Acoustic Absorption of Foams Coated with MR Fluid under the Influence of Magnetic Field

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ABSTRACT: The article presents results of the acoustic measurements on open-cell porous media coated with a magnetorheological (MR) fluid. Sound absorption of polyurethane foams of different, single and dual porosity was tested in the impedance tube. The measurements were conducted in three stages using clean samples, the same samples moistened with MR fluid, and finally, exposing the MR fluid-coated samples to a constant magnetic field. The transfer function method was employed to determine the acoustic absorption coefficient. Two significant, controllable effects were observed in the curve illustrating the variation of the acoustic absorption coefficient with frequency, especially, for the foams of dual porosity. Namely, relative to the field-free conditions, or to the clean foams, the most substantial peak in the absorption curve could be shifted by applying a magnetic field. Moreover, a resulting significant increase in acoustic absorption yields, in a wide frequency range directly behind the peak.

Key Words: magnetorheological foams, acoustic absorption, adaptive sound insulator, dual-porosity foams.

INTRODUCTION

MAGNETORHEOLOGICAL (MR) foams belong to a class of smart materials whose rheological properties may be controlled by the application of an external magnetic field. Two main groups of MR foams can be distinguished, namely, dry foams with ferromagnetic particles entrapped in a frame, and foams saturated with a MR fluid. Usually, the saturation will be partialy, since in practical applications one would tend to reduce the volume of MR fluid to the quantity which can be retained within the frame by capillary action. It is worth to notice that, due to structural differences, the two aforementioned materials behave in a distinct way, both in micro- and macroscale, when subjected to an external magnetic field. In either case, ferromagnetic particles are apt to line up along the field lines.

Although MR foams are already used in industrial products (Carlson and Jolly, 2000), they still remain poorly investigated. The main field of application for such composites, which are made up of porous sponge-like carrying material (matrix) soaked with MR fluid, is damping of vibrations (Carlson and Jolly, 2000; Kaleta et al., 2003). However, new areas of applications are constantly proposed.

The idea of using MR foams for active acoustic absorption was proposed for the first time by Scarpa et al. (2004). This pioneering study was aimed principally at proofing the active approach concept on a special type of open-cell auxetic (i.e., with a negative Poisson's ratio) polyurethane (PU) foam seeded with magnetically susceptible particles immersed in a silicon oil carrier. The authors investigated changes of acoustic absorption coefficient for the auxetic MR foam both in the absence and in the presence of magnetic field. The measurements were conducted using impedance tube and two types of permanent magnet of different intensity. The authors compared the results with the clean auxetic foam and a PU foam from which the auxetic foam had been made. The results presented in (Scarpa et al., 2004) indicate that the magnetic field improve sound absorption of MR foams in a higher frequency range.

In another paper Scarpa and Smith (2004) present a comparative experimental study concerning the mechanical, acoustic, and electromagnetic properties of an auxetic rigid PU foam with a MR fluid coating. Nevertheless, in this article the acoustic properties of MR foam were measured only in the absence of magnetic field. This was probably caused by the fact that a clean sample of the auxetic foam showed much better performance in acoustic absorption in the whole frequency range than the sample coated with the MR fluid.

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The present article describes an experimental study solely devoted to the influence of constant magnetic field on the acoustic properties of PU foams coated with MR fluid. Moreover, unlike the works by Scarpa and Smith (2004) and Scarpa et al. (2004) here, conventional foams – with positive Poisson ratio – are investigated. The foam samples are saturated with MR fluid. To ensure uniform distribution of the fluid throughout the frame, the procedure of saturation consists in soaking and squeezing the samples so that the MR fluid creates a thin coating of the skeleton of porous medium. The squeezing is finished when the fluid ceases to flow out from the pores. Such procedure is repeated several times for one sample. Scarpa and Smith (2004) used another technique, namely, after rolling the foams in a tray filled with MR fluid the obtained MR fluid surface-coated samples were left for 48 h to expel an excess of the liquid. Finally, it must be emphasized that the measurements of acoustic absorption coefficient presented here were made for a much wider frequency range than the one used in (Scarpa and Smith, 2004; Scarpa et al., 2004). Attention was paid also to the influence of the thickness of foams. Moreover, in the present work the tests were carried out for two types of PU foams, namely:

- a foam of dual porosity – where, in a micro-porous domain, bigger, irregular, mesoscopic pores are distributed,
- foams with single, microscopic-scale (homogeneous) porosity.

The methodology of the experiment is thoroughly explained below, in the next section, where the two-microphone transfer-function method, which was used for the measurements of acoustic absorption, is also briefly described. Finally, the results of the most representative tests are thoroughly discussed.

EXPERIMENT

The general purpose of the experiment was to measure acoustic absorption of foams whose pores are partially filled with MR fluid. It was investigated whether such a composite had a potential to be used as an acoustic absorber and if its acoustic absorption might be improved in magnetic field. Eventually, the effect of variable magnetic field should be checked to investigate the effectiveness of adaptive acoustic absorber.

All measurements were performed by the transfer function method (Chung and Blaser, 1980; Dalmont, 2001; Boonen and Sas, 2004) according to the ISO 10534-2 standard (ISO, 1998) using the two-microphone configuration of impedance tube. A diagram of the instrumentation is shown in Figure 1. A loudspeaker, mounted at one end of the impedance tube, is driven by a broadband, stationary random signal. The loudspeaker generates plane sound waves, which arrive at a sample placed at the other end of the tube, and are reflected. Obviously, in standard measurements the magnet shown in Figure 1 is not present, and the sample is set at the wall of rigid piston. A standing-wave interference pattern results due to the superposition of forward and backward-traveling waves inside the tube. By measuring the sound pressure at two fixed locations and calculating the so-called complex transfer function, it is possible to determine acoustical properties of the sample, namely, the complex acoustic impedance at normal incidence, the complex reflection coefficient, and the sound absorption coefficient of the sample. Operating frequency range of the instrument depends on the spacing between the microphone positions as well as on the size of samples. The correctness and accuracy of the method strongly depend on the calibration of microphones (Boonen and Sas, 2004). The calibration involves measurement of the transfer function for two configurations of the microphones, in their normal and interchanged positions. The improved calibration procedure proposed by Boonen and Sas (2004) eliminates the calibration of the speed of sound, and consequently, the temperature and ambient pressure measurements are superfluous.

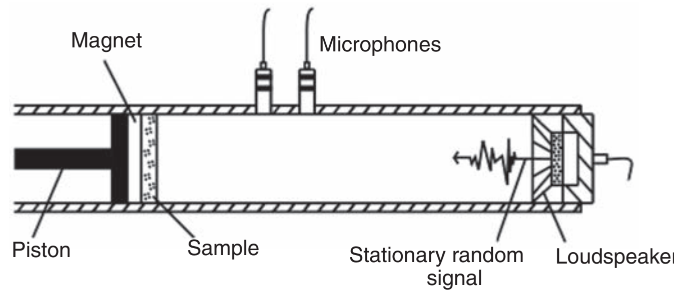

Figure 1. Diagram of an impedance tube with a magnet installed.

As mentioned above the experiment was carried out for two types of foams: one of dual (micro- and mesoscale) porosity, and the other of single, microscopic porosity. The foams were PU, open-cell foams manufactured by *Eurofoam*. The global porosity ratio, declared by the producer, was ~97–98%. An impedance tube manufactured by Bruel & Kjaer, equipped with two condenser microphones and a loudspeaker with a diameter of 80 mm, was employed to perform the measurements. The loudspeaker was excited with a Gaussian white noise. Atmospheric pressure along with temperature and relative humidity were monitored during the tests. Cylindrical samples of diameter 29 mm and various thickness (see, for example, Figure 2), depending on the type of foam, were used.

After the first test in which the clean samples were used, the samples were soaked with a MR fluid (Figures 3 and 4) manufactured by Fraunhofer Institut Silicatforschung. The fluid was a suspension of iron

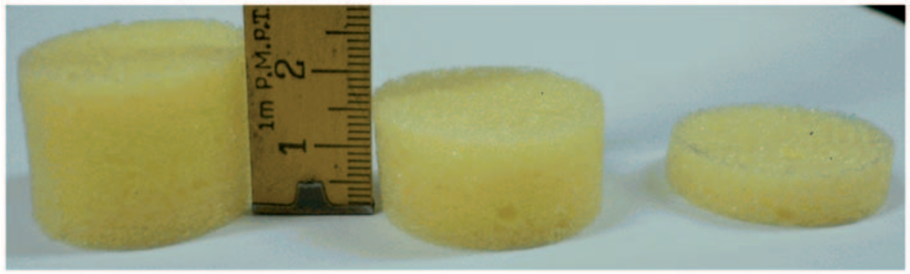

Figure 2. *Three samples of different thickness (21, 16, and 7 mm).*

Figure 3. *Clean foams (outermost samples) and MR fluid-coated foams (two samples in the middle) of inhomogeneous (leftmost samples) and homogenous porosity (rightmost samples).*

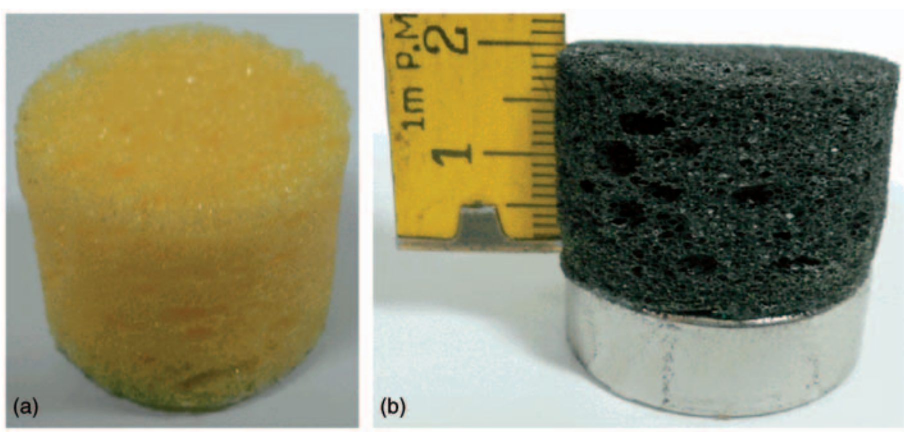

Figure 4. *A 21 mm thick sample of PU foam of dual porosity: (a) clean, and (b) MR fluid-coated and placed on a magnet.*

particles of mean size equal to 5 μm in a carrier liquid being a mixture of mineral and aromatic oil. The MR fluid density was 3.32 g/cm^3 with volumetric content of iron particles of 35%. After the saturation, the foams were squeezed to drain off the fluid. The squeezing was systematically repeated many times until there was no decanting fluid, and the resulting samples were, indeed, foams with a very thin inner-coating of MR fluid (consequently, the weight of MR samples was similar to the weight of clean samples). Such procedure allowed to reach a good repetitiveness in preparation of samples, that is, the discrepancies in results (discussed below) obtained for different samples prepared from the same PU foam were small and definitely not bigger than the discrepancies between clean samples (cut from the same foam). As a matter of fact, the coating seemed to increase the homogeneity of the samples. Moreover, the samples were left to dry for a couple of hours, and during the tests the measurements were also repeated for the same sample a few times during few hours and no significant discrepancies were observed.

After the MR-coated samples had been prepared in the way described above, the measurements of the acoustic absorption coefficient were carried out for the coated samples, exactly in the same way as for the clean samples. The frequency range for both tests was from 500 to 6400 Hz.

Figure 5. *Tube with the magnet and with the magnet and a sample of MR foam.*

In the last stage of experiment the MR-coated samples were exposed to an external magnetic field during the test. To this end, a permanent neodymium magnet (MW29x10/N38 manufactured by *Enes*), with a measured magnetic flux density of ~1.25 T, was used. (The remanence declared by the producer was 1.21–1.25 T.) Its cylindrical shape and dimensions (diameter 29 mm, thickness 10 mm) were chosen deliberately to fit the tube since both factors are critical to the accuracy of the measurements. The direction of magnetization was along the thickness of the magnet, which means that one circular surface of magnet formed the pole 'N', and the opposite one – the pole 'S'. The measured (in the air, close to the magnet surface) intensity of magnetic field was ~950 kA/m. The magnet was placed between a sample and the rigid disk of piston being the bottom of a sample holder so there was no air gap between the three objects (Figures 1, 4(b), and 5). Additional tests were conducted to verify the influence of the magnetic field on the microphones performance, and no changes in the response of the transducers were observed.

It is important to mention that the tests for all the three scenarios were carried out several times for each sample, and the obtained results were very similar (even though a few hours passed between tests performed on coated samples, which proves a stable behavior) so that a simple average curve can be treated as a very good representative. Some differences were observed between the results obtained for different samples (as discussed below) yet their general character was still the same.

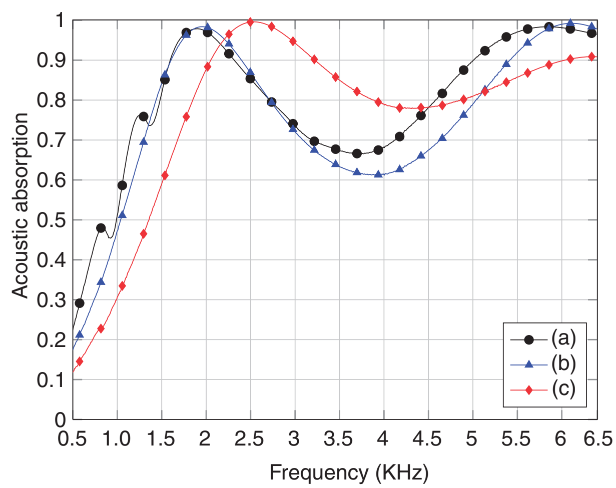

Figure 6. *Acoustic absorption coefficient for PU foam of dual porosity, sample A: (a) clean, (b) MR fluid-coated, and (c) MR fluid-coated and exposed to a magnetic field.*

DISCUSSION OF THE RESULTS OF TESTS

Foam of Dual Porosity

First, the tests were carried out for a PU foam of dual porosity. When examining the foam it was observed that though the microscale porosity was obviously homogeneous, the mesoscale pores were quite irregularly shaped and localized. Moreover, their size should be considered as rather significant in comparison with the dimensions of samples (see, for example, Figure 4, also the two leftmost samples in Figure 3). Therefore, two different samples (marked A and B), both 21 mm thick, were used for the tests. Results of the measurements are presented in Figures 6 and 7. Curves in the graphs show how the acoustic absorption coefficient varies with frequency for the three testing scenarios mentioned above, namely, for:

- clean samples (no coating) – the curves (a) in Figures 6 and 7,
- samples with MR coating (no magnet) – the curves (b) in Figures 6 and 7,
- MR-coated samples in magnetic field – the curves (c) in Figures 6 and 7.

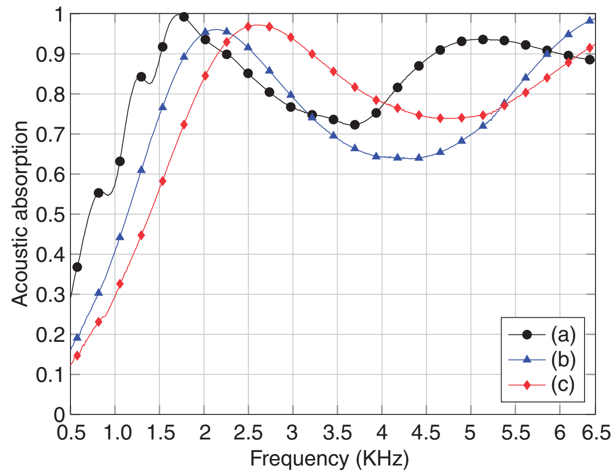

Figure 7. *Acoustic absorption coefficient for PU foam of dual porosity, sample B: (a) clean, (b) MR fluid-coated, and (c) MR fluid-coated and exposed to a magnetic field.*

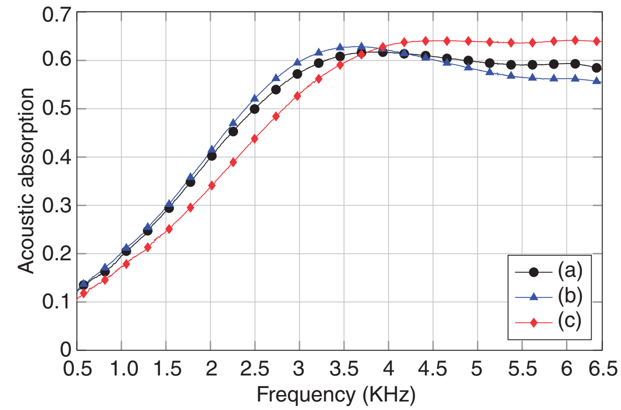

Figure 8. *Acoustic absorption of a stiffer foam of single, microscopic porosity: (a) a clean sample, (b) samples with MR coating (no magnet), and (c) the MR fluid-coated samples in magnetic field.*

As mentioned above, the tests were performed, independently, a few times for each sample: the discrepancies were very small and negligible, which proves the repeatability of tests and credibility of results. Therefore, only the average curve is presented for each of the testing scenarios. However, when comparing the results obtained for different samples (Figures 6 and 7) the differences are more distinct, though still remain very similar in character. This is due to the irregularity of big pores, and (consistently) because of some differences ensuing from the moistening process.

The results of tests show that the acoustic absorption of foam samples coated with MR fluid, in the absence of magnetic field, does not rather exceed the absorption of the clean samples. An interesting observation is that the characteristic peaks, which occur around 800–1000 Hz and 1200–1400 Hz in the case of the clean samples, are smoothed out when the same samples are coated with MR fluid.

The curves obtained for the saturated foams exposed to a constant magnetic field exhibit considerable differences when compared to the analogous characteristics made in the absence of the field. Moreover, their acoustic absorption performance can be better than for the clean foams. Thus, taking into account potential applications of such MR foams to the active noise absorption, two changes play a prominent role. First, the peak value of the absorption coefficient, which appears at ~2000–2200 Hz (depending on the sample), is shifted by ~400–500 Hz. This is followed by the second effect, namely, the acoustic absorption of the MR foams subject to a magnetic field can be higher (by up to 25%) than the absorption of clean foams, in the range of ~2200 to 4000 Hz or 4500 Hz (depending on the sample), and to 5000 or 5400 Hz, respectively, when comparing with the absorption of MR foams in the absence of magnetic field. It is noteworthy that the graphs plotted for the two samples under the influence of magnetic field tend to be quite similar which indicates that homogeneity of the material increases when the field is applied.

Foams of Single, Microscopic Porosity

The tests carried out for single porosity foams yielded less satisfactory results, though still similar in character to the results obtained for the dual-porosity foam. As a matter of fact, two different foams of microscopic porosity were tested.

The results presented in Figure 8 are for the foam which was significantly stiffer than the other foams. The absorption curves were obtained for different samples of thickness equal 26 mm. The foam was very 'homogeneous' so that the results obtained for various samples are similar. The differences between clean and coated samples are rather small, yet sufficiently distinct to confirm the influence of a constant magnetic field on the acoustic absorption of sample. Here, an improvement is gained in higher frequency range, above 3.8 kHz.

The results obtained for a soft foam of single porosity are presented in Figures 9 and 10. Now, samples of different thickness (namely, 21, 16, and 7 mm, see Figure 2) were tested accordingly with the procedure described above, that is: first, the clean samples, and then, the samples coated with MR fluid in the absence and in the presence of magnetic field. As it has been already observed in the case of dual-porosity foam, now, it is again clear that the coating smooths out the acoustic absorption curve. Nevertheless, this effect tends to be rather neutral, since the overall acoustic absorption performance is not decreased, especially, in the case of thicker samples (Figure 9). When a constant magnetic field is applied, a reduction of acoustic absorption is clearly observable in lower frequencies, that is,

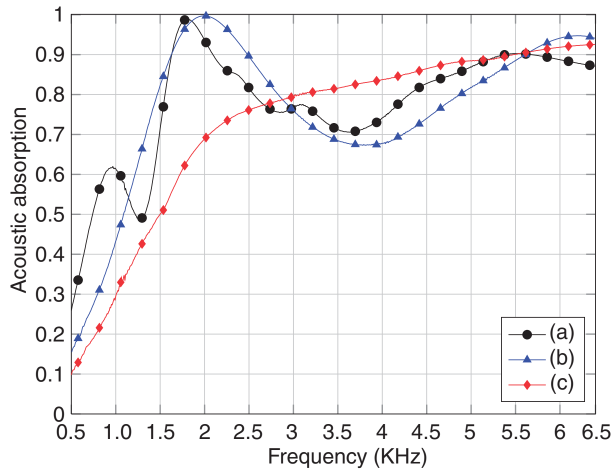

Figure 9. Acoustic absorption of a PU foam of single, microscopic porosity: (a) a clean sample, 21 mm thick, (b) the same sample with MR coating (no magnet), and (c) the MR fluid-coated sample in magnetic field.

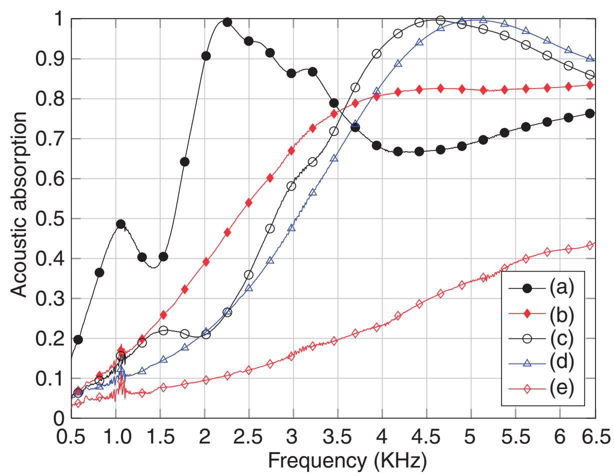

Figure 10. Acoustic absorption of a PU foam of single, microscopic porosity: (a) a clean sample, 16 mm thick, (b) the 16 mm thick sample coated with MR fluid and exposed to a magnetic field, (c) a clean sample, 7 mm thick, (d) the 7 mm thick sample coated with MR fluid (no magnet), and (e) the 7 mm thick MR fluid-coated sample in magnetic field.

below ~3 kHz for the 21 mm thick samples (Figure 9), and below ~3.5 kHz for the 16 mm thick samples (Figure 10). Above these frequencies a moderate improvement is achieved. For the thinnest sample of 7 mm, no improvement is gained at all: the acoustic absorption in magnetic field is very poor indeed in the whole frequency range (see the curve (e) in Figure 10). Anyway, even the moderate increase in value of the acoustic absorption coefficient in higher frequencies, reported for the thicker samples, does not seem to justify using such material to magnetically controlled noise absorption.

CONCLUSIONS

The study presented in the article was intended to investigate the possibility of using MR foams as active or adaptive materials for sound absorption and insulation. To this end, passive tests were carried out by measuring the acoustic absorption coefficient of samples placed in a constant magnetic field. The results of tests were compared with the analogous measurements performed in the absence of the field, and with the results obtained for clean foams.

For the tests, samples based on open-cell PU foams of different porosity (and stiffness) were used. Two main types of foams were investigated: a soft dual-porosity foam (with pores of micro- and mesoscale), and single-porosity foams (with microscopic pores, only); in this latter case, soft and substantially stiffer foams were tested. After initial measurements the foams were coated with magnetically susceptible particles immersed in an oil carrier in order to manufacture MR foams.

The acoustic response of the soft MR foams (of single as well as dual porosity) altered significantly in a magnetic field produced by a constant magnet. The influence of magnetic field on the stiffer MR foam (of single porosity) was not so strong, though still evident and similar in character. The possible reason is that, in general, for the stiffer foam the acoustically induced vibrations of skeleton were less significant, and so the effect of coating and the influence of magnetic field were weaker. This seems to be an explanation for the experimental observations. As a matter of fact, theoretical and experimental investigations on acoustic wave propagation in porous media (see, for example Allard (1993)) show that, depending on the stiffness of frame and on the frequency, the vibrations of skeleton can be often neglected at all, and a porous medium is then treated as one having a rigid frame. Thus here, a general conclusion can be drawn that MR foams of softer frame seem to be more suitable for the magnetically controlled absorption of noise. Another important conclusion from the experiment is that the observed effect is repeatable (for different samples and PU foams), and thus, a qualitatively similar effect should be attainable by experiments reproduced in a similar manner (that is, by moistening in MR fluid and thoroughly squeezing samples of typical PU foams).

It has been noticed that – regarding the acoustic absorption performance – the results obtained for the MR foam of dual porosity are better than the results for MR foams of single porosity. Peaks in the absorption curves of dual-porosity MR foams under the influence of magnetic field are slightly shifted (by ~400–500 Hz) relative to the field-free conditions, or to the clean foams. A similar 'shifting effect' had been achieved by Scarpa et al. (2004) for auxetic MR foams: compare Figure 2 from (Scarpa et al., 2004) with Figures 6 and 7 from the present article. The shift in frequency results in the increase of acoustic absorption in a higher frequency range. In the case of single-porosity MR foams, the acoustic absorption curves were rather flattened in lower frequencies under the influence of a constant magnetic field. In a higher frequency range a very moderate improvement on acoustic absorption was observed. Generally speaking, the sound-absorbing properties of the tested single-porosity MR foams subject to a magnetic field, were rather unsatisfactory, though for other single-porosity foams coated with MR fluid the results might be different. Nevertheless, it seems that foams of dual porosity are more suitable for sound absorbing MR composites. Moreover, an interesting idea to investigate are dual-porosity MR foams with mesoscopic porosity of a regular pattern, since it was demonstrated that perforations could improve the sound absorption of porous materials (Sgard et al., 2005).

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