Gradient metamaterial layers as impedance matching devices for efficient sound absorption

Abdelhalim Azbaid El Ouahabi, Victor V. Krylov, Daniel J. O'Boy

Department of Aeronautical and Automotive Engineering,
Loughborough University,
Loughborough, Leicestershire LE11 3TU, UK

Summary

The performance of acoustic absorbers can be improved by providing a smooth transition from the impedance of air to the impedance of the absorbing material in question. In the present work, such a smooth transition is materialised via application of gradient index metamaterial layers formed by quasi-periodic arrays of solid cylinders (tubes) with their external diameters gradually increasing from the external row of tubes facing the open air towards the internal row facing an absorbing porous layer. If acoustic wavelengths are much larger than the periodicity of the array, such a structure provides a gradual increase in the acoustic impedance towards the internal row of cylinders. This allows the developer to achieve an almost perfect impedance matching between the air and porous absorbing materials, such as foams, sponges, etc. Measurements of sound reflection coefficients from different absorbing materials combined with matching metamaterial layers formed by the arrays of brass tubes have been carried out in an anechoic chamber at the frequency range of 500-3000 Hz. The results show that the presence of matching metamaterial layers brings substantial reduction in the sound reflection coefficients, thus increasing the efficiency of sound absorption.

PACS no. 43.50.Gf, 43.55.Ev

1. Introduction

Over the last few years, significant attention has been paid to acoustic metamaterials, mainly because they can provide acoustic properties that otherwise would be hard or impossible to find in nature. Like metamaterials in other areas of physics, acoustic metamaterials gain their properties from structure rather than composition, using the inclusion of small inhomogeneities to achieve desirable macroscopic behavior [1-3]. As one of the recent examples of such metamaterials one can mention periodic arrays of acoustic black holes for flexural waves that provide efficient vibration damping [4, 5]. In some recent publications (see e.g. [6-9]) the attention has been paid to the design of cylindrical or spherical omnidirectional sound absorbers using acoustic metamaterials for gradual impedance matching between the air and the absorbing core.

In the present work, a new type of "Quasi-Flat Acoustic Absorber" (QFAA) enhanced by the presence of gradient metamaterial layers for efficient sound absorption in air is described and investigated. A typical example of such a device consists of an absorbing layer and a quasi-periodic array of solid cylinders (brass cylindrical tubes) with their filling fractions varying from the external row facing the open air towards the internal row facing the absorbing layer made of a porous material. A gradient metamaterial layer formed by such cylinders is used to gradually adjust the impedance of the air to that of the porous absorbing material and thus to reduce the reflection. Two types of common porous absorbers (Sponge and Fiberglass) are tested in this work to demonstrate the importance of matching the effective acoustic impedance at the exit of the metamaterial layer to that of the porous material in order to ensure maximal absorption into the QFAA. All the brass tubes are of the same length (305 mm) and arranged as a rectangular array placed into a wooden box with the dimensions of 569 x 250 x 305 mm. The designed structure was manufactured and experimentally tested in an anechoic chamber at the frequency range of 500 – 3000 Hz. Part of the material described in this paper was presented at the ASA meeting in October 2014 [10].

2. Experiments

A wooden box with the dimensions of 569x250x305 mm was designed with two zones, one for the impedance matching metamaterial and the other - for a porous absorbing material. The zone of matching metamaterial was drilled in opposite sides to provide an array of holes with the diameters gradually increasing from the external row facing the open air towards the internal row facing the absorbing material. The holes were arranged in 12x51 pattern with the square lattice constant a = 11 mm.

Figure 1 shows a 3D schematic view of a Quasi-Flat Acoustic Absorber (QFAA). By inserting 305 mm long Brass cylinders (tubes) with the increasing external diameters D_n = 1.6 mm + (n-1)·0.8 mm between the opposite-sides of the wooden box into the holes, where n is the row number, a Quasi-Flat Acoustic Absorber is constructed as a system of solid cylinders with varying filling fraction backed by a layer of the absorbing material.

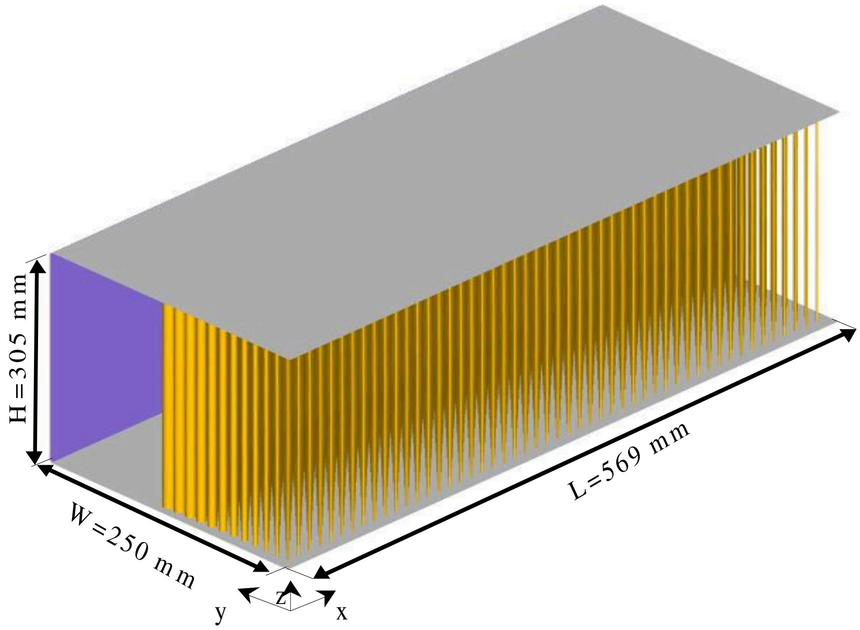

Fig. 1. Schematic 3D view of a Quasi-Flat Acoustic Absorber (QFAA) showing the absorbing material zone (on the back) and the impedance matching metamaterial layer formed by a quasi-periodic array of Brass cylinders.

Filling fraction *ff* and effective acoustic impedance Z_{eff} are defined as follows [8]:

$$ff = \pi\left(\frac{D}{2a}\right)^2, \tag{1}$$

$$Z_{eff} = Z_0 \frac{\sqrt{1+ff}}{1-ff}, \tag{2}$$

where D is the diameter of the cylinders and Z_0 = 413 Rayl is the impedance of air. The calculated effective impedance defined by equation (2) and normalized to the impedance of air is shown in Fig. 2 as a function of a row number *n*.

The experiments have been carried out in the anechoic chamber of the Department of Aeronautical and Automotive Engineering at Loughborough University. As a sound source, a loudspeaker was used. It was suspended on a pulley system that allowed its center to be located at 853 mm height above ground. The centre of QFAA surface was aligned with the loudspeaker and placed at 2 m from the source in order to produce the desired almost plane wave fronts when the sound reaches the sample.

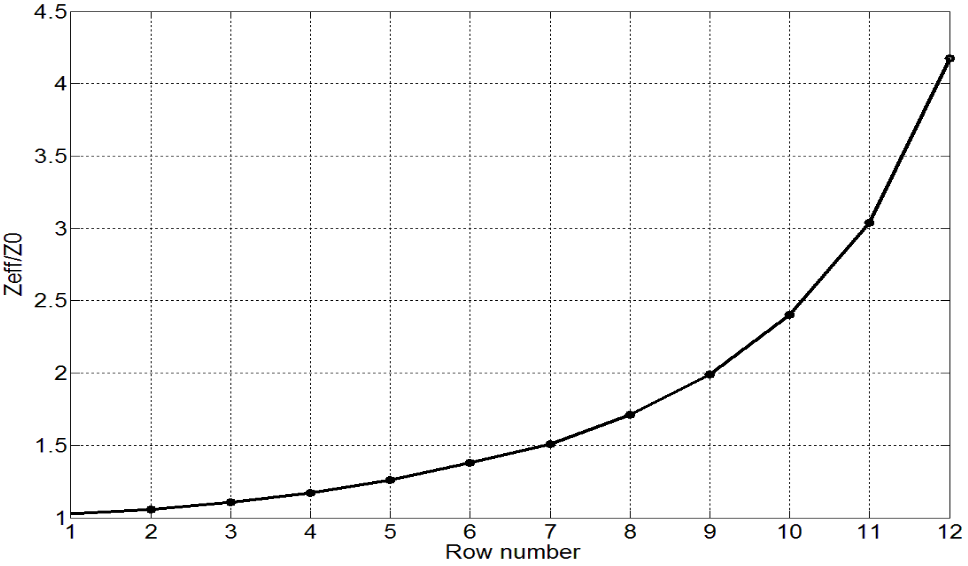

Fig. 2. Normalized effective impedance of the metamaterial layer as a function of a row number.

Fig. 3. Photograph of the experimental set up showing the QFAA (left) and the loudspeaker (right).

Two G.R.A.S. 40AE, pre-polarized ½ inch free-field microphones (their sensitivities are 44 mV/Pa (Mic1) and 42 mV/Pa (Mic2)), with G.R.A.S. preamplifiers type 26CA, were used to measure sound pressure. Figure 3 shows the photograph of the experimental set up utilised to measure the sound pressure reflection coefficients. Two methods of measuring the sound pressure reflection coefficients have been used: the traditional Standing

Wave Ratio method (SWR) and the Two Microphone Transfer Function Method (TFM). In the latter case, a white noise generator was used to drive the loudspeaker. Two microphones have been used to measure sound pressure, and a computer program was used to compute the transfer function between two microphone positions and then calculate the reflection coefficient from the sample. The distance from the sample face to the first microphone was 155 mm, and the distance between the microphones was 35 mm. The microphones were connected to a PC via a four-channel dynamic signal acquisition module NI-USB-4431 card.

3. Results and discussion

Two types of absorbing porous materials, sponge and fiberglass, have been used in the absorbing material zone. Impedance measurements have been carried out using the Two Microphone Transfer Function Method. The normalized acoustic impedances of sponge and fiberglass (relative to the acoustic impedance of air Z_0) calculated from the measured reflection coefficients are shown in Fig. 4 as functions of frequency.

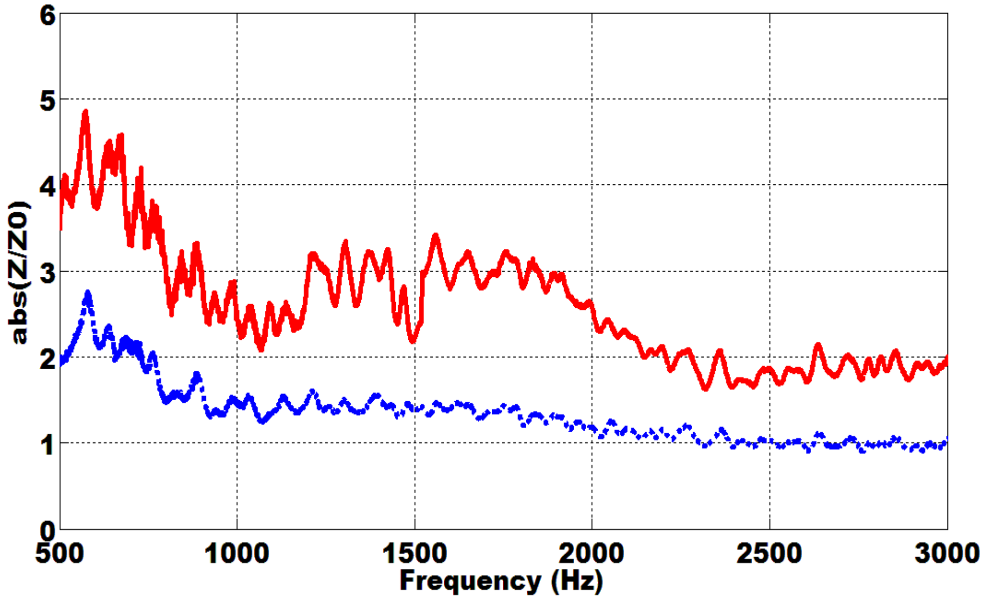

Fig. 4. Normalised acoustic impedances of fiberglass (red line) and sponge (blue line) calculated from the measured reflection coefficients.

The measurements of the reflection coefficients, at frequencies from 500 Hz to 3000 Hz, for the box with inserted fiberglass and for the full QFAA (the quasi-periodic array of cylinders with fiberglass inserted) have been carried out. The results demonstrate (not shown here for brevity) that at the frequency ranges of 500 - 1581 Hz and of 2434 - 2745 Hz, the QFAA with fiberglass inserted provides lower reflection coefficient than the box with fiberglass inserted.

Although these results clearly demonstrate the benefit of using a matching metamaterial layer to reduce reflection, further improvement can be made. In order to achieve better results, one needs to adjust the effective acoustic impedance at the exit of the metamaterial layer to make it even closer to the acoustic impedance of the inserted fiberglass. Therefore, it has been decided to remove a few last rows of Brass cylinders to reduce the effective impedance at the exit of the metamaterial layer and to get an adequate matching of the impedances. Two last rows have been removed, thus reducing the relative effective impedance at the exit of the matching metamaterial layer down to 2.4.

Measurement of the reflection coefficient have been carried out for the QFAA containing 11 and 10 rows of Brass cylinders, with fiberglass inserted. The results are shown in Fig. 5 in comparison with the results for the box with fiberglass inserted, but in the absence of the metamaterial layer. It can be seen that at all frequencies the reflection coefficient for the box with fiberglass inserted is strongly reduced when the QFAA (with 10 rows of Brass cylinders and with fiberglass inserted) has been added. This demonstrates the functionality of matching the impedances using metamaterial layers. The device with 10 rows strongly outperforms the device with 12 and 11 rows in terms of the values of reflection coefficient. At frequencies above 750 Hz the values of reflection coefficient do not exceed 26 %. This means that at these frequencies the full QFAA with 10 rows of solid cylinders acts as an efficient acoustic absorber, with more than 93% of the impinging acoustic energy being absorbed.

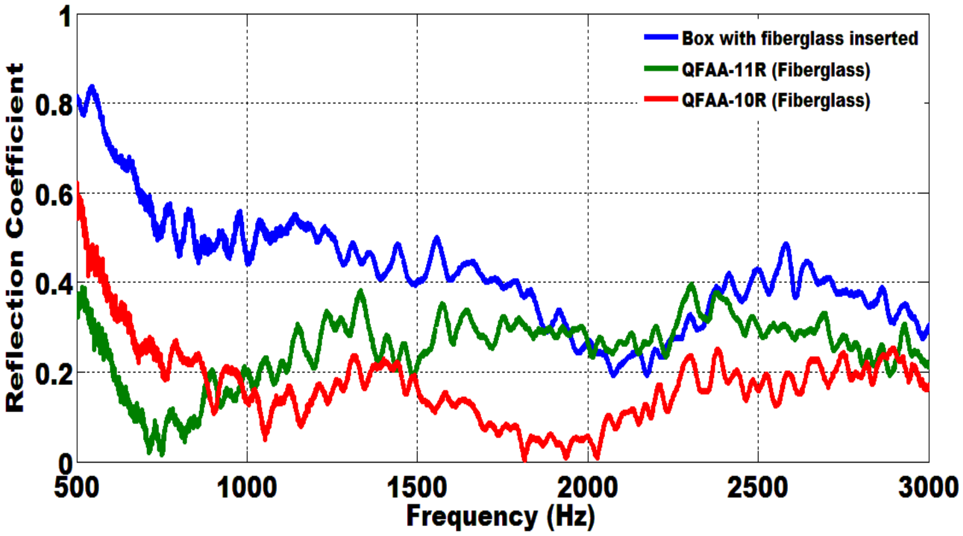

Fig. 5. Sound reflection coefficients measured for the box with fiberglass inserted (blue line) and for the QFAA with 11 and 10 rows of Brass cylinders and fiberglass inserted (green and red lines respectively); measurements made using TFM method.

Measurement of the reflection coefficient have been repeated for the full QFAA with sponge inserted for varying numbers of rows of Brass cylinders (10, 9, 8 and 7 rows). The results for 8 and 7 rows are shown in Fig. 6 in comparison with the results for the box with sponge inserted, but in the absence of the metamaterial layer.

It can be seen that the lowest value of the reflection coefficient takes place for the QFAA with 7 rows. This is in agreement with Fig. 2 showing that for 7 rows of cylinders the value of relative impedance of the metamaterial layer at the 7th row is about 1.5, which is close to the relative impedance of the sponge (see Fig. 4). This demonstrates once again the functionality of impedance matching using metamaterial layers for enhancing the behaviour of acoustic absorbers.

4. Conclusions

A quasi-flat acoustic absorber (QFAA) enhanced by the presence of a gradient metamaterial layer has been designed, manufactured and tested. The impedance matching metamaterial layers were formed by rows of Brass cylinders of equal length and with diameters gradually increasing towards the internal row facing the absorbing layer.

It has been demonstrated experimentally that the values of sound reflection coefficient for the QFAA depend strongly on the impedance matching between the porous absorbing material and the exit of the gradient metamaterial layer. In particular, it has been shown that the QFAA with 10 rows of cylinders and with fiberglass as inserted absorbing material provides the lowest value of the reflection coefficient. This can be explained by a nearly perfect impedance matching achieved in this case. For the QFAA with sponge as inserted absorbing material, the lowest value of the reflection coefficient was observed for 7 rows of Brass cylinders, which again can be explained by a nearly perfect impedance matching in this case.

The obtained results show that, for the quasi-flat geometrical configuration considered in this work, the presence of the impedance matching metamaterial layers in front of different porous absorbing material can bring a substantial reduction in sound reflection coefficient in comparison with the case of reflection from the porous materials alone.

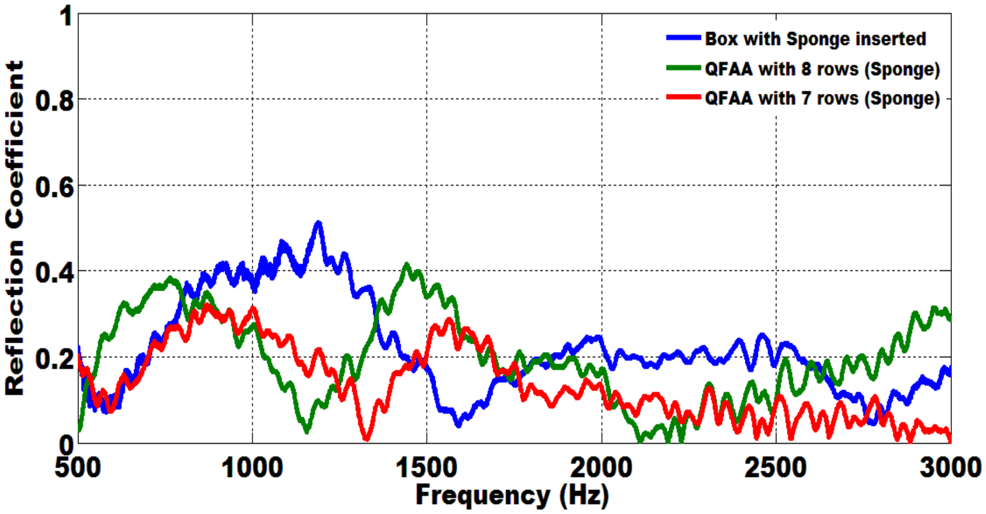

Fig. 6. Sound reflection coefficients measured for the box with sponge inserted (blue line) and for the full QFAA with 8 and 7 rows of Brass cylinders and sponge inserted (green and red lines respectively); measurements made using TFM method.

Acknowledgement

The research reported here has been supported by EPSRC grant EP/K038214/1.

References

[1] N. Engheta, R.W. Ziolkowski: Metamaterials: physics and engineering explorations. Wiley & Sons, Danvers, 2006. (Chapter 1).

[2] V.G. Veselago: The electrodynamics of substances with simultaneously negative values of ε and μ. Soviet Physics - Uspekhi 10 (1968) 509-514.

[3] R.A. Shelby, D.R. Smith, S. Schultz: Experimental verification of a negative index of refraction. Science 292 (2001) 77-79.

[4] E.P. Bowyer, D.J. O'Boy, V.V. Krylov, F. Gautier: Experimental investigation of damping flexural vibrations in plates containing tapered indentations of power-law profile. Applied Acoustics 74 (2013) 553–560.

[5] V.V. Krylov: Acoustic black holes: Recent developments in the theory and applications. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency control 61 (2014) 1296-1306.

[6] R. Li, X. Zhu, B. Liang, Y. Li, X. Zou, J. Cheng: A broadband acoustic omnidirectional absorber comprising positive index materials. Applied Physics Letters 99 (2011) 193507.

[7] A. Climente, D. Torrent, J. Sanchez-Deseha: Omnidirectional broadband acoustic absorber based on metamaterials. Applied Physics Letters 100 (2012) 144103.

[8] O. Umnova, B. Zajamsek: Omnidirectional graded index sound absorber. Proc. Conf. Acoustics 2012, 3631-3637.

[9] C.J. Naify, T.P. Martin, C.N. Layman, M. Nicholas, A.L. Tangawng, D.C. Calvo, G.J. Orris: Underwater acoustic omnidirectional absorber. Applied Physics Letters 104 (2014) 073505.

[10] A. Azbaid El Ouahabi, V.V. Krylov, D.J. O'Boy: Quasi-flat acoustic absorber enhanced by metamaterials. Proceedings of Meetings on Acoustics 22 (2014) 040002.