Acoustic study of different mufflers based on metamaterials using the black hole principle for aircraft industry

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Summary

Noise reduction in aviation industry is a major problem that led to numerous research papers and projects mainly focused on the noise generated by the engines. One of the most studied solutions for in duct noise consists in reactive structures of the acoustic liner types, which dissipates the acoustic energy in the neck of micro-perforations of a panel (MPP). In this paper a different approach for duct noise reduction is adopted which consist in metamaterials that lead to a so-called acoustic black hole effect ABH. This term is relatively new and researches of acoustic properties of metamaterials in ducts were made but only from acoustic point of view. Taking into account that the pressure loss is sensible even for small perforations, designing of such metamaterial in aviation industry must take into account this aspect. Existing studies of mufflers using metamaterials and ABH principles were carried out just from the acoustic point of view. In this paper we shall consider the mean flow effect on acoustic attenuation. In this study, several designs for the muffler are proposed to be studied. The comparison of the designs is performed using numerical CFD and FEM simulations to calculate acoustic attenuation and pressure loss resulted, considering a duct with mean flow. In order to decrease the pressure loss caused by the perforated section we also propose a novel noise solution which consists in a MPP placed in this section, to reduce the pressure loss, and in the back cavity a structure with ABH effect is placed. Using the MPP an additional absorption will appear caused by the visco-thermal losses.

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1. Introduction

Mufflers are low pass acoustic filters, used to attenuate noise levels from machinery and other noisy sources. Automotive and aviation sectors, as well as other sectors try to develop improved devices for tonal and broadband noise attenuation using compact devices. One important challenge is the reduction of low frequency noise using small devices comparing with the wavelengths. Traditionally the low frequency noise is reduced by using bulky mufflers. Higher frequency broadband noise is reduces by using absorbing materials like mineral wool and foams. The disadvantage is that these materials deteriorates easily when used in mufflers. A novel solution came with the introduction of the acoustic metamaterials concept. These are sub wavelength structures capable to manipulate acoustic waves as no natural materials can do it. Total absorption, zero transmission, negative refraction are some of the phenomena that can be achieved. Acoustic black hole (ABH) is one concept developed due to the metamaterials. It relies on the principle of total absorption and impedance matching. It has been theoretically demonstrated by Mironov and Pislyakov[1] that ABH effect can be applied to a noisy medium through a terminating structure. The paper presented that a total absorption of sound can be achieved in the tube with quasi-periodic ribbed internal structures, whose radii decreased to zero with the structure's termination, and without the use of absorbing materials. To complement this study, the only experimental investigation of the ABH based sound absorption through a terminating structure, considering both using /no using absorbing materials have been presented by [2]. The same concept adapted for an open pipe muffler was presented and discussed by N.Sharma et al. [3][4][5]. Several setups were studied using both analytical and numerical calculation for acoustic field simulation with no grazing flow. Since a muffler requires grazing flow in real applications we found interesting to complete that study with the flow addition during simulations. This paper uses a similar general configuration as in Sharma et. al paper [3] but it adds several new model and most important it adds grazing flow at different Mach numbers. Just numerical simulation was considered using MSC ACTRAN and ANSYS CFX.

2. ABH muffler evaluation

The first step in the present study was to model the muffler designed by Sharma et. al. [3] and to evaluate its acoustic attenuation properties. As is presented in Figure 1 the inlet is represented by the biggest section with a diameter of 100mm and the outlet with a diameter of 50 mm. The convergent section and the multiple thin walls can produce a high pressure loss and this type of muffler it may not be feasible for applications where the pressure loss is a crucial parameter.

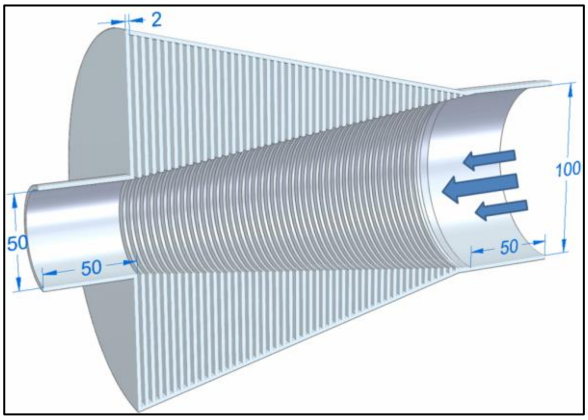


Figure 1. Baseline muffler–geometric parameters (solid domain).

2.1. Total pressure loss

To determine the pressure loss of this kind of muffler, a CFD computation is proposed to be performed using ANSYS CFX software. The boundary conditions used in simulations are: for inlet section air velocity, (two cases were studied for 10 and 25m/s), for outlet static pressure of 1 atm and static temperature of 20^{o}C and the k-Epsilon turbulence model. In order to reduce the pressure loss a thin perforated shell was modelled, and placed in the neck of the slits as is presented in Figure 2. This perforated shell is represented with red.

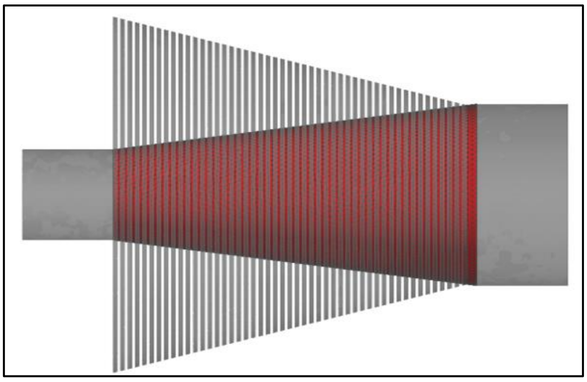


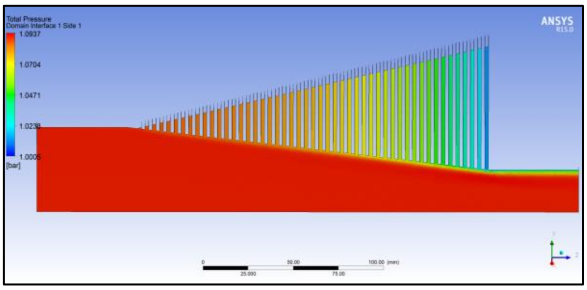
Figure 2. Baseline with perforated shell – perforated shell represented with red.

The properties of the perforated shell are: shell thickness t=0.5mm, perforation percent σ=8.37%, perforation diameter d=1mm. The pressure losses for both models (baseline and baseline with perforated shell) for different inlet air velocities are presented in Table I.

Table I. Pressure losses for both models

Configuration	Baseline		Perforated shell	
Velocity inlet [m/s]	10	25	10	25
Total pressure loss [Pa]	85	539	70	408

The total pressure and velocity fields are presented in Figure 3. To reduce the CFD computational time, a sector of 30 deg. was chosen.



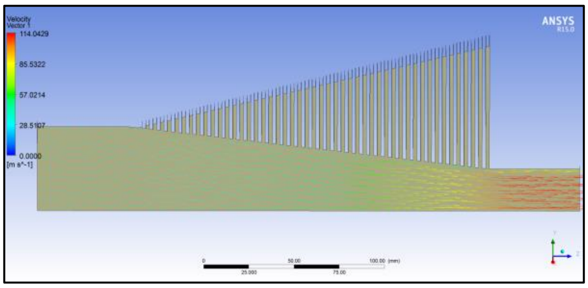


Figure 3. Total pressure and velocity field (inlet air velocity 25m/s).

2.2. Acoustic evaluation

The next step was to evaluate the acoustic attenuation properties of these mufflers. In the present paper, the transmission loss parameter was computed using the Finite Element Method using the commercial software Actran from MSC Software. The acoustic analysis was made using a mesh for which the maximum dimension of the elements is given by the wavelength of the upper frequency, which is studied. As a general rule for tetrahedrons elements, minimum six element per wavelength must be created in order to capture the acoustic fluctuation. Considering that the width of a slit is 2 mm smaller elements were used. For the fluid, the standard properties of air were used: speed of sound 340m/s and density 1.225kg/m^3. The inlet section represents the boundary condition of the acoustic radiating surface with plane waves, for which an intensity of 1 W/m^2 was defined in direction of the muffler. Also on the same surface, a free field condition in the opposite direction was imposed. At the other end, on the outlet section, a free field condition was applied. Based on the acoustic power from the inlet and the computed acoustic power from the outlet section the acoustic transmission coefficient is determined. The transmission loss (TL) is determined using the transmission coefficient (τ) which is the ration between the transmitted acoustic power and the inlet acoustic power.

$$TL = 10 * log\frac{1}{\tau} \qquad (1)$$

The frequency domain of the analysis was set to 10 Hz – 2500Hz due to the cut-off frequency of the inlet and outlet tubes. Therefore, in this study only the plane waves are taking into account.

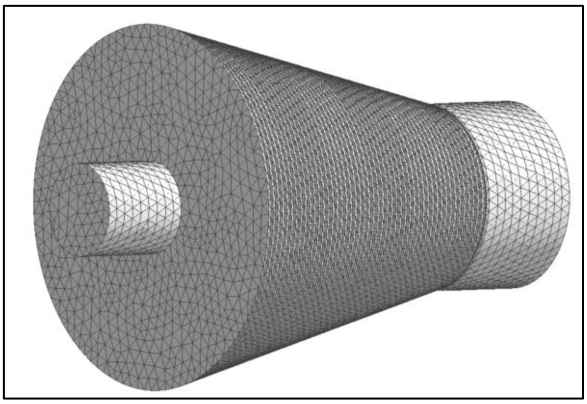


Figure 4. Acoustic mesh for baseline model (fluid domain).

The results for the baseline model are presented in the Figure 5 and these are quite similar with the Sharma results [3]. As can be seen the perforated shell model produce a shift in frequency response and a smoothing of the attenuation curve. The peaks from the baseline attenuation curve represent the response of each slit.

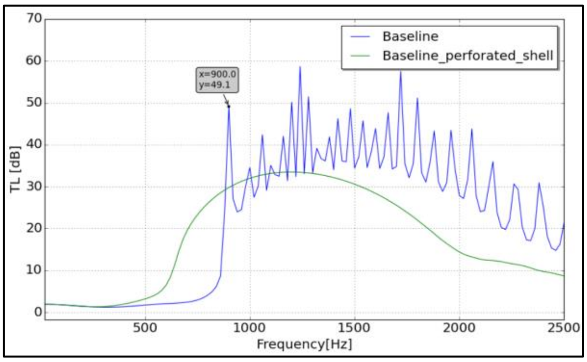


Figure 5. Transmission loss (blue: baseline, green: baseline with perforated sheel).

As can be seen from the Figure 5 and 6 each slit acts on a narrow frequency domain, where the second slit acts at 900Hz. Decreasing the slit depth conducts to attenuation at higher frequency. The attenuation results from Figure 5 were obtained for the mufflers without taking into account the convected wave propagation due to the flow field. The next step in our study is to determine the attenuation modification caused by the air flow.

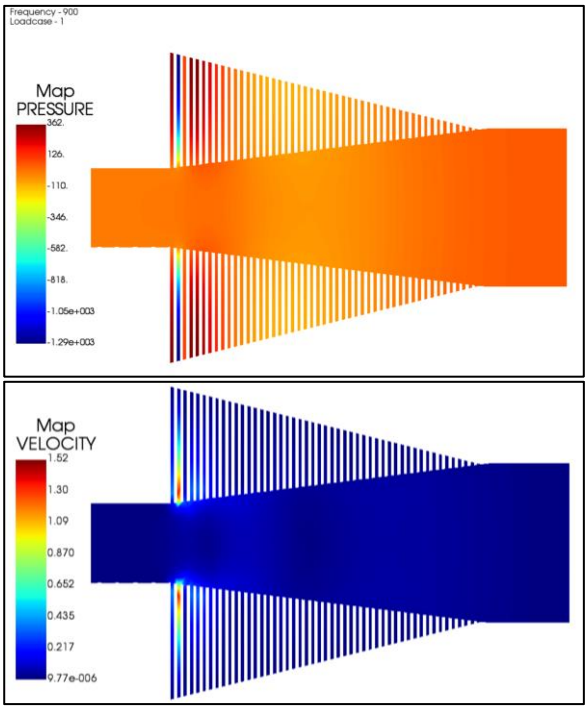


Figure 6. Acoustic pressure and acoustic velocity fields for baseline model.

From the CFD analysis, the density and speed of sound fields were used as input in Actran to determine the influence of the flow on the acoustic attenuation. Therefore, the Figure 7 presents the influences of different flow speed on the TL of the baseline model.

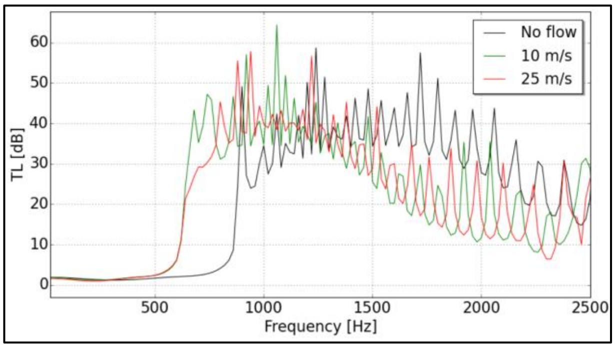


Figure 7. Flow influences on TL (baseline model).

3. Investigation of other muffler designs

Based on the above ABH muffler, in the following section other designs of muffler are investigated. The main objective of this investigation was to obtain a higher attenuation than the baseline and to identify a muffler with attenuation capabilities even for low frequencies. The first model is similar with the Sharma muffler, the only modification is related by the depth of the slits. To increase the slits depth, these were deepened by changing the slits direction as is presented in Figure 8.

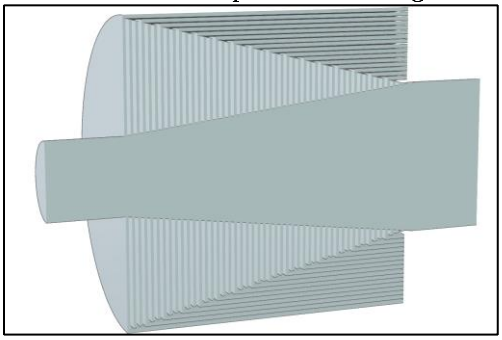


Figure 8. Deepened slits model (fluid domain).

Another design of muffler, consist in adding a porous material with a thickness of 10 mm in the neck of the slits, region with high particle velocity, leading to an increase of acoustic energy dissipation due to the friction of air particles from porous material fibers. As is presented in Figure 6 for the baseline model, at 900 Hz the particles velocity have the highest values in the neck region of the slit.

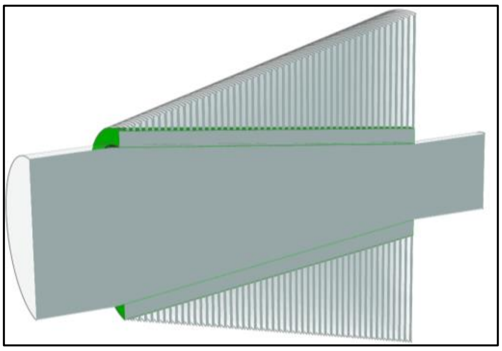


Figure 9. Porous material in the neck of slits (green: porous domain).

Another design of muffler, which was analysed, consists in several ABH structure disposed transversal to the convergent section, as is presented din Figure 10. The principle of this muffler is that the acoustic wave enters into the ABH structure and it is trapped there. To reduce the potential pressure losses caused by the wide openings of the transversal ABH structures, disposed on the convergent section, a perforated shell was modelled as is represented in Figure 10. The parameter of the perforated shell are: t=0.5mm, d=1mm, σ=8.37%. One more muffler design, evaluated in this paper, is a well know solution, which consists in three acoustic treated portions with acoustic liner, presented in Figure 11.

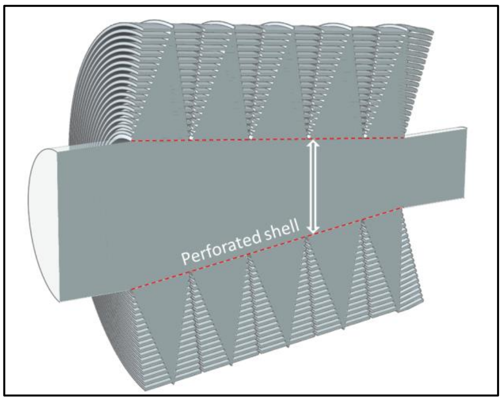


Figure 10. Muffler with transversal ABH structure (fluid domain).

For this computation, the acoustic impedance of the acoustic liner were determined using the approximate Maa model. [6] For the acoustic liner the following parameters were introduced: d=0.3mm, t=0.5mm, σ=2.37%. Also to obtain a broadband attenuation, three different cavity depths (D_1=55mm, D_2=35mm, D_3=15mm) were modelled as is presented in the Figure 11.

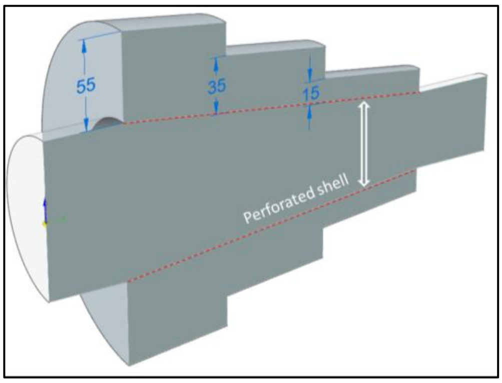


Figure 11. Muffler with acoustic liner (fluid domain).

The comparative analysis between the baseline and the proposed mufflers is presented in the Figure 12. As was expected the muffler model with deepened slits obtained good attenuation even at low frequencies (260Hz-13.2dB, 500Hz-26.8dB) without significantly affecting the attenuation in the frequency domain of 800-2kHz. The baseline model with porous material in the neck of the slits and the model with acoustic liner obtained similar results, with broadband attenuation starting from 500Hz-2.5kHz but with lower attenuation capacity comparing with the baseline. Interesting results are obtained for model with ABH structures disposed transversally on the convergent section, for which the TL reaches 114dB at 810Hz and for the second attenuation peak 81dB at 2220 Hz.

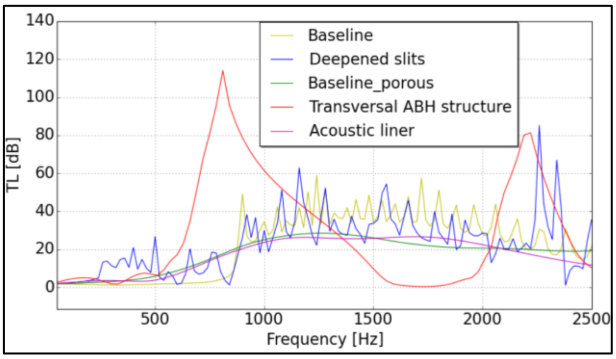


Figure 12. Comparative analysis of the proposed mufflers.

4. Conclusions

Considering the convergent section and the thin slits, the obtained pressure loss is quite low. Adding the thin perforated shell at the entrance of the slits the pressure loss is not significantly reduced. The acoustic convected analysis highlighted that for an air velocity of 25m/s, applied in the same direction as the sound waves, the TL is shifted in frequency and also an increasing of the air velocity is leading to lower attenuation. Our investigation regarding other muffler designs, found that the muffler with ABH structures disposed transversally, obtains a very good attenuation even at low frequencies. This type of muffler can obtains good results in cases where the noise has a tonal character.

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