Acoustic Metamaterials in Aeronautics

Subjects: Materials Science, Composites | Engineering, Aerospace | Acoustics

Submitted by: Giorgio
Palma

Definition

Metamaterials, man-made composites that are scaled smaller than the wavelength, have demonstrated a huge potential for application in acoustics, allowing the production of sub-wavelength acoustic absorbers, acoustic invisibility, perfect acoustic mirrors and acoustic lenses for hyper focusing, and acoustic illusions and enabling new degrees of freedom in the control of the acoustic field. The zero, or even negative, refractive sound index of metamaterials offers possibilities for the control of acoustic patterns and sound at sub-wavelength scales. The potential of metamaterial-based technologies has recently caught the interest of the aeronautics community. Their effect in the presence of realistic flows in the surrounding domains, with boundary layer, turbulence, is currently a hot research topic. The interaction with flow requires a careful design of the metamaterial to avoid detrimental effects and enabling the device maximum capabilities in aeronautics.

1. Introduction

The first definitions for the term metamaterial were given by researchers in the electromagnetic (EM) field. In 1999, Wieglhofer and Lakhtakia [1] defined a metamaterial as a “three-dimensional, periodic cellular architecture, designed to produce an optimized combination not available in nature of two or more responses to a specific excitation”. This definition was completed and extended by Cui, Liu and Smith [2] in 2010 who stated that a metamaterial is “a macroscopic composite of periodic or non-periodic structures whose function is due to both its cellular architecture and chemical composition”. From these principal definitions, there emerges the possibility to achieve properties that are hard or impossible to find in nature by conventionally engineered materials. Metamaterials derive their properties from their designed structures and geometries more than from their chemical composition, and the response of properly defined unit cells can be translated into averaged effective parameters, e.g., an effective density and effective bulk modulus.

Research on metamaterials started in the electromagnetic field. Veselago [3] first demonstrated analytically that a negative refraction index is attainable if a medium exhibits both negative permeability and negative permittivity simultaneously, and this preliminary concept was experimentally realized by Pendry [4] in 2000, when a superlens was proposed, exhibiting a negative refraction index in the frequency bandwidth of visible light or microwaves [4].

The results of this left handed behavior of negatively refracting metamaterials obtained in the EM field sparked the interest of the scientific community in other fields, such as (but not only) acoustics. This was the case for the early work by Liu et al. [5], who proposed an acoustic metamaterial that attenuates noise in the mid-frequency range (40 to 1100 Hz), which is composed of periodically-arranged, high density, spherical cores (made of lead), uniformly coated with a layer of soft and elastic material (silicone rubber). In 2004, Li and Chan [6] mathematically demonstrated, for the first time, the possibility of designing a metamaterial to achieve a negative effective bulk modulus and density, acoustically introducing slow inclusions in a faster medium. In a frequency range such that the wavelength inside one inclusion is comparable to the dimension of the inclusion itself, but still much larger than the distance between the inclusions, the effective density and bulk modulus of the metamaterial appear to be negative [7][8].

Physically, a double negative metamaterial shows counterintuitive behaviors—it expands when compressed and reacts with an acceleration in phase opposition with respect to the force that induces it. This consideration better explains the meaning of negative density, which reads asthe negative dynamic mass density term in Newton’s second law [9][10].

When both mass density (ρ) and the bulk modulus (K) are negative, an acoustic wave is allowed to propagate inside the medium, thus exhibiting a negative refractive index. This causes energy to flow in the opposite direction with respect to the wave, i.e., the wave vector and the Poynting vector (describing the energy flow associated with the acoustic propagation) point in opposite directions. A metamaterial exposing the negative refraction index can be exploited for applications like acoustic superlenses [4][11], i.e., a device capable of focusing an incident acoustic wave (with a sub-wavelength spacial resolution), even beyond the diffraction limit, in a sub-wavelength spot, and, in general, for bending waves and shaping the acoustic field almost arbitrarily.

Near-total reflection can be obtained when only one of the two material parameters, $\rho$and K, becomes negative. This can be achieved using resonant elements to let ρ turn negative [5], or with a membrane decorated with a resonant mass(es) [12][13][14][15], even without [16][17]. The frequency working range can be tuned, adjusting the weight of the masses, if present, or other constructive parameters to place the resonant effect even in the low frequency range. Stacking more than one metamaterial panel together can be a strategy to obtain a more broadband effect.

Another type of singular negative metamaterial can be obtained when the effective bulk modulus turns negative. In Fang et al. [18], inspired by results obtained in the electromagnetic field, an array of sub-wavelength Helmholtz resonators is used to obtain this effect in the ultrasonic regime. Dipolar and monopolar local resonances were proved to be the essential wave mechanisms for producing, respectively, a negative effective mass density and a negative effective bulk modulus of the metamaterial.

Double negative acoustic metamaterials can be achieved by combining negative density and negative compressibility materials, or by overlapping monopolar and dipolar resonances in the same frequency range, or to design phononic crystals to generate a band folding through multiple scattering in a periodic structure.

Different and more complex devices with equivalent dynamic or electromagnetic lumped models have been developed so far [19] to obtain metamaterials, based on locally resonant elements that show single or double negativity, depending on the considered frequency working range [19][20][21].

Other approaches have also been successfully adopted to realize metamaterials with interesting properties, such as coiling up space by using labyrinthine structures to introduce local phase delay in sound propagation. The phase shift can be designed in the full 0–2π range to obtain flat surfaces to act as arbitrarily-shaped virtual surfaces [22][23][24], modifying the reflection angle, or it could be random to maximize acoustic diffusion [25][26] (Figure 1). Space-coiling metamaterials can be adopted to obtain lens-like behaviors or even to transform the propagation pattern from spherical to plane waves [27][28]. Furthermore, this approach allows for an effective dynamic ρ<0 and K<0, and hence, a negative refractive index to be obtained in the deep sub-wavelength regime with a quite simple device [29][30].

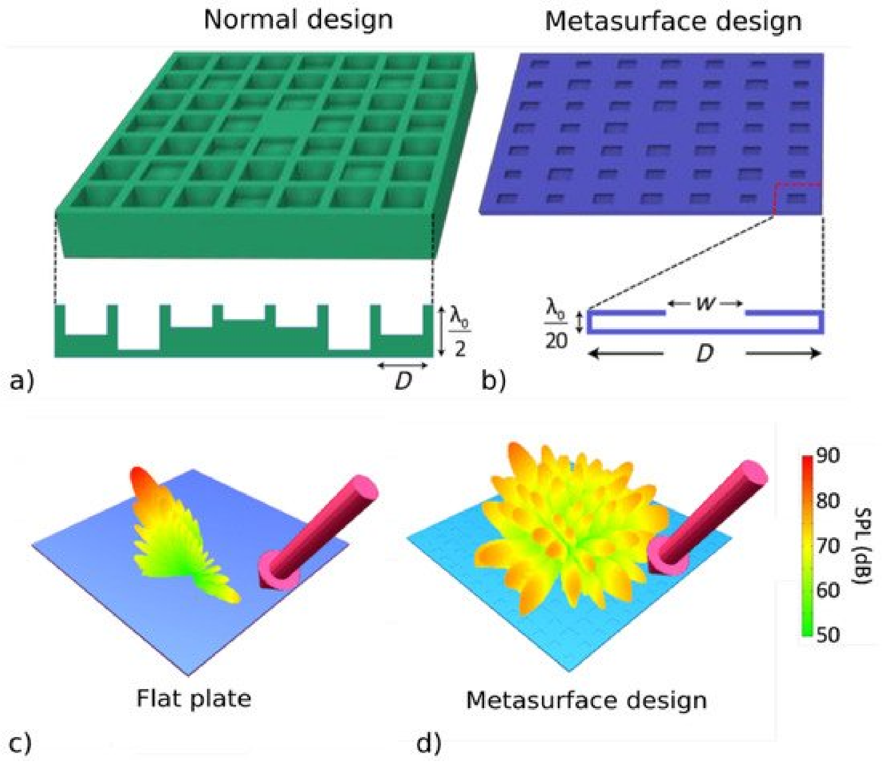

Figure 1. Metasurface design of a Schroeder Diffuser from [26]: diffuse scattering is achieved through a deep sub-wavelength metasurface. Each cell adds a different and random arranged phase-shift in the reflected field. In (**a**,**b**) the standard and the metasurface designs are compared. The simulated far-field scattering pattern for a flat plate and for the metasurface diffuser are shown in (**c**,**d**) in terms of sound pressure level (the arrow indicates the incident acoustic perturbation) evidencing the achieved metabehavior.

When a metamaterial device is built with a thickness below a tenth of the working wavelength, it is commonly called a metasurface. There is obviously a great interest in developing metasurfaces, as a reduced thickness is often desirable for real applications. Coiled-up space devices and resonant membranes were intrinsically designed to lead to metasurfaces, and hence, the majority of the so-based work presented in previous paragraphs classifies as metasurfaces, due to their deep sub-wavelength thickness. However, for each of the approaches presented above, some engineered metasurfaces can be found in the literature [31][32][33][34][35].

A very interesting superabsorber with micro-bubble insertions was presented in [36]. A significant sub-wavelength attenuation of sound was shown due to the resonance of the bubbles in a soft elastic matrix, breaking the mass density law (which states that the amplitude of transmittance for a solid panel is proportional to the inverse of the product of the density and the thickness of the panel and the frequency of the acoustic perturbation).

Thermo-viscous losses at the solid–fluid interfaces inside metamaterial components are crucial in determining the behavior of metamaterials. This is particularly true for concepts that consider micro-slits, micro-cavities and/or narrow channels as part of the design, like space-coiling metamaterials. The visco-thermal loss mechanism becomes non-negligible even when the widths of the slits are about two order of magnitude bigger than the viscous and thermal boundary layers (in the order of 10−5 m) and is enhanced by the fact that high amplitude standing waves can form in small cavities. Such losses can deeply modify the expected behavior of the metamaterial under study and hence, should be carefully taken into account and exploited when dissipation and absorption are sought [37][38]. The geometric parameters of a metamaterial can even be tuned to achieve high transmission, high absorption or high reflection from the same basic concept [39].

2. Potential Applications of Aeroacoustic Metamaterials

Sustainable development of the air transport system implies that the fundamental issues related to the rapid and continuous expansion of the urban areas surrounding airports, and, in parallel, the increase in air traffic increasing the community noise levels, both have to be tackled. This has been the driving force over the last decade that has led national and international funding bodies throughout the world to provide increasing financial support to research projects focused on the mitigation of the impact of aeronautical noise on the residential community (see, e.g., the call for Mobility for Growth within the context of the Small, Green and Integrated Transport challenge of the Horizon 2020 Program). Airlines also have an economic interest in operating quieter aircraft, as airport authorities impose the payment of fees proportional to the noise generated by their airplanes and in the future, property taxes will be introduced for owners of noisy aircraft to encourage the innovation of operating fleets and the spreading of the most advanced noise-reduction technologies. This development scenario is worsened by the apparent stagnation in the development of new technologies typically adopted on commercial aircraft, thus imposing the need for a breakthrough to guarantee further reductions in noise emissions. Metamaterials may very well prove to be the breakthrough technology needed to advance beyond the current state-of-the-art in noise reduction technology.

The introduction of any type of metamaterial-based device in aeronautical applications is restricted in several different ways. The first condition that has to be met is the weight: an excessive weight penalty is, in general, not acceptable as it would compromise the performance and fuel efficiency of the aircraft. For this reason, concepts involving a high mass density will be excluded from our analysis. As far as community noise is concerned, take-off and landing are the most critical phases of an aircraft operational cycle. Most of the noise emitted comes from the propulsion system and the high lift devices required during climb and descent. From these particular source locations, the application of metamaterials aimed at providing significant noise reductions could be the engine nacelle, the internal ducts of the engine itself, and the trailing and side edges of the wings and flaps.

3. Challenges

During the last decade, great effort has been made by the research community on the development of acoustic metamaterials and the ability to shape the acoustic field.

However, most of the so far presented works, even the concepts selected as the most promising for aeronautical applications, have dealt with quiescent hosting media, and have often focused on the development of noise-reducing material and structures for building acoustics. On the, still, long road towards the application of effective metamaterial concepts in the aeronautical framework for noise reduction, the first issue to be tackled is the inclusion of flows in models and simulations. As a moving fluid fundamentally affect acoustic wave propagation, corrections and modifications in models and concepts that depends on Mach numbers and/or flow field shapes, are expected to make them effective in the aeroacoustic domain.

Another challenge to face is the development of suitable numerical methods to simulate the behavior of acoustic metamaterials under aeronautical operating conditions. When it comes to evaluating the system response, one may consider analytical (or semi-analytical) approaches or numerical simulations. The former typically guarantees very fast evaluations, at the cost of a preliminary analytical resolution of the problem, which are not always available, especially for complex geometries and conditions with non-uniform complex background flows. Numerical approaches are more versatile, but versatility comes with a cost as well. Simulating acoustic metamaterials is a non-trivial challenge from the numerical point of view. Many concepts have labyrinthine complex micro-structures with audacious designs, and often, their behaviors rely on acousto-elastic interactions in structures where thermo-viscous losses are not negligible, thus they deeply affect the solution . A direct numerical simulation of such concepts, e.g., using the Finite Element Method (FEM) on fully detailed geometries, would result in computationally-expensive, high resource-demanding calculations, due to the fine mesh needed toaccurately reproduce the smallest geometrical details and solve the frequency of interest. This often does not allow for performance optimization testing, in which simulations are repeated a large number of times.

Hence, new efficient and accurate numerical models are needed that can combine advantages from different existing methods. This is the case, for example, of the one proposed in [40] for meta poro-elastic laminates with thin coatings, that couples the FEM, which simulates the response in the poro-elastic medium with inclusions, and the Bloch expansion, which simulates the surrounding media using a technique similar to the transfer matrix method to account for the coatings. Multiscale and homogenization modeling techniques are also attractive ways of addressing the issue when different scales are involved, such as microporous materials where one is interested in the macroscopic effect due to the microstructure of the system [41], and they can be adopted in a metamaterial design process [42][43].

As a final remark, the actual manufacturing of metamaterial devices poses significant challenges. Often, metamaterials come with complex geometries that are needed to exploit particular physical phenomena, but may increase production complexity and hence, costs. It is obviously of fundamental importance to control the latter aspects to enable the deployment of metamaterial technologies in an industrial context. During the last two decades, additive manufacturing (AM) techniques have experienced a boost in terms of versatility and reliability, and several new processes have been developed that use a large variety of materials, including polymers and metals. The aerospace industry is introducing AM, and through this technique, exploiting the possibilities offered to obtain lighter and still durable components with less geometrical restrictions in the design of the parts. In the authors' opinion, AM may be the key to successfully addressing the challenge of a low-cost manufacturing process that can handle the complex geometries required for metamaterial designs.

References

1. Weiglhofer, W.S.; Lakhtakia, A. Introduction to Complex Mediums for Optics and Electromagnetics; SPIE Publications: Bellingham, WA, USA, 1999.
2. Cui, T.J.; Smith, D.; Liu, R. Metamaterials; Springer: Berlin/Heidelberg, Germany, 2010.
3. Veselago, V.G. The electrodynamics of substances with simultaneously negative values of ϵ and μ. Sov. Phys. Uspekhi 1968, 10, 509.
4. Pendry, J.B. Negative refraction makes a perfect lens. Phys. Rev. Lett. 2000, 85, 3966.
5. Liu, Z.; Zhang, X.; Mao, Y.; Zhu, Y.Y.; Yang, Z.; Chan, C.T.; Sheng, P. Locally Resonant Sonic Materials. Science 2000, 289, 1734–1736.
6. Li, J.; Chan, C.T. Double-negative acoustic metamaterial. Phys. Rev. E 2004, 70, 055602.
7. Ding, Y.; Liu, Z.; Qiu, C.; Shi, J. Metamaterial with Simultaneously Negative Bulk Modulus and Mass Density. Phys. Rev. Lett. 2007, 99, 093904.
8. Brunet, T.; Merlin, A.; Mascaro, B.; Zimny, K.; Leng, J.; Poncelet, O.; Aristégui, C.; Mondain-Monval, O. Soft 3D acoustic metamaterial with negative index. Nat. Mater. 2014, 14, 384.
9. Lee, S.H.; Wright, O.B. Origin of negative density and modulus in acoustic metamaterials. Phys. Rev. B 2016, 93, 024302.
10. Ma, G.; Sheng, P. Acoustic metamaterials: From local resonances to broad horizons. Sci. Adv. 2016, 2, e1501595.
11. Zhang, S.; Yin, L.; Fang, N. Focusing Ultrasound with an Acoustic Metamaterial Network. Phys. Rev. Lett. 2009, 102, 194301.
12. Yang, Z.; Mei, J.; Yang, M.; Chan, N.H.; Sheng, P. Membrane-Type Acoustic Metamaterial with Negative Dynamic Mass. Phys. Rev. Lett. 2008, 101, 204301.
13. Yang, Z.; Dai, H.M.; Chan, N.H.; Ma, G.C.; Sheng, P. Acoustic metamaterial panels for sound attenuation in the 50–1000 Hz regime. Appl. Phys. Lett. 2010, 96, 041906.
14. Langfeldt, F.; Riecken, J.; Gleine, W.; Von Estorff, O. A membrane-type acoustic metamaterial with adjustable acoustic properties. J. Sound Vib. 2016, 373, 1–18.
15. Mei, J.; Ma, G.; Yang, M.; Yang, Z.; Wen, W.; Sheng, P. Dark acoustic metamaterials as super absorbers for low-frequency sound. Nat. Commun. 2012, 3, 756.
16. Cselyuszka, N.; Sečujski, M.; Crnojević-Bengin, V. Novel negative mass density resonant metamaterial unit cell. Phys. Lett. A 2015, 379, 33–36.
17. Sheng, P. Coupled membranes with doubly negative mass density and bulk modulus. J. Acoust. Soc. Am. 2013, 134, 4026.
18. Fang, N.; Xi, D.; Xu, J.; Ambati, M.; Srituravanich, W.; Sun, C.; Zhang, X. Ultrasonic metamaterials with negative

modulus. Nat. Mater. 2006, 5, 452–456.
19. Liu, X.N.; Hu, G.K.; Huang, G.L.; Sun, C.T. An elastic metamaterial with simultaneously negative mass density and bulk modulus. Appl. Phys. Lett. 2011, 98, 251907.
20. Graciá-Salgado, R.; García-Chocano, V.M.; Torrent, D.; Sánchez-Dehesa, J. Negative mass density and ρ-near-zero quasi-two-dimensional metamaterials: Design and applications. Phys. Rev. B 2013, 88, 224305.
21. Lee, S.H.; Park, C.M.; Seo, Y.M.; Wang, Z.G.; Kim, C.K. Composite Acoustic Medium with Simultaneously Negative Density and Modulus. Phys. Rev. Lett. 2010, 104, 054301.
22. Li, Y.; Liang, B.; Gu, Z.M.; Zou, X.Y.; Cheng, J.C. Reflected wavefront manipulation based on ultrathin planar acoustic metasurfaces. Sci. Rep. 2013, 3, 2546.
23. Li, Y.; Jiang, X.; Li, R.Q.; Liang, B.; Zou, X.Y.; Yin, L.L.; Cheng, J.C. Experimental Realization of Full Control of Reflected Waves with Subwavelength Acoustic Metasurfaces. Phys. Rev. Appl. 2014, 2, 064002.
24. Zhu, Y.F.; Fan, X.D.; Liang, B.; Yang, J.; Yang, J.; Yin, L.l.; Cheng, J.C. Multi-frequency acoustic metasurface for extraordinary reflection and sound focusing. AIP Adv. 2016, 6, 121702.
25. Gu, Z.M.; Liang, B.; Zou, X.Y.; Cheng, J.C. Broadband diffuse reflections of sound by metasurface with random phase response. EPL (Europhys. Lett.) 2015, 111, 64003.
26. Zhu, Y.; Fan, X.; Liang, B.; Cheng, J.; Jing, Y. Ultrathin Acoustic Metasurface-Based Schroeder Diffuser. Phys. Rev. X 2017, 7, 021034.
27. Wang, W.; Xie, Y.; Konneker, A.; Popa, B.I.; Cummer, S.A. Design and demonstration of broadband thin planar diffractive acoustic lenses. Appl. Phys. Lett. 2014, 105, 101904.
28. Xie, Y.; Wang, W.; Chen, H.; Konneker, A.; Popa, B.I.; Cummer, S.A. Wavefront modulation and subwavelength diffractive acoustics with an acoustic metasurface. Nat. Commun. 2014, 5, 5553.
29. Liang, Z.; Feng, T.; Lok, S.; Liu, F.; Ng, K.B.; Chan, C.H.; Wang, J.; Han, S.; Lee, S.; Li, J. Space-coiling metamaterials with double negativity and conical dispersion. Sci. Rep. 2013, 3, 1614.
30. Tang, K.; Qiu, C.; Ke, M.; Lu, J.; Ye, Y.; Liu, Z. Anomalous refraction of airborne sound through ultrathin metasurfaces. Sci. Rep. 2014, 4, 6517.
31. Zhai, S.; Chen, H.; Ding, C.; Shen, F.; Luo, C.; Zhao, X. Manipulation of transmitted wave front using ultrathin planar acoustic metasurfaces. Appl. Phys. A 2015, 120, 1283–1289.
32. Christensen, J.; Martín-Moreno, L.; García-Vidal, F.J. All-angle blockage of sound by an acoustic double-fishnet metamaterial. Appl. Phys. Lett. 2010, 97, 134106.
33. Zhao, J.; Li, B.; Chen, Z.N.; Qiu, C.W. Redirection of sound waves using acoustic metasurface. Appl. Phys. Lett. 2013, 103, 151604.
34. Zhao, S.D.; Wang, Y.S.; Zhang, C. A continuously tunable acoustic metasurface for transmitted wavefront manipulation. arXiv, 2017; arXiv:1711.09701.
35. Díaz-Rubio, A.; Tretyakov, S.A. Acoustic metasurfaces for scattering-free anomalous reflection and refraction. Phys. Rev. B 2017, 96, 125409.
36. Leroy, V.; Strybulevych, A.; Lanoy, M.; Lemoult, F.; Tourin, A.; Page, J.H. Superabsorption of acoustic waves with bubble metascreens. Phys. Rev. B 2015, 91, 020301.
37. Starkey, T.A.; Smith, J.D.; Hibbins, A.P.; Sambles, J.R.; Rance, H.J. Thin structured rigid body for acoustic absorption. Appl. Phys. Lett. 2017, 110, 041902.
38. Cai, X.; Guo, Q.; Hu, G.; Yang, J. Ultrathin low-frequency sound absorbing panels based on coplanar spiral tubes or coplanar Helmholtz resonators. Appl. Phys. Lett. 2014, 105, 121901.
39. Molerón, M.; Serra-Garcia, M.; Daraio, C. Visco-thermal effects in acoustic metamaterials: From total transmission to total reflection and high absorption. New J. Phys. 2016, 18, 033003.
40. Gaborit, M.; Schwan, L.; Dazel, O.; Groby, J.P.; Weisser, T.; Göransson, P. Coupling FEM, Bloch Waves and TMM in Meta Poroelastic Laminates. Acta Acust. United Acust. 2018, 104, 220–227.
41. Gao, K. Multiscale Modelling of Acoustic Porous Materials. Ph.D. Thesis, Technische Universiteit Eindhoven, Eindhoven, The Netherlands, 2016.
42. Roca, D.; Lloberas-Valls, O.; Cante, J.; Oliver, J. A computational multiscale homogenization framework accounting for inertial effects: Application to acoustic metamaterials modelling. Comput. Methods Appl. Mech. Eng. 2018, 330, 415–446.
43. Sridhar, A.; Kouznetsova, V.G.; Geers, M.G.D. Homogenization of locally resonant acoustic metamaterials towards an emergent enriched continuum. Comput. Mech. 2016, 57, 423–435.

Keywords

metamaterials;aviation noise;aeroacoustics;noise absorption;noise reflection;noise trapping;acoustic cloaking