

Experimental Investigations of Quasi-flat Acoustic Absorbers Enhanced by Metamaterial Layers

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Abstract

The efficiency of acoustic absorbers used for noise control 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 sponges, fibreglass, etc. In the present work, a wide range of 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 at the frequency range of 500-3000 Hz. Both normal and oblique incidence of sound have been considered. The results show that the presence of matching metamaterial layers brings substantial reduction in sound reflection coefficients, thus increasing the efficiency of acoustic absorbers.

Keywords: Acoustic metamaterials; Quasi-flat acoustic absorber; Impedance matching; Acoustic reflection.

Экспериментальные исследования квази-плоских акустических поглотителей, обогащенных слоями из метаматериалов

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Аннотация

Эффективность акустических поглотителей, используемых для контроля уровня шума, может быть улучшена за счет обеспечения плавного перехода от акустического импеданса воздуха до акустического импеданса поглощающего материала. В данной работе, такой плавный переход материализуется с помощью применения градиентных слоев из метаматериалов, образованных квазипериодическими решетками твердых цилиндров (трубок) с внешними диаметрами, постепенно увеличивающимися от внешнего ряда трубок, граничащих с открытым воздухом, к внутреннему ряду, соприкасающемуся с поглощающим пористым материалом. Если длины акустических волн намного больше чем периодичность решетки, такая структура обеспечивает постепенное увеличение акустического импеданса метаматериала в направлении к внутренним рядам цилиндров. Это позволяет разработчику достичь почти идеального согласования импедансов между воздухом и пористыми абсорбирующими материалами, такими как губки, стекловолокно, и т.д. В настоящей работе, широкий диапазон измерений коэффициентов отражения звука от различных абсорбирующих материалов в сочетании с соответствующими согласующими слоями метаматериала, образованными решетками латунных трубок, проводились в диапазоне частот 500-3000 Гц. Исследовались как нормальное, так и

наклонное падение звука. Полученные результаты показывают, что наличие согласующих слоев метаматериала приводит к существенному снижению коэффициентов отражения звука, тем самым увеличивая эффективность акустических поглотителей.

Ключевые слова: Акустические метаматериалы; Квази-плоский акустический поглотитель; Согласование импедансов; Акустическое отражение.

Introduction

Acoustic metamaterials are artificially created materials which can provide acoustic properties that otherwise would be hard or impossible to find in nature. Like metamaterials in other areas of physics and technology [1-3], acoustic metamaterials gain their properties from structure rather than composition, using the inclusion of small inhomogeneities to achieve desirable macroscopic behavior (see e.g. [4, 5]). In particular, in some recent publications [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 paper, a new type of metamaterial-based absorbers is described and investigated - a 'Quasi-Flat Acoustic Absorber' (QFAA) enhanced by the presence of a gradient metamaterial layer for efficient sound absorption in air. 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. Different types of common porous absorbers (Sponges, 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 forming the impedance matching metamaterial layers 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.

A wide range of measurements of sound reflection coefficients at normal and oblique incidence from different absorbing materials combined with matching metamaterial layers formed by the arrays of brass tubes have been carried out. Part of the material described in this paper was presented at the conferences [10, 11]. 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.

1. Experimental Setup and Procedure

As part of the Quasi-Flat Acoustic Absorber (QFAA) investigated in this work, 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 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. 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 quasi-periodic system of solid cylinders with varying filling fraction ff backed by a layer of the absorbing material. Figure 1 shows a 3D schematic view of a Quasi-Flat Acoustic Absorber.

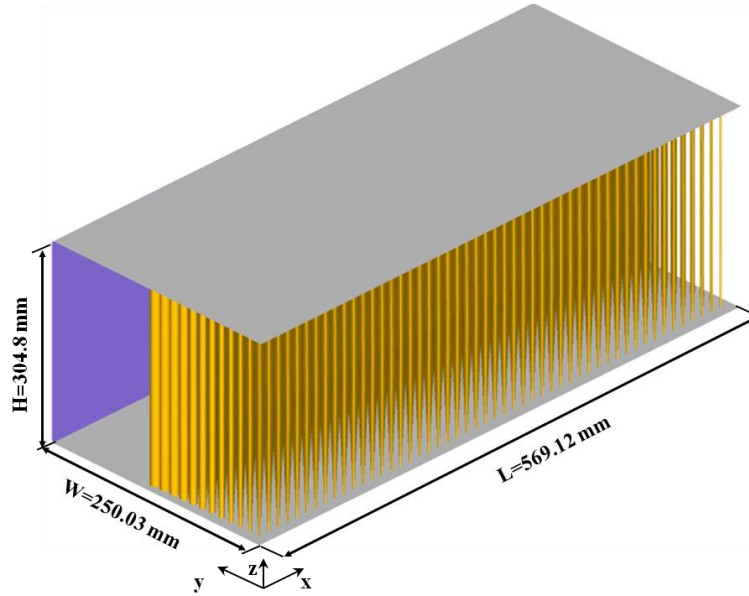


Fig. 1. Schematic 3D view of a Quasi-Flat Acoustic Absorber (QFAA) showing the absorbing material zone (on the back) and the impedance matching metamaterial layer formed by a quasi-periodic array of Brass cylinders

The varying filling fraction ff and the effective acoustic impedance Z_{eff} for the system under consideration can be defined as follows [8]:

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

$$Z_{eff} = Z_0 \frac{\sqrt{1+ff}}{1-ff}. \quad (2)$$

Here 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 under normal and oblique incidence of sound. As a sound source, a loudspeaker was used to produce the constant broadband sound using a white noise generator. It was fixed on a vertical bar that allowed it to be rotated around the central point of the QFAA surface in order to allow for measurements at oblique incidence.

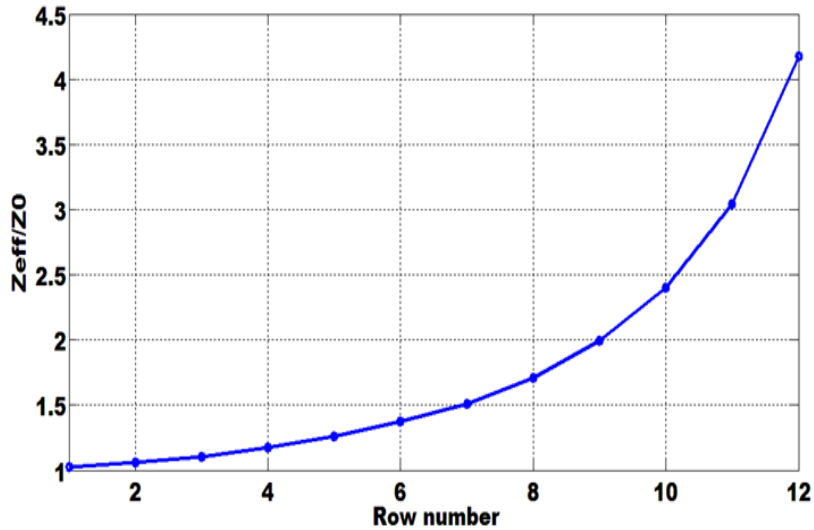


Fig. 2. Normalized effective impedance of the metamaterial layer as a function of a row number

Figure 3 shows the photograph of the experimental set-up used to measure the sound pressure reflection coefficients in the general case of oblique incidence of sound. The selected spacing between the centre of QFAA surface and the loudspeaker was $d = 2$ m in order to generate the desired almost plane wave front when the sound reaches the sample. Two nominally identical microphones (G.R.A.S. 40AE, pre-polarized $\frac{1}{2}$ inch free-field) were calibrated via the same pistonphone and connected to a PC via a dynamic signal acquisition module NI-USB-4431 card (four analog input channels and one output channel) for making sound measurements.

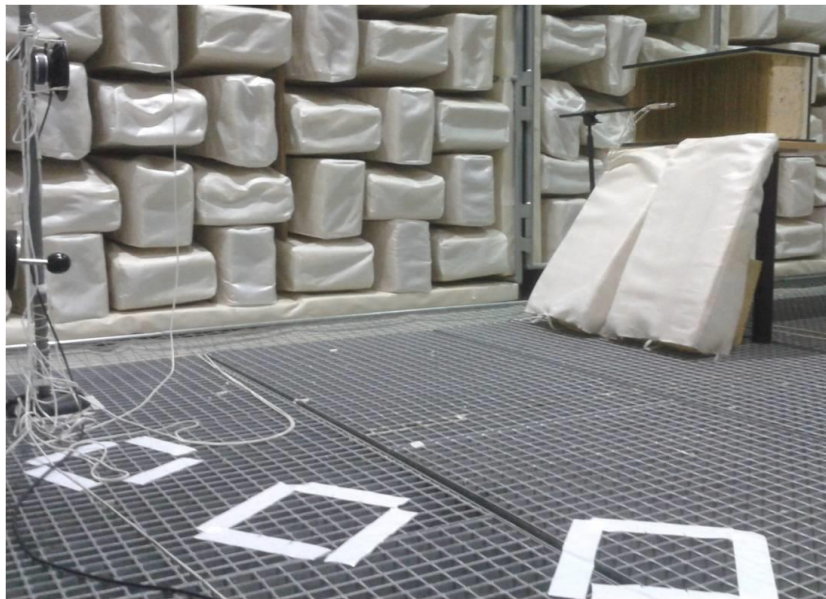


Fig. 3. Photograph of the experimental set-up showing the QFAA (right) and the position of a loudspeaker (left) for normal and oblique incidence

The two microphone transfer function method was applied over a relatively large number of time samples, where the frequency response functions were processed to obtain the reflection coefficients from the QFAA. The distance from the sample face to the first microphone was $l = 2$ cm, and the distance between the microphones was $s = 3.5$ cm. Figure 4 shows a schematic diagram of the experimental setup.

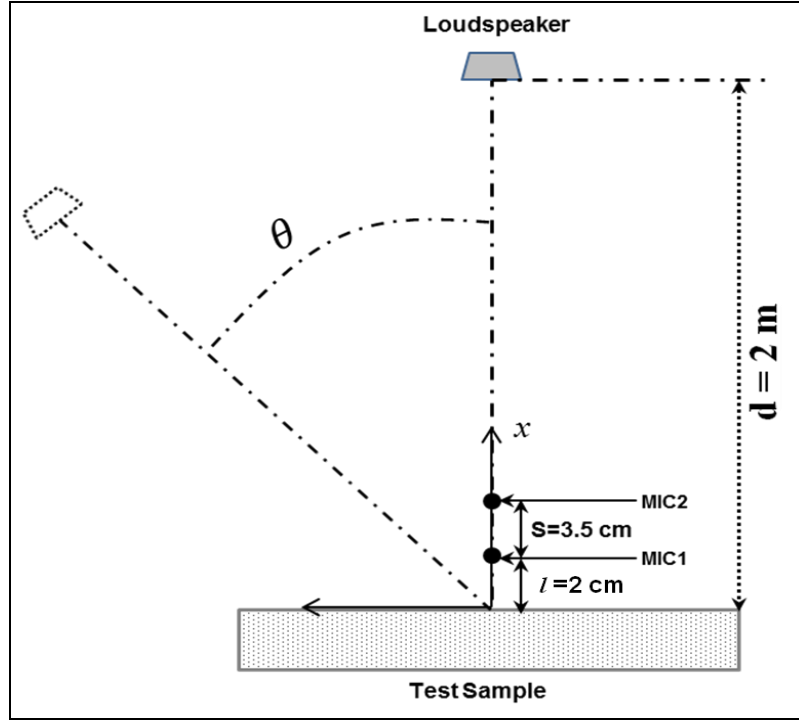


Fig. 4. Schematic of the experimental arrangement

If a plane wave is assumed to be incident upon a test sample, then for an incident angle θ the superposition of the incident and reflected waves in the x -direction is:

$$p = A(e^{ikx \cos \theta} + R e^{-ikx \cos \theta}), \quad (3)$$

where R is the reflection coefficient; k is the acoustic wavenumber, and A is a complex amplitude constant (the sample is assumed to be at $x = 0$). The dependence on y -coordinate is the same for incident and reflected waves. Therefore, it is not written down here for shortness.

The transfer function between the two microphones' positions is given by

$$H_{21} = \frac{e^{ikx_1 \cos \theta} + R e^{-ikx_1 \cos \theta}}{e^{ikx_2 \cos \theta} + R e^{-ikx_2 \cos \theta}}, \quad (4)$$

where x_1 and x_2 are the positions of the microphones shown in Fig. 4. A rearrangement of formula (4) leads directly to the expression for the reflection coefficient:

$$R = \frac{H_{21} - e^{-ik s \cos \theta}}{e^{ik s \cos \theta} - H_{21}} e^{2ik(l+s) \cos \theta}. \quad (5)$$

There are some restrictions on the microphone spacing [12]. The lower and upper frequency limits are given by

$$\frac{0.05c}{s} < f < \frac{0.45c}{s}, \quad (6)$$

where c is the sound velocity. In the present work, the testing frequency range is chosen to be between 500 Hz and 3000 Hz.

2. Results and Discussion

Measurements of sound reflection coefficients from different absorbing porous materials combined with matching metamaterial layers formed by the arrays of Brass tubes have been carried out at normal and oblique incidence. Four types of absorbing porous materials have been used in the absorbing material zone. Sponges with different densities: sponge1 (medium density), sponge2 (reflex medium), sponge3 (reflex firm), and fibreglass. Impedance measurements for absorbing porous materials have been carried out at normal incidence of sound using the above-mentioned Two Microphone Transfer Function Method. The normalized acoustic impedances of sponges and fibreglass (relative to the acoustic impedance of air Z_0) calculated from the measured reflection coefficients are shown in Fig. 5 as functions of frequency.

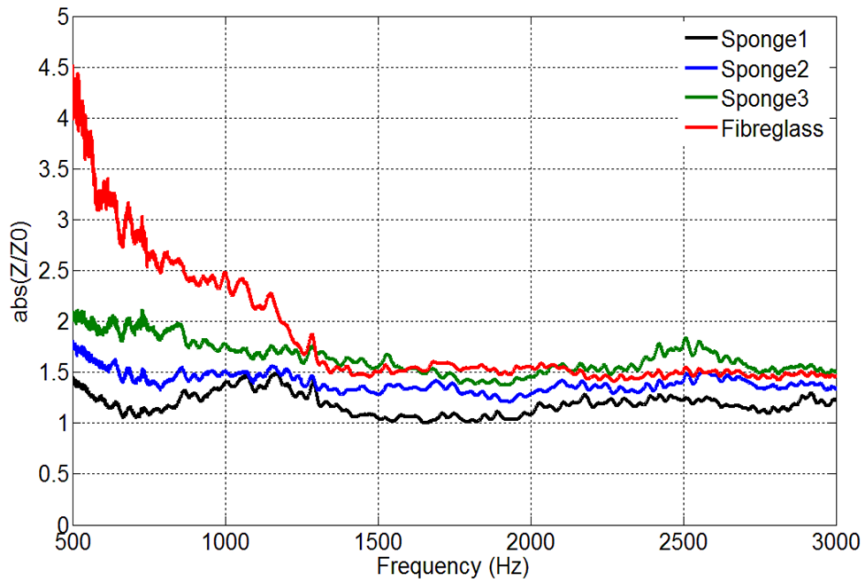


Fig. 5. Normalized acoustic impedances of sponges with different densities and of fibreglass calculated from the measured reflection coefficients

Different configurations of QFAA, containing 6, 7, 8 and 9 rows of Brass cylinders, with sponges of different densities backed the last row of metamaterial layer, and QFAA containing 10 rows with fibreglass inserted in the absorbing material zone have been investigated at normal and oblique incidence. Measurements of the reflection coefficients have been carried out using the Two Microphone Transfer Function Method. The incident angle θ was varied from 0^0 (normal incidence) to 45^0 with a step of 15^0 (oblique incidence).

For normal incidence, the measurements of the reflection coefficients, at frequencies from 500 Hz to 3000 Hz, for the box with sponge1 (medium density) and for QFAA containing 6 to 9 rows of Brass cylinders with sponge1 backed the last row of metamaterial layer are shown in Fig. 6.

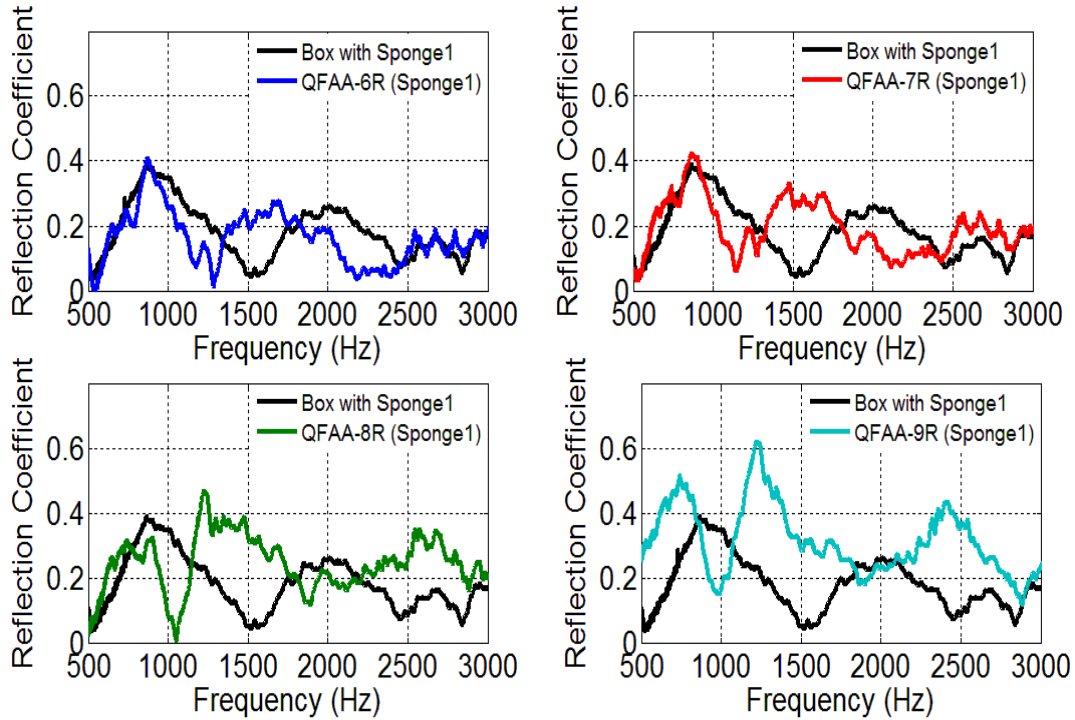


Fig. 6. Sound reflection coefficients measured at normal incidence for the box with sponge1 (medium density) (black line) and for the QFAA with 6, 7, 8 and 9 rows of Brass cylinders (blue, red, green and light-blue lines respectively), with sponge1 inserted

The results show almost similar reflection coefficients (in comparison with the box with sponge1 only) for the QFAA containing 6, and 7 rows with sponge1 inserted, and the QFAA with 8 and 9 rows with sponge1 inserted shows similar and even higher reflection coefficients than the box with sponge1 alone at some frequency range. These observations show that in this case there is no impedance matching between the sponge1 (medium density) and the metamaterial layers containing all the above-mentioned numbers of rows (6, 7, 8 and 9). Indeed, the impedance of this sponge is already almost equal to the impedance of the air (see Fig. 5), and the addition of a metamaterial layer only makes things worse for all numbers of rows of cylinders (Fig. 2).

In order to study the influence of oblique incidence on the reflection coefficients from the QFAA containing 6, 7, 8 and 9 rows with sponge1 inserted, measurements of the reflection coefficients have been repeated for the angles of incidence 15° , 30° and 45° . The results are shown in Figs. 7, 8, and 9 respectively.

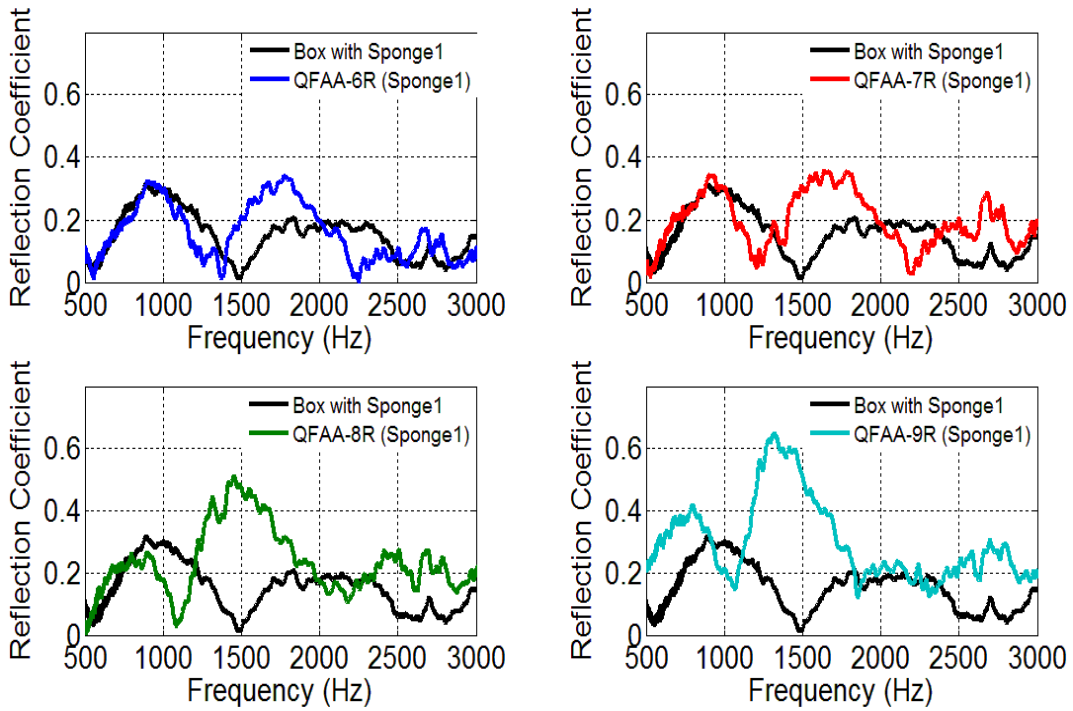


Fig. 7. Sound reflection coefficients measured at angle of incidence 15^0 for the box with sponge1 (medium density) (black line) and for the QFAA with 6, 7, 8 and 9 rows of Brass cylinders (blue, red, green and light-blue line respectively), with sponge1 inserted

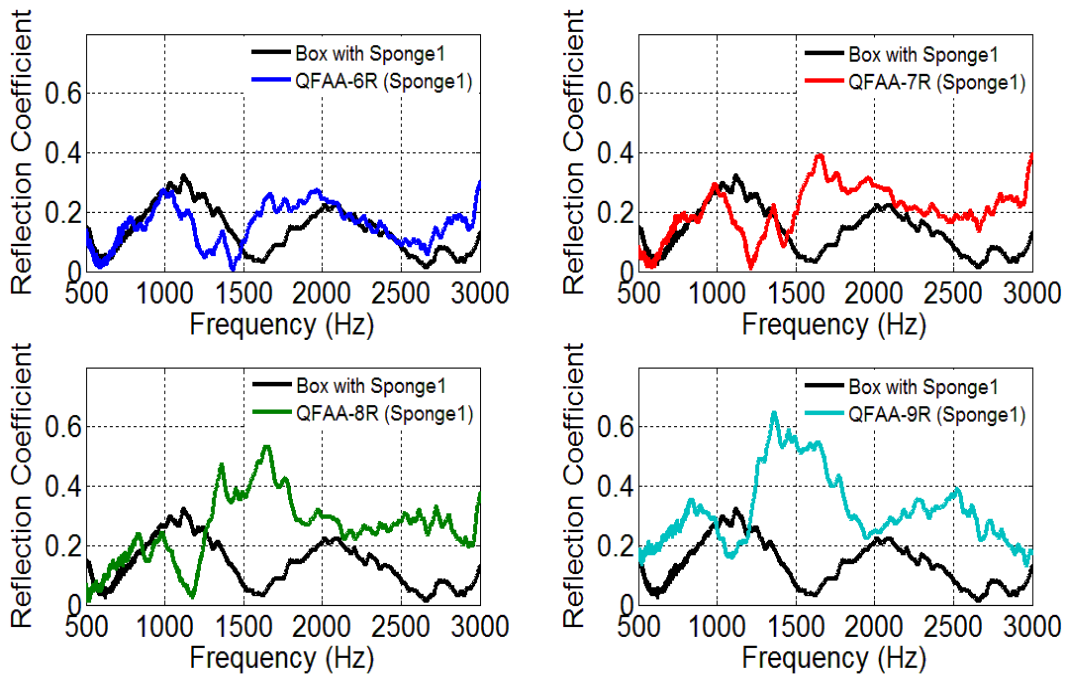


Fig. 8. Sound reflection coefficients measured at angle of incidence 30^0 for the box with sponge1 (medium density) (black line) and for the QFAA with 6, 7, 8 and 9 rows of Brass cylinders (blue, red, green and light-blue line respectively), with sponge1 inserted

It can be seen that the reflection coefficients at oblique incidence from QFAA containing 6, 7, 8 and 9 rows with sponge1 inserted are still similar or higher than the reflection coefficients from the box with sponge1 alone. For the case of sponge2 (reflex medium) backed the last row of metamaterial layer of QFAA with 6, 7, 8 and 9 rows, the measurements of the reflection coefficients have been carried out in the same way as above at normal incidence, and the angles of incidence 15° , 30° and 45° . The results, that are not shown here for shortness, demonstrate that the insertion of the sponge2 does not bring noticeable reductions in the reflection coefficients. This can be explained by the fact that acoustic properties of sponge2 are similar to those of sponge1 (see Fig. 5), and there is no impedance matching between the sponge2 (reflex medium) and the last rows of the metamaterial layer.

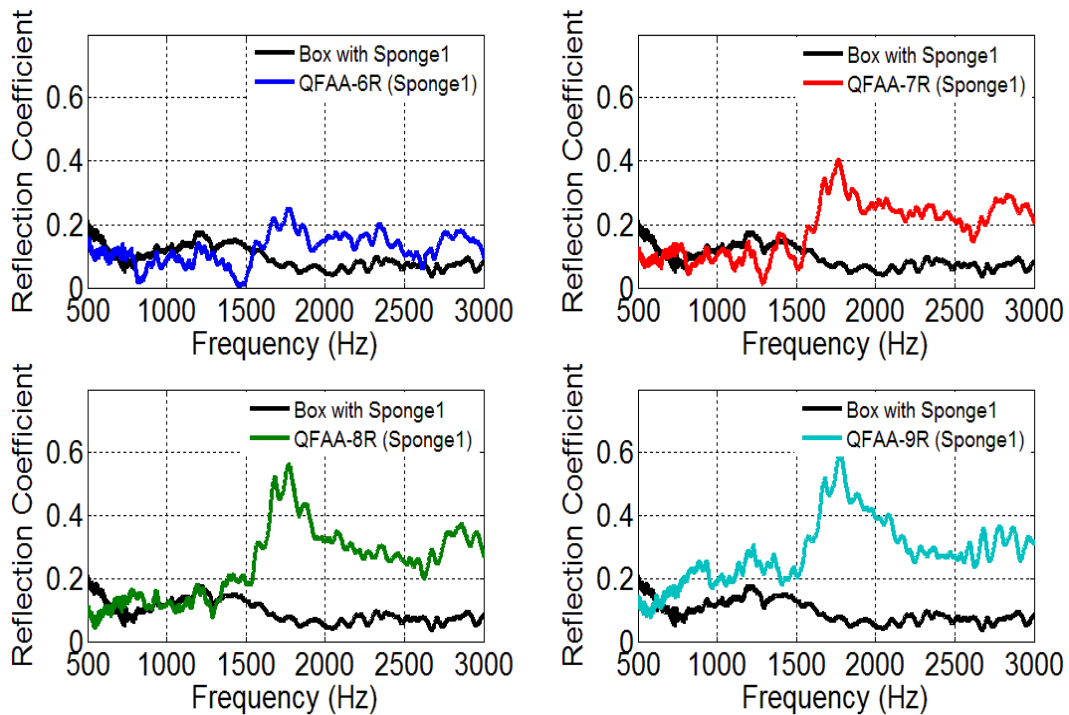


Fig. 9. Sound reflection coefficients measured at angle of incidence 45° for the box with sponge1 (medium density) (black line) and for the QFAA with 6, 7, 8 and 9 rows of Brass cylinders (blue, red, green and light-blue line respectively), with sponge1 inserted

The same tests as above were repeated for sponge3 (reflex firm) as an absorbing porous material. Its acoustic impedance is greater than that for the sponge1 and sponge2, see Fig. 5, so that one would expect its better matching to the effective impedance at the last row of the metamaterial layer of QFAA with 7, 8 and 9 rows. The results of the measurements of the reflection coefficients at normal incidence for the box with inserted sponge3 and for the QFAA with 6, 7, 8 and 9 rows with sponge3 inserted are shown in Fig. 10. It can be seen that there is no significant difference among the measurement values of reflection coefficients from box with sponge3 inserted and QFAA with 6 rows with sponge3 inserted. However, the QFAA with 7, 8 and 9 rows with sponge3 inserted provides lower reflection coefficients than the box with sponge3 alone. This demonstrates the functionality of matching the impedances using metamaterial layers.

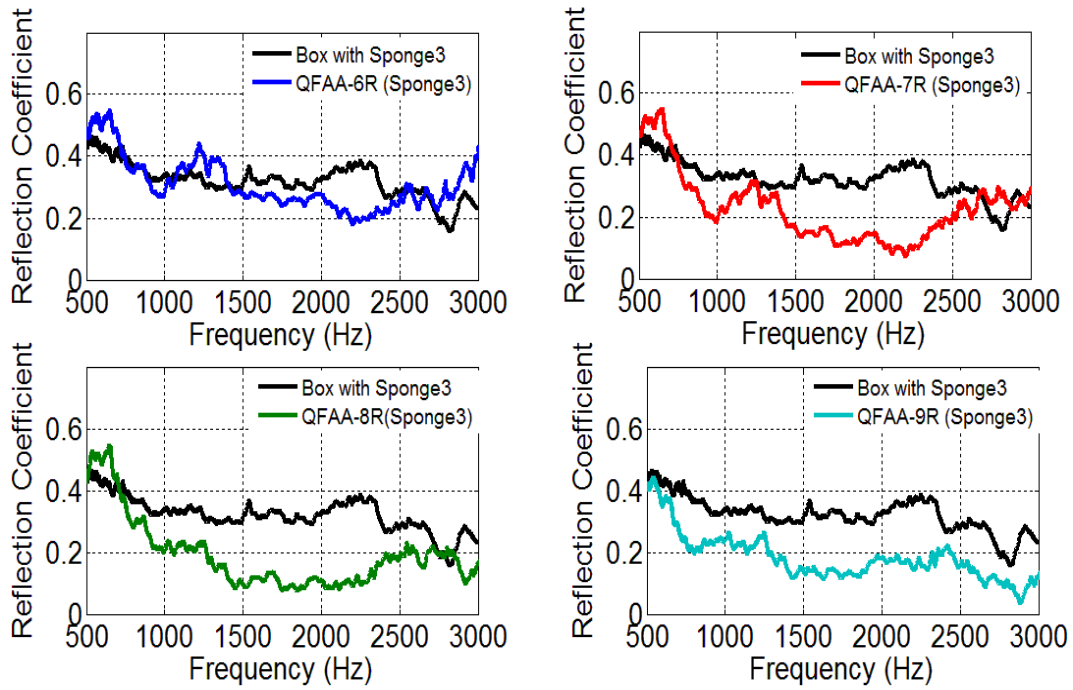


Fig. 10. Sound reflection coefficients measured at normal incidence for the box with sponge3 (reflex firm) (black line) and for the QFAA with 6, 7, 8 and 9 rows of Brass cylinders (blue, red, green and light-blue line respectively), with sponge3 inserted

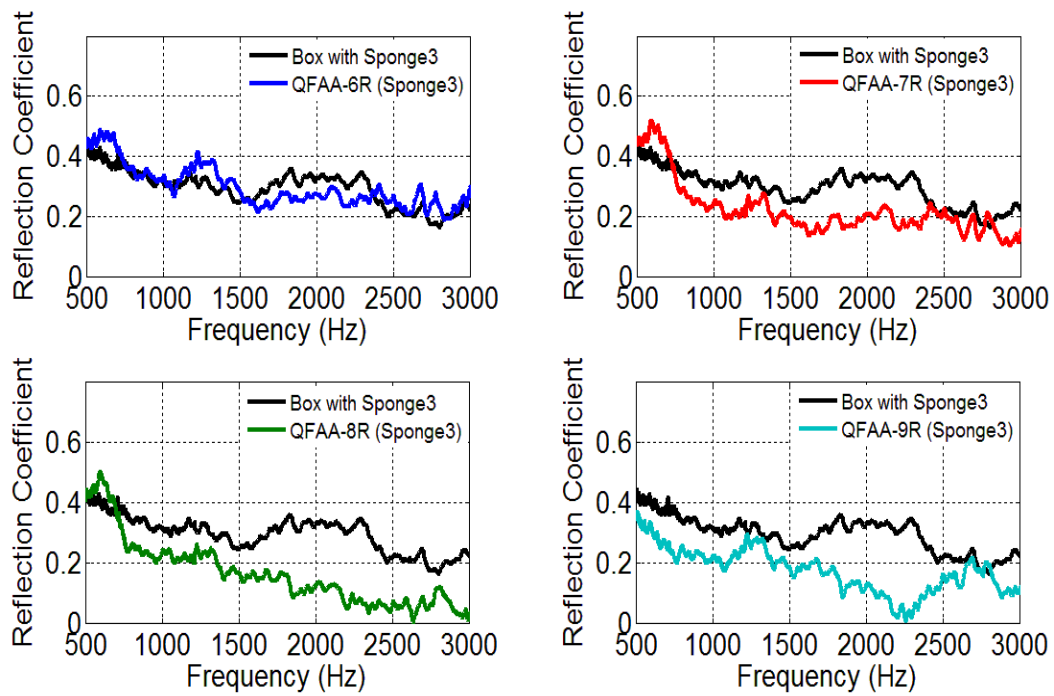


Fig. 11. Sound reflection coefficients measured at angle of incidence 15° for the box with sponge3 (reflex firm) (black line) and for the QFAA with 6, 7, 8 and 9 rows of Brass cylinders (blue, red, green and light-blue line respectively), with sponge3 inserted

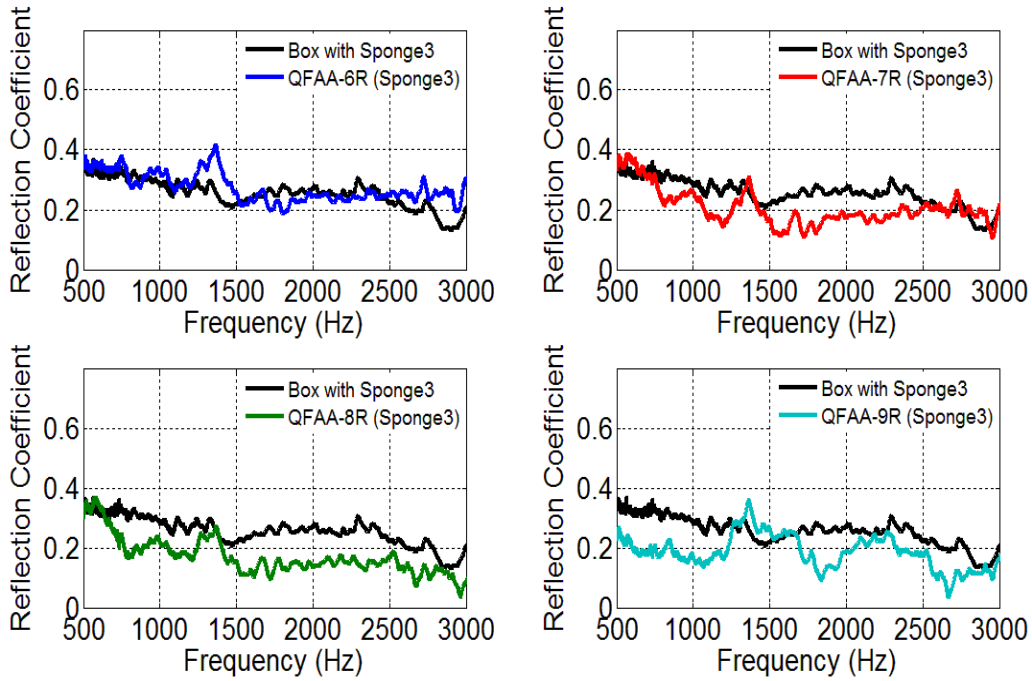


Fig. 12. Sound reflection coefficients measured at angle of incidence 30° for the box with sponge3 (reflex firm) (black line) and for the QFAA with 6, 7, 8 and 9 rows of Brass cylinders (blue, red, green and light-blue line respectively), with sponge3 inserted

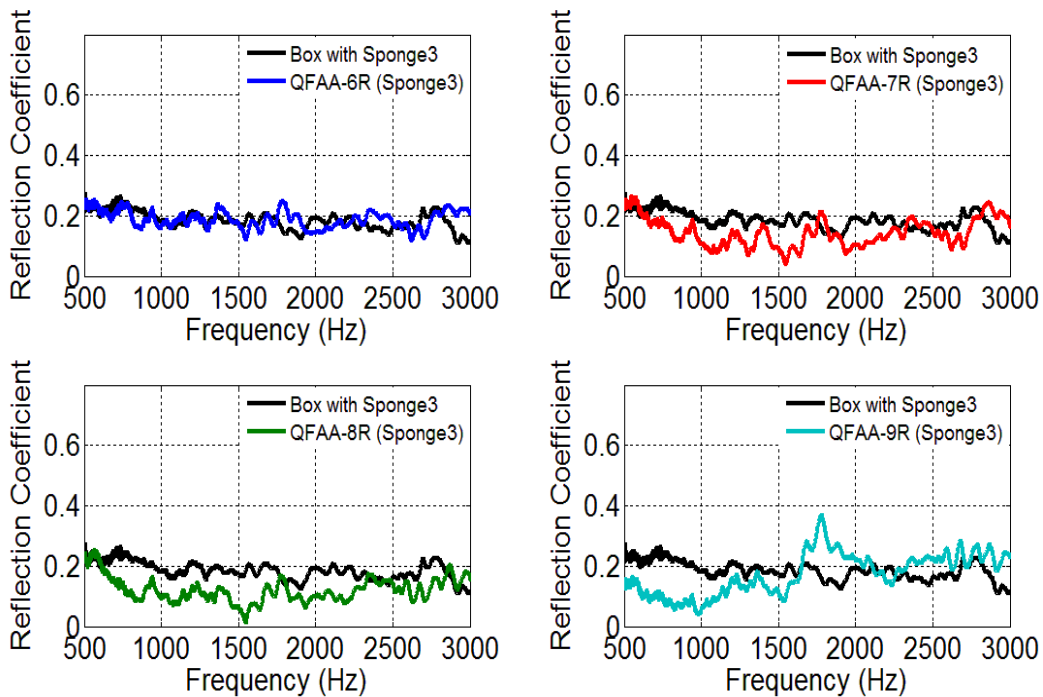


Fig. 13. Sound reflection coefficients measured at angle of incidence 45° for the box with sponge3 (reflex firm) (black line) and for the QFAA with 6, 7, 8 and 9 rows of Brass cylinders (blue, red, green and light-blue line respectively), with sponge3 inserted

For the angles of incidence 15° , 30° and 45° , the measurements of the reflection coefficients for the box with sponge3 and for QFAA containing 6 to 9 rows of cylinders with sponge3 inserted, are shown in Figs. 11, 12 and 13 respectively. It can be seen from Figs. 11, 12 and 13 that at angles of incidence 15° , 30° and 45° the QFAA containing 6 rows with sponge3 inserted produces similar reflection coefficients that the box with sponge3 does. However, the QFAA containing 7, 8 and 9 rows produces lower reflection coefficients than the box with sponge3, and the values of reflection coefficients increase toward the values of reflection coefficients from the box with sponge3 inserted with the increase of the incident angle. As the angle of incidence increases, the role of QFAA (7, 8, and 9 rows, with sponge3) becomes less significant.

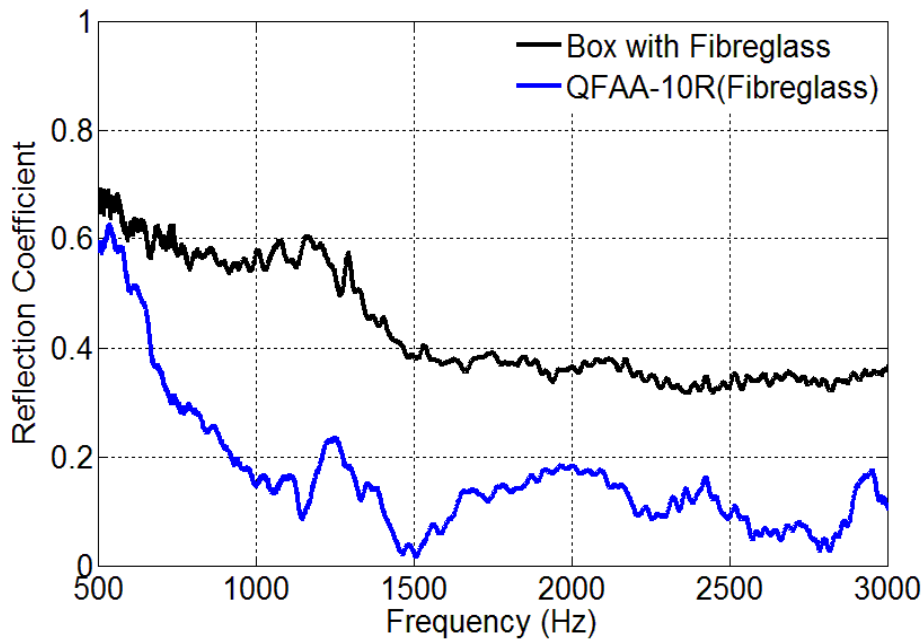


Fig. 14. Sound reflection coefficients measured at normal incidence for the box with fibreglass (black line) and for the QFAA with 10 rows of Brass cylinders (blue line), with fibreglass inserted

Let us now consider the effect of matching metamaterial layers on sound reflection from fibreglass as an absorbing material. A fibreglass as a porous absorbing material for QFAA has been earlier investigated at normal incidence [10, 11]. In what follows, the results of further experimental investigations of QFAA containing 10 rows and with fibreglass inserted are reported, both at normal incidence and at oblique incidence. The results for normal incidence are shown in Fig. 14, in comparison with the results for the box with fibreglass alone. It can be seen that at all frequencies the reflection coefficient for the box with fibreglass inserted is strongly reduced when the QFAA containing 10 rows with fibreglass inserted has been added.

Measurement of the reflection coefficients at oblique incidence have been carried out for the QFAA containing 10 rows and with fibreglass inserted. The results for angles of incidence 15° , 30° and 45° are shown in Figs. 15, 16 and 17 respectively, in comparison with the results for the box with fibreglass alone. It can be seen that at all angles of incidence the QFAA containing 10 rows with fibreglass provides lower reflection coefficients than the box with fibreglass alone, but the effect of QFAA (10 rows with fibreglass inserted) becomes more complicated as the angle of incidence increases.

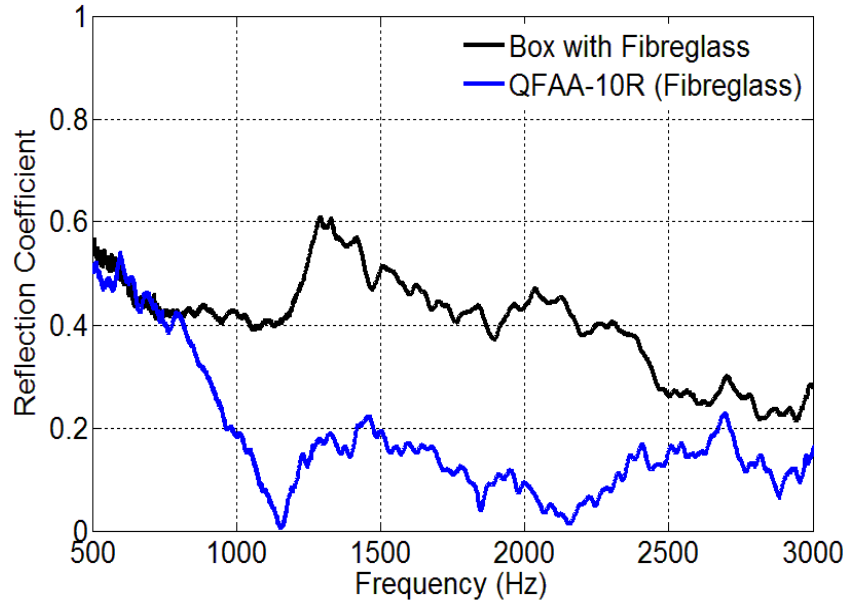


Fig. 15. Sound reflection coefficients measured at angle of incidence 15° for the box with fibreglass (black line) and for the QFAA with 10 rows of Brass cylinders (blue line), with fibreglass inserted

This behaviour can be related to the fact that the reflection coefficients in these cases depend not only on impedances of the absorbing materials and of the last row of a metamaterial layer, but on the angle of incidence of sound as well. Also, the effects of edge diffraction on the measurements of reflection coefficients at oblique incidence could have played a role.

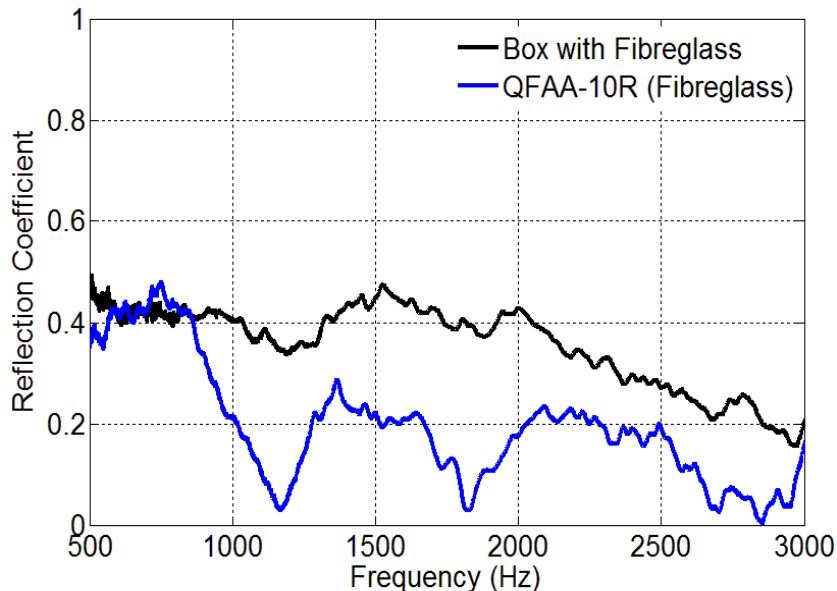


Fig. 16. Sound reflection coefficients measured at angle of incidence 30° for the box with fibreglass (black line) and for the QFAA with 10 rows of Brass cylinders (blue line), with fibreglass inserted

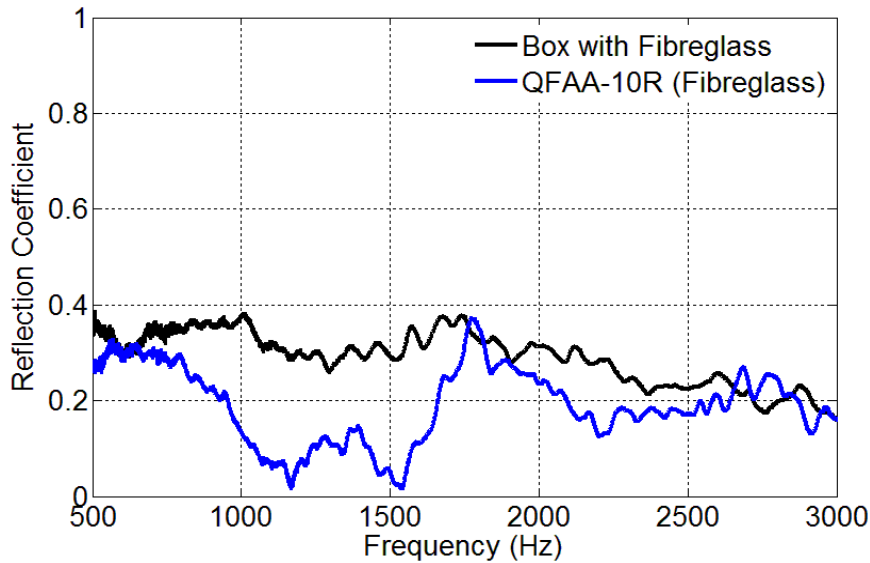


Fig. 17. Sound reflection coefficients measured at angle of incidence 45° for the box with fibreglass (black line) and for the QFAA with 10 rows of Brass cylinders (blue line), with fibreglass inserted

It can be seen from Figs. 14, 15, 16 and 17 that, for the QFAA with fibreglass as absorbing material, the presence of the impedance matching metamaterial layer reduces the acoustic reflection coefficients for all angles of incidence. This can be explained by the fact that fibreglass has higher values of the acoustic impedance in comparison with sponges. Therefore, using impedance matching metamaterial layers in this case brings more substantial benefits from the point of view of reduction of sound reflection.

3. Conclusions

A quasi-flat acoustic absorber (QFAA) enhanced by the presence of gradient index metamaterial layers 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 in the case of normal incidence of sound the values of sound reflection coefficient for the QFAA depend strongly on the impedance matching between the porous absorbing material (different types of sponge and fibreglass) and the exit of the gradient metamaterial layer. In particular, for certain numbers of rows of cylinders very low values of the reflection coefficient can be achieved. This can be explained by a nearly perfect impedance matching achieved in such cases.

In cases of oblique incidence of sound on the impedance matching metamaterial layers, the effects of metamaterial layers become more complicated. This behaviour can be attributed to the fact that the reflection coefficients in these cases depend not only on impedances of the absorbing materials and of the last row of a metamaterial layer, but on the angle of incidence of sound as well.

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 porous absorbing materials with high values of acoustic impedance can bring substantial reductions in sound reflection coefficients in comparison with the case of sound reflection from the porous materials alone, which improves the efficiency of sound absorption.

Acknowledgement

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

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