavity should be chosen as small as possible. To achieve these objectives, the scattering matrix of the lined duct section is obtained experimentally for two specific muffler configurations operating in multimodal propagation conditions. The good agreement with numerical predictions serves to validate the perforate plate impedance model used in our calculation. Finally, given an incident acoustic pressure which is representative of typical combustion noise spectrum, the best cavity configuration achieving the maximum overall acoustic Transmission Loss is selected numerically. The study also illustrates how the acoustic performances are dependent on the nature of the incident field.

1. Introduction

Despite significant technology improvements over the past twenty years, aircraft noise is still a major problem in Europe. In 2001, the Advisory Council for Aeronautics Research in Europe (ACARE) put forward a vision for the European aerospace industry and set some challenging targets for 2020 in terms of noise (50% reduction in perceived noise) and greenhouse gas emission reduction also valid for helicopter transportation.

Until now, turboshaft engine noise which is the second most dominant helicopter noise source has received much less attention than aircraft engine noise. However, Friendcopter [1] a previous European project (2004–2009) has demonstrated through flight tests the significance of medium frequency exhaust engine noise in take-off flight conditions. Turboshaft engine noise is emitted by both the air intake and the exhaust duct. The predominance of these two sources depends on the engine installation on helicopters. If inlet noise due to the compressor has been widely studied, only a few studies have tackled the reduction of exhaust noise. The latter is a mix of combustion and turbine noise with very little jet noise. Although, turbines generate high amplitude tonal noise, their high revolutions per minute (RPM) and blade count result in frequencies being above the audible threshold. Previous work have been conducted in order to identify and model combustion noise source mechanisms. Amongst these, could be mentioned studies on the propagation of direct combustion noise through turbine stages leading to the generation of the indirect combustion noise [2,3] and the FP7 European project TEENI [4] (Turboshaft Engine Exhaust Noise Identification) which addresses experimental identification (location and physical mechanisms) of the contribution of engine modules to exhaust broadband emission.

Because exhaust noise still needs an increased attenuation, the HEXENOR project (Helicopter EXhaust Engine NOise Reduction) supported by Cleansky European program, focused on the development and manufacturing of a muffler to be mounted on a turbo-shaft engine exhaust duct. The specifications provided by the Helicopter manufacturer Turbomeca which in addition to be compatible with the exhaust engine design and harsh environmental conditions, require to find a good compromise between sound reduction performance, weight and cost constraints. The liner concept based on perforated screens backed by air cavities was

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therefore selected. This type of liner is commonly used in inlet aircraft engines for which perforated plates are backed with small cavities (honeycomb-like structures). Because sound propagation occurs only along the cavity depth [5], these locally reacting liners have narrow peaks of absorption around the liner resonant frequency [6]. To extend the absorption bandwidth, double or triple layer structures locally reacting liners can be used [7], but this has the consequence of increasing the muffler volume and weight which may cause substantial departures from the original specifications.

One way of making broadband liners is to enlarge air cavities so that sound propagates not only in the direction normal to the liner but also along the transverse directions. This gives rise to additional resonant effects producing more attenuation over a broader frequency range. The concept of partition spacing in the air backing is discussed in the standard textbook of Ingard [8]. When only the plane wave is allowed to propagate in the main duct, that is below the cut-off frequency of the first transverse mode, the author suggests that optimum partitions spacing should be chosen to be twice the liner thickness, i.e. the cavity depth. The concept was pushed further by Jing et al. [9] for sound propagation in rectangular ducts with mean flow. Their theoretical and experimental results demonstrate that broadband liners performances can be improved by subdividing axially the back cavity into sub-cavities of different size. Another similar study was recently conducted by the same authors using Finite Element Method (FEM) [10]. The concept was also investigated by Allam et al. [11,12] for circular ducts lined with micro-perforated panels (MPP) backed by annular air cavities. In a somewhat different context, the effect of adding a partition in the back cavity of a MPP absorber have been investigated by Liu et al. [13] who showed that cavity resonance effects can improve the performance of the absorber and that attenuation gains can vary deeply depending on the direction of propagation of the incident wave.

In all above-mentioned references, except the latter one which is not concerned with duct acoustics, the analysis is restricted to the low frequency regime whereby only the plane wave mode is allowed to propagate in the main duct. In these circumstances, some of the physical mechanisms involved can be described and anticipated by analyzing the resonance frequencies of the liner sub-cavities as in [9]. In the context of the present work, the broadband nature of combustion noise and the exhaust duct dimensions imply that the frequency range of interest typically lies within the interval $ka \in [0, 5]$ (k is the wavenumber and a is the duct radius) so the muffler necessarily operates in multimodal propagation conditions with a maximum of 8 propagating modes.

In order to meet some geometric and mechanical specifications, perforated plate characteristics as well as the liner thickness and length are fixed and design parameters are simply the cavity dimensions in both longitudinal and azimuthal directions. The methodology used in this paper is based on the determination of the scattering matrix of the muffler using both numerical and experimental approaches. Numerical computations are carried out with a multi-domain finite element method whereas experimental measurements are conducted on an acoustic test bench developed during the European project DUCAT [14]. This is described in detail in Section 3. Comparisons between measured and computed scattering matrix coefficients are performed for two muffler configurations in Section 4. The good agreement between results serves to validate the FE model as well as the perforated impedance formula used in our calculation. The paper ends in Section 5 with a parametric study in order to identify the best muffler configuration. In all cases noise reduction performances are measured in terms of Global Transmission Loss assuming an equi-power distribution with random phases.

2. The circular multicavity muffler

2.1. Geometry

We consider a circular duct with diameter $2a$ = 15 cm s acoustically treated with a 0.3 m long liner made of perforated plate backed with cavities which size can be varied in both longitudinal and azimuthal directions, i.e. along z and θ as shown in Fig. 1. The geometrical characteristics of the liner are the cavity depth $h = 10$ mm, the plate thickness $t = 0.5$ mm, the hole diameter $d = 1.89$ mm and the perforation rate $\sigma = 2.51\%$. In order to determine the best cavity configuration satisfying some specifications, an experimental and numerical study is carried out by varying the number of axial (N_z) and angular cavities (N_θ). The case with $N_\theta \times N_z = 8 \times 16 = 128$ cavities can be considered as locally reacting and this configuration will serve as a reference solution.

Fig. 2 shows a picture of the multi-cavity muffler used for our experimental campaign. The muffler which was designed and manufactured by the French Company ATECA, is composed of a 0.5 m long duct. Cavities size can be varied thanks to 9 removable disks separating the axial cavities and 16 ‘combs' separating the angular cavities. The plate separating the cavities from the central channel is perforated by laser drilling.

2.2. The perforated plate impedance model

Many works have been conducted in order to model the perforated plate impedance but today no unique model is available and most of the several existing models are semi-empirical requiring additional experiments. Nowadays the theory developed by Crandall in 1927 [15] who calculated the impedance of a hole, modelized as if it was an infinite cylindrical duct, is generally used as a basis for the development of extended expressions taking into account a more realistic environment. This normalized model of Crandall is expressed as:

$$Z_p^{\mathrm{Cr.}} = \frac{\mathrm{i}\omega t}{\sigma c}\left(1 - \frac{2}{\kappa\sqrt{-\mathrm{i}}}\frac{J_1(\kappa\sqrt{-\mathrm{i}})}{J_0(\kappa\sqrt{-\mathrm{i}})}\right)^{-1}. \tag{1}$$

The parameter κ is given by $\kappa = d\sqrt{\frac{\omega}{4\nu}}$, with ν the kinematic viscosity. For all the impedance models derived from the model of Crandall, the expression of the impedance Z_p is generally composed of three terms [11,16–20] each corresponding to a specific physical phenomenon: a linear or viscous term which represents the dissipa-

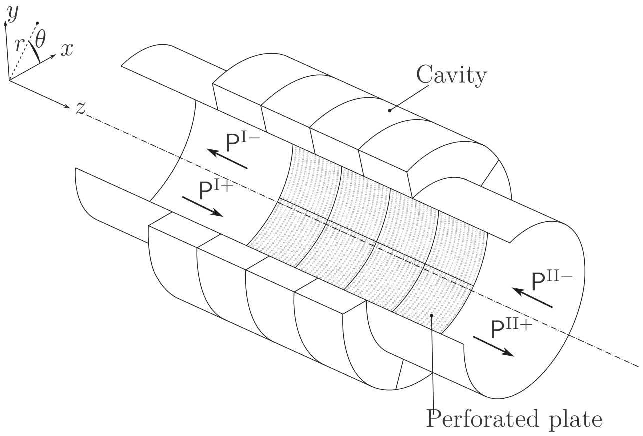

Fig. 1. Sketch of the lined duct with multiple cavities.