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Review

Acoustic Metamaterials in Aeronautics

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Abstract: Metamaterials, man-made composites scaled smaller than the wavelength, have demonstrated a huge potential in their applications in acoustics, opening up for sub–wavelength acoustic absorbers, acoustic invisibility, perfect acoustic mirrors and acoustic lenses for hyper focusing, 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 in control of the acoustic pattern and sound at sub–wavelength scales. Despite the tremendous growth of the research on acoustic metamaterials during the last decade, the potential of metamaterial-based technologies in aeronautics is still not fully explored and its utilization is still in its infancy. Thus the principal concepts mentioned above could very well provide means to develop devices that would allow the mitigation of the impact of the civil aviation noise on the community. This paper gives a review of the state of the art of the most relevant works on acoustic metamaterials, analyzing them against their potential applicability in aeronautics, and in this process identifying possible implementation areas and interesting metabehaviors. It also identifies some technical challenges and possible future directions for research with the goal of unveiling the potential of metamaterials technologies in aeronautics.

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

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1. Introduction

The first definitions for the term metamaterial were given by researchers in the electromagnetic 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 both to the 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., effective density and effective bulk modulus.

Research on metamaterials started in the electromagnetic field, Veselago [3] first analytically demonstrated 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, where a *superlens* was proposed, exhibiting negative refraction index in the frequency bandwidth of visible light of microwaves[4].

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 is the case of the early work by Liu et al. [5], who proposed an acoustic metamaterial that

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attenuates noise in the mid frequency range (40 and 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 to design a metamaterial to achieve both negative effective bulk modulus and density, introducing acoustically 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 induced it. This consideration better explains the meaning of negative density, that has to be read as negative dynamic mass density term in Newton's second law [9,10].

When both mass density (ρ) and bulk modulus ($\mathcal{K}$) 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 to the acoustic propagation) point in opposite directions. A metamaterial exposing negative refraction index can be exploited for applications like acoustic superlenses [4,11], *i.e.* a device capable to focus 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, ρ and $\mathcal{K}$, becomes negative. This can be achieved using resonant elements to let ρ to go negative[5], or with a membrane decorated with a resonant mass(es) [12–15], 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 goes 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, negative effective mass density and negative effective bulk modulus of the metamaterial.

Double negative acoustic metamaterials can be achieved by combining negative density and negative compressibility materials, or overlapping of 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 [19–21].

Other approaches have also been successfully adopted to realize metamaterials showing 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[22–24] modifying the reflection angle, or it could be random to maximize acoustic diffusion[25,26]. Space–coiling metamaterials can be adopted to obtain also lens like behaviors or even transforming the propagation pattern from spherical to plane waves[27,28]. Furthermore, this approach allows for an effective dynamic $\rho < 0$ and $\mathcal{K} < 0$, and hence negative refractive index, to be obtained in the deep sub–wavelength regime with a quite simple device[29,30].

When a metamaterial device is built with a thickness under a tenth of the working wavelength, it is commonly called *metasurface*. There is obviously a great interest in developing metasurfaces, as a

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reduced thickness is often desirable for real applications. Coiling–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 were classifiable as metasurfaces for their deep sub–wavelength thickness. However, for each of the approach presented above, some metasurfaces engineering can be found in literature [31–35].

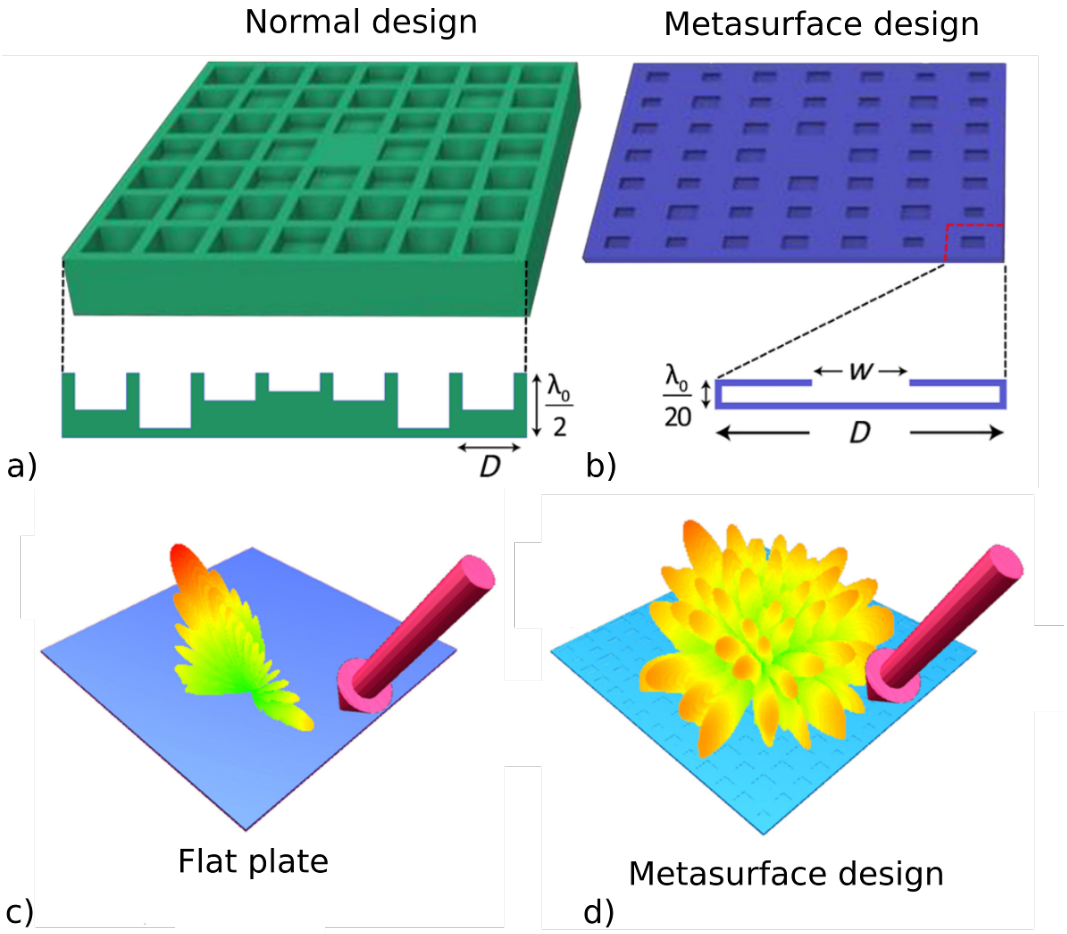

Figure 1. Metasurface design of a Schroeder Diffuser from [26]: diffuse scattering is achieved through a deep sub–wavelength metasurface. Each cell adds a different and random arranged phase–shift in the reflected field. In a) and b) the standard and the metasurface design are compared, c) and d) evidences the achieved metabehavior.

A very interesting superabsorber with micro–bubble insertions is presented in [36], a significantly sub–wavelength attenuation of sound is shown due to 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 metamaterials behavior. 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

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should be carefully taken into account and exploited when dissipation and absorption are sought[37, 38]. Geometrical parameters of a metamaterial can even be tuned to achieve high transmission, high absorption or high reflection from the same basic concept[39].

The great potential of acoustic metamaterials has not yet been totally disclosed and this is even more true when thinking about aeroacoustic and aeronautical applications. This paper will highlight interesting behavior and promising concepts, focusing on the reduction of the community noise produced by aircraft and will also show some interesting cabin noise reduction applications. Section 2 considers different metabehaviors, introducing their possible applications on aircraft and the sought effect, specifically: Section 2.1 focuses on absorption, 2.2 on unusual reflection by metasurfaces, 2.3 on noise trapping and 2.4 on scattering abatement from objects, *i.e.* acoustic cloaking. For each subsection, the most promising existing concept is shown, emphasizing possible limitations and/or potential improvement needed for its implementation on aircraft. Section 3 addresses challenges that need to be addressed in the near future by researchers in order to make metamaterial technologies mature for aeronautical industrial applications, towards higher Technology Readiness Level (TRL), and finally some conclusion remarks can be found in section 4.

2. Potential applications of aeroacoustic metamaterials

A 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 during the last decade that 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 Mobility for Growth within the context of the *Small, Green and Integrated Transport* challenge of the Horizon 2020 Program). Airlines have also 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 the 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 the 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 technologies.

The introduction of any type of metamaterial-based devices in aeronautical applications is restricted in several different ways. The first condition that has to be met is about weight: an excessive weight penalty is in general not acceptable as it would compromise the performance and fuel efficiency. 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 come from the propulsion system and the high lift devices required during climb and descent. From these particular source locations, the application of meta-materials aimed to provide significant noise reductions could be the engine nacelle, the internal ducts of the engine itself, trailing and side edges of wings and flaps.

2.1. Absorption and dissipation

Typically, the strategy adopted to reduce the exposure of citizens to aircraft noise is based on a minimization of the sound energy at ground location, hence shrinking the area inside the critical isophonic curves. Reducing the noise level gives indeed a major contribution to the alleviation of community noise[40].

As stated above, engines are a significant source of noise in all flight conditions, largely dominating during take–off and being comparable to airframe noise during landing. Among the engine sources, fan noise is one of the biggest component in the overall and its relative importance

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has increased in the last twenty years as the bypass ratio of modern turbofan engines have increased. This latter development has been led by the needs to reduce the specific fuel consumptions, but has as a side effect also a reduction of the jet noise in comparison to the other noise components.

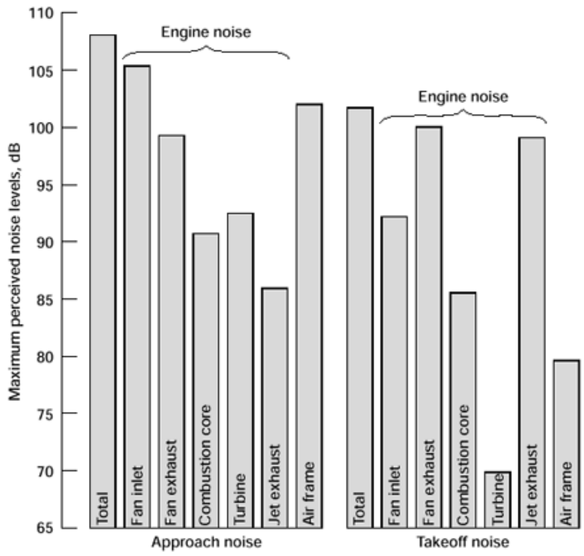

Figure 2. Aircraft noise typical distribution between different sources in takeoff and approach. Picture from https://www.nasa.gov/centers/glenn/images/content/83522main_fs003_fig3.gif

On modern aircraft most of the engine noise attenuation is provided by liners, which are absorbing panels positioned in the internal walls of the nacelle designed to reduce both broadband and tonal noise. The basic Single Degree of Freedom liner is typically made by an hard–backed honeycomb, behaving like a quarter-wavelength resonator, covered by a perforated plate that on one side enhances sound absorption of the liner and on the other maintains the aerodynamic flow as clean as possible on the walls of the nacelle. Liner design is one of the most active research field in aeronautics and recently metamaterials are starting to be taken into consideration for future and more effective absorbing panels for liners, adopting *e.g.* dual–resonant materials covered by microperforated panels [41,42] or variable depth liners with spherical inclusions and microporous panels embedded within melamine [43].

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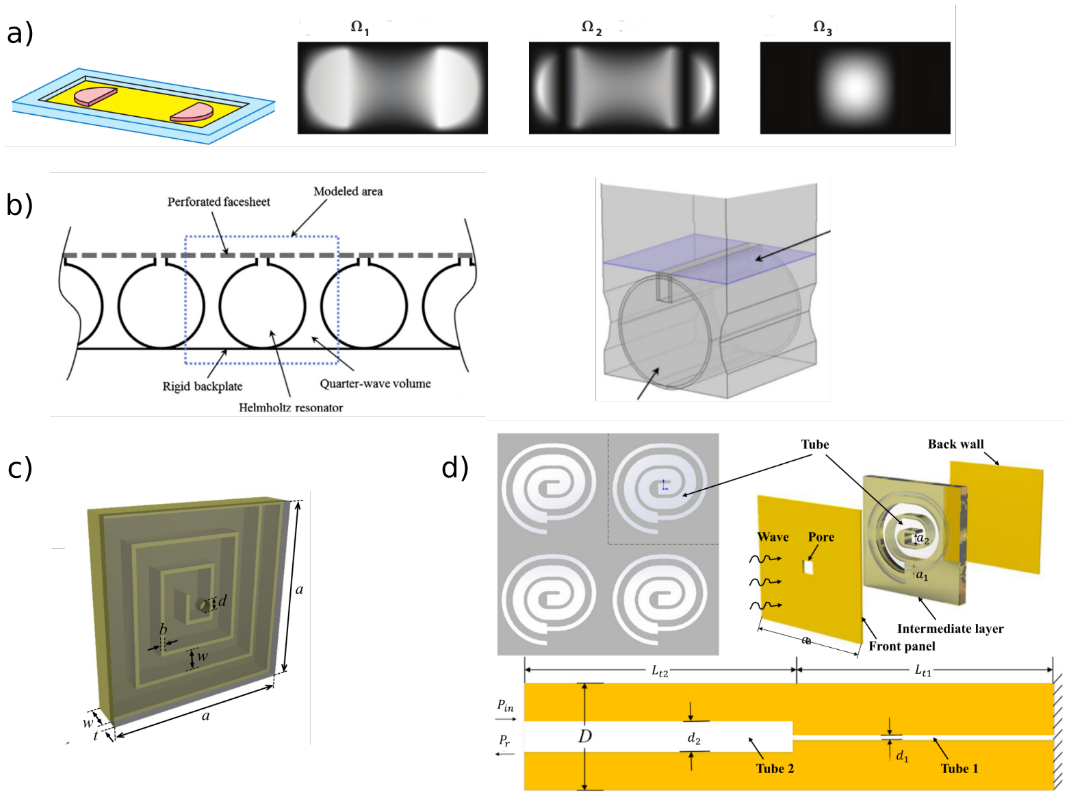

Figure 3. Various metamaterial design for low–frequency absorption: a) a membrane decorated with added platelets and displacement related to the first three eigenfrequencies of the structure from [44], b) a dual resonant metamaterial composed by Helmholtz's resonators and a perforated sheet adopted as innovative liner in [42], c) and d) two different space coiling designs respectively from [45] and [46]. Dissipation of acoustic energy is fundamental in each design.

The most desired effect that could be possibly achieved by adopting metamaterial inspired liners is low frequency absorption, *i.e.* in the range 100-1000 Hz, which is difficult to achieve with classical approaches due to the long wavelengths of sound involved at those frequencies. Several authors have proposed new metamaterials for low frequency noise absorption that are of interest and could possibly be applied for new liners design, such as thin film membranes with rigid platelets as presented in [15], in which the incident acoustic wave is dissipated at resonances of a cavity system due to enhanced energy concentration at discontinuities in the slope of the displacement profile. Coiling space metamaterials have been proposed as dissipative media with proven sound absorption ability in combination with microperforated panels covering [39,45,46]. One of the advantages promised by such design is a deep sub–wavelength functionality, often reached by exploiting Fabry–Peròt resonance in long coiled narrow channels, enhancing dissipation phenomena at resonant frequency. Another valuable contribution in this field is the work by Yang *et al.*[44], who derived a "causality" constraint that dictates trade–off conditions between the sample thickness, frequency bandwidth and magnitude of absorption in the low frequency range and presented a design strategy to realize the target absorption coefficient profile with the minimum possible thickness. Resonance and viscous dissipation is also exploited in a very interesting design by Tang *et al.*[47]. A series of different acoustic Helmholtz resonators is obtained inserting inclined microporous septa in a honeycomb structure, with a microperforated panel on top. The corrugated structure hence exhibits several resonant frequencies that cause the air in the perforation to oscillate severely when excited, thus dissipating energy in the viscous boundary layer, obtaining a broadband high absorption coefficient for a wide range of incident angles of the acoustic perturbation.

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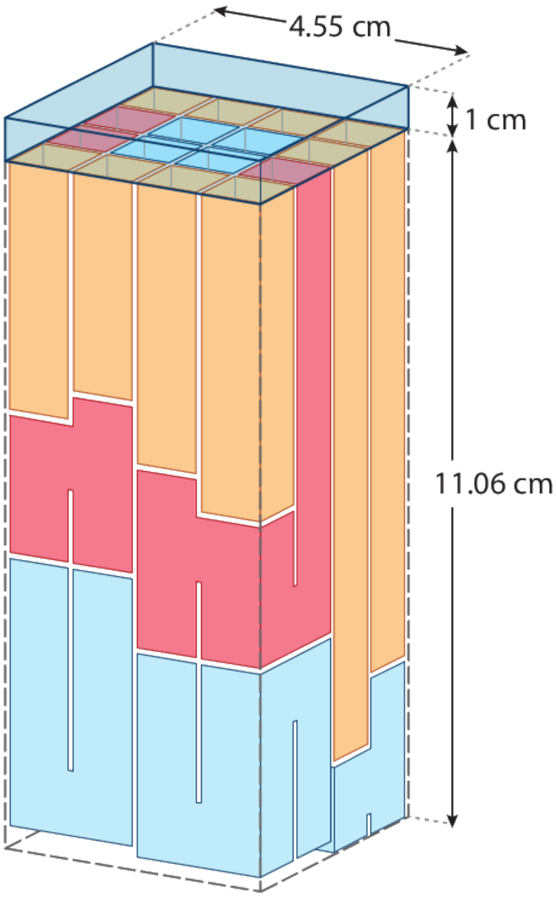

Figure 4. The original "optimal" absorbing metamaterial obtained by Yang *et al.*. The unit cell is composed by 16 resonant channels differing in length, folded to compact the sample, image from [44]

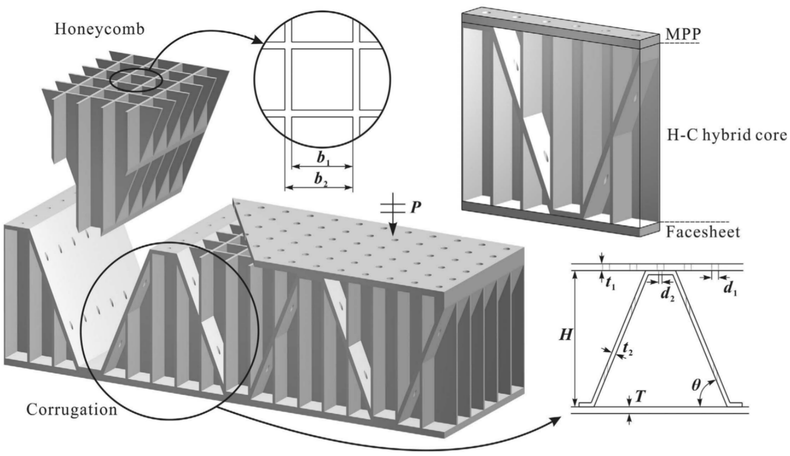

Figure 5. Image from [47], an absorbing metamaterial composed by various different Helmholtz resonators separated by microporous septa.

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The annoyance from a noise, however, is not only related to its intensity. The mathematical description of the annoyance is not a simple task, due to the subjectivity of the sound event perception, and the ongoing EU–financed project ANIMA (Aviation Noise Impact Management through novel Approaches) will, among other objectives, make an effort to better understand the non-acoustical factors which influence noise annoyance. Projects like SEFA (Sound Engineering for Aircraft) and COSMA (Community Oriented Solutions to Minimise aircraft noise Annoyance) demonstrated [48,49] that the spectral content of the signal is fundamental in defining its effect on listeners. Extensive psychometric test campaigns performed during the projects were able to identify *weakly–annoying* target sounds, that usually were characterized by attenuated tonal components, drawn in broadband noise. This illustrate how important it would be to enhance the acoustic absorption at specific frequencies for improving quality of sound/noise from an aircraft and hence its acceptability from the community, *i.e.* reducing acoustic pollution while even maintaining the sound level unaltered. Such devices would enable the possibility to engineer the noise signature from an aircraft and hence rethinking the conceptual design procedure including the "desired noise" as a variable to optimize[50–52].

2.2. Reflection

A smart way to reduce the incidence of noise pollution from aircraft is to deflect the sound waves in order to redirect it away from the ground and community. Upward redirection of part of the emitted acoustic energy has been tested in the past using negatively scarfed nacelle inlets. The main characteristic of such engine intakes is to have the bottom part longer than the upper, causing a greater reflection of acoustic waves to the upper direction. Despite the promising community noise reduction achievable, aerodynamic side effects of such design have been found to be too severe, affecting the overall aircraft performance and thus making its usage not suitable[53]. Also here, metamaterials that would be able to effectively modify the reflection of acoustic waves could be candidates for engineered "virtually scarfed nacelles", obtaining the desired acoustic effect without compromising the inlet shape, which can still be optimized for aerodynamic and engine efficiency.

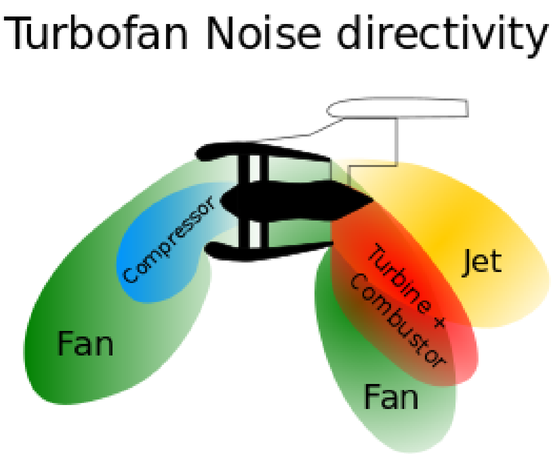

Figure 6. Typical noise directivity from components of a modern turbofan

Many of the coiling–space metamaterials studied in the papers mentioned in the introduction show intriguing and abnormal reflection capabilities. In the authors' opinion, one of the most interesting contribution is presented in the works by Li *et al.* both numerically and experimentally[22, 23]. The main idea is to impose a phase shift profile to the reflected field by properly selecting

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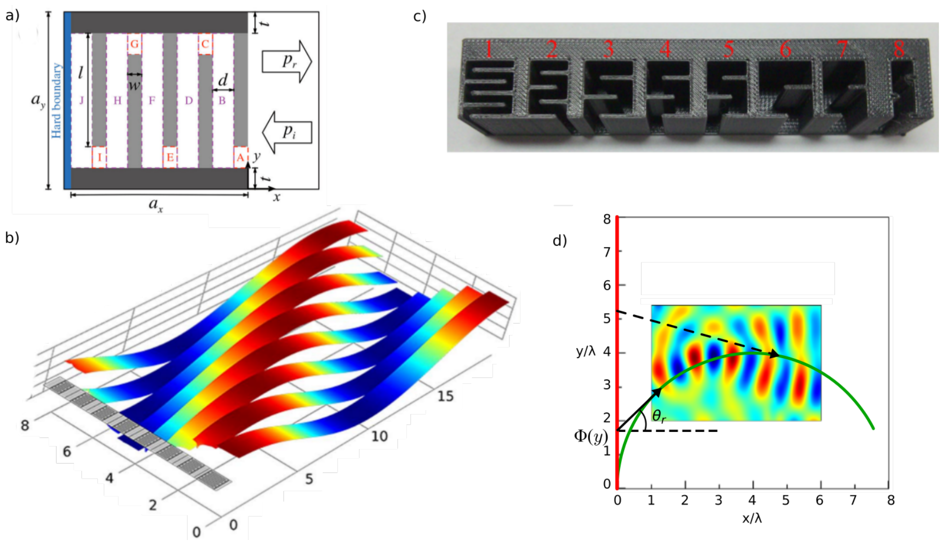

Figure 7. Shaping the reflection field, from [22,23]. The unit cell is easily parametrized (a) to obtain a phase shift profile (b) combining different cells in an array (c). Arbitrary shape can be obtained imposing different $\phi(y)$ to the reflected field (d).

geometrical parameters of an ultrathin planar metasurface, which elementary unit is made of two stiff "corrugated beams" with a hard back–end. Reduced wall thickness and overall depth (in the order of 1/20 of wavelength) are strengths of the proposed approach, together with an ease of tuning of the design to work at a desired frequency. Clearly, a continuous phase profile is not achievable with the proposed design due to the necessary width of the unit cell. The cited works[22,23] successfully adopt a $\pi/4$ discretization step over the 2π range. The ideal theoretical phase profile is hence approximated using 8 unit cells providing discrete phase shifts. When a sound wave enters a cell, it is forced to follow a longer path with respect to the thickness of the cell itself, coming out with a phase delay directly connected to the equivalent straight path of the considered cell. Considering an incident wave normal to the metasurface, the propagation angle of the reflected wave can be evaluated as $\theta_r = \arcsin\left(\frac{\lambda}{2\pi}\frac{d\phi(y)}{dy}\right)$ where λ is the wavelength of the incoming noise disturbance. If the actual interest is not to achieve an exact reflection angle but, as in a virtually scarfed nacelle application, a value within a range is a sufficient approximation, then the metasurface can be considered effectively broadband, and for multiples of the working frequency it would still have the exact expected behavior. For example, when the desired behavior of the metasurface is to act like an inclined wall in deflecting sound, the metasurface should be effective in a wide frequency range, provided that each frequency has a different reflection angle, or a different virtual inclination of the wall.

While this concept proved to be effective in a purely acoustic domain, deeper investigation would be needed when the hosting fluid is moving, *i.e.* a background aerodynamic flow is present. In the virtually scarfed nacelle example, the metasurface will be grazed by the flow, and likely a new "corrected" phase shift profile should be defined, taking into account among others the flow Mach number.

Near–total reflecting metasurfaces can also be exploited to achieve high transmission losses for cabin noise reduction. Although take–off and landing are the loudest moments, cruise is clearly the longest section of a civil aviation aircraft mission, and hence the most interesting for passenger comfort improvements by noise reduction treatments. In this flight condition, excluding internal sources like air–conditioning systems, the main external cabin noise contributions are from the engines and the turbulent boundary layer excitations that produce vibrations that transmit to the fuselage stringers and skins that radiate noise inside the cabin.

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With the increasing emphasis on noxious emissions reduction and fuel consumption efficiency there is a renewed interest in different engine concepts beyond turbofans like propfans, *i.e.* open rotor engines, to obtain the speed and performance of a turbofan with the intended fuel economy of a turboprop (for instance, Airbus has patented aircraft designs with twin rear-mounted contra-rotating propfans[54] and Boeing did as well []). One of the main outcome that discouraged so far the usage of propfan is the excessive cabin noise produced by this type of engine compared to the classic turbofan. The spectrum of the noise measured inside the cabin would show discrete intense peaks at low–frequencies, *i.e.* in the 50–1500 Hz range, correlated with the engine rotators at their fundamental and higher harmonics.

Most kinds of treatment for cabin noise reduction are difficult to implement due to the small space available in the cabin sidewalls and to the strict limits for the overall aircraft weight. Several works employ resonant membranes as an effective way to suppress the low frequency noise inside the cabin. Metasurfaces composed by membranes with added masses[55] can be attached to aluminum panels to guarantee a huge effective dynamic mass at resonance frequency, suppressing the bending vibrations of the structure and inducing radiation cancellation from the surface due to the anti–phase motions at anti–resonance working frequencies. Furthermore, a double wall design involving resonant decorated membranes can be adopted to improve its noise shielding efficiency at low frequencies, keeping the overall structure lightweight[56–59]. Lightweight structures showing up to 50 dB in transmission loss at low frequencies, that may also exhibit good mechanical properties have also been presented[60–62] using an honeycomb frame as a core, covered by very thin rubber membranes. Multilayer sandwiches showed very good acoustic insulation over the 50–1500 Hz range. This kind of layout seems to be the most promising due to its ability to yield the desired acoustic properties with a typically strong structure like honeycomb without the need to add masses on the membranes, hence respecting the requisite of lightness and not negatively affecting the aircraft efficiency and maximum payload.

2.3. Noise trapping

Noise trapping is one of the most intriguing metamaterial applications, allowing a sound wave to enter into a domain where it is contained and forbidden to exit, creating a sort of insulation of the exterior domain from the trapped sound. The most interesting application, in the author's opinion, of sound trapping[63] shows a one–way metasurface, made by a layer of Helmholtz resonators with different depths attached to a near–zero index space–coiling based metamaterial (in a zero index acoustic metamaterial the sound wave is infinitely stretched in space, and it travels with extremely high phase velocity). A normal incident wave, with uniform phase profile, is allowed to pass through the zero index metamaterial, the phase array steers the wave phase profile and once the wave is reflected it is no longer allowed to pass through the zero index layer due to its high incident angle selectivity. The described effect could very well turn out to be useful in aeronautical applications, it can be for example exploited as a way to enhance absorption and to be used in synergy with focusing devices, or negatively refractive surfaces and absorbers. In a box delimited on one side by a suitable absorbing layer and on the other side by this metasurface, oriented such that the layer of resonator points inside the considered domain, a sound wave can enter the domain through the zero index material, experiencing a redirection due to the phase shift obtained by tuning the depths of the resonators. Then the wave can be, partially, absorbed by the absorbing layer. The reflected wave, however, is not allowed to exit the box due to the presence of the one–way metasurface, on the contrary it is reflected back towards the absorber, enhancing its effect. The effectiveness of a non perfect absorber with a non negligible reflection coefficient can be improved forcing the acoustic noise perturbation to repeatedly impinge on the absorbing device.

Nowadays, acoustic liners are used to reduce engine noise. Liners are applied on the internal walls of the engine nacelle, both in the intake and by-pass ducts and uses the Helmholtz resonance principle for the dissipation of incident acoustic energy. Placing a one–way metasurface at the

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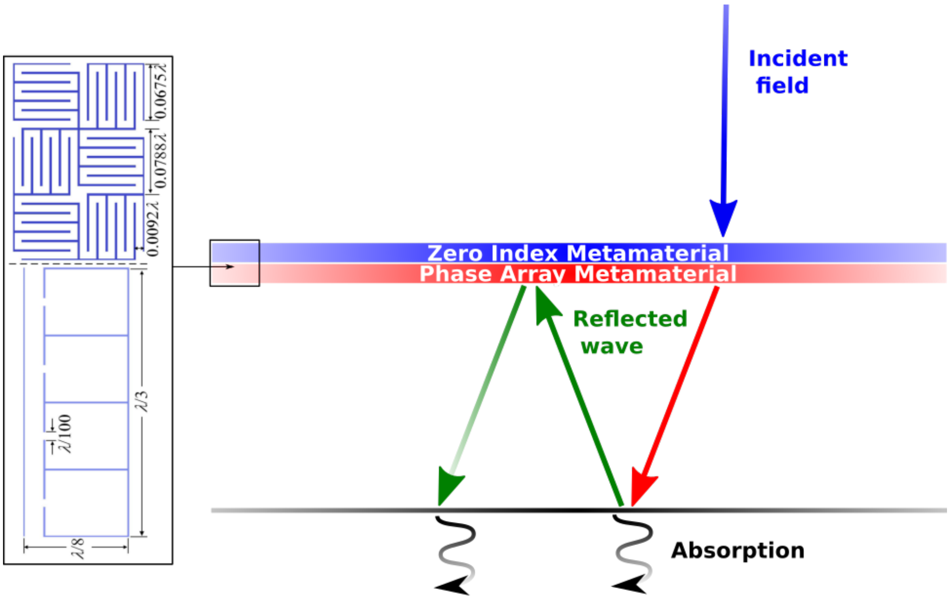

Figure 8. Noise trapping unit cell, from [63] and the functioning scheme of a noise trapping concept: the incident wave is allowed to pass through the metamaterial and it is steered by the phase array into an absorbing material. The reflected fraction of the sound can't escape and multiple reflections and absorption occurs

interface between a liner and the internal side of the nacelle can result in an enhanced effect of the liner itself, especially at low frequencies, provided that sound waves can not escape the domain occupied by the absorber. Obviously one could imagine to enhance the overall effect by both optimizing the metasurface and the liner positioning, and a totally new generation of liners can be designed using for example a metamaterial absorber from the previous section 2.1. The phase shift can also be tuned to maximize the number of possible reflections for a wide range of incident angle of the primary acoustic field. Note also that the phenomenon of near-zero index is frequency-dependent, which means that the asymmetric acoustic behavior can be realized within a relatively narrow band, allowing for a shaping of the noise signature from the aircraft as mentioned in section 2.1, as multilayered structures can easily extend the working range of the concept.

A limitation of the design presented in [63] can be the resulting thickness, near to one half of the wavelength of interest, which leads to excessive thicknesses to be effective at the typical BPF of current turbofan engines and would thus not fit in the nacelle, especially if multiple layers have to be stacked. However, in the authors' opinion, its size can be further reduced combining other metamaterial concepts. As the thickest part of the design is the phase–controlling metasurface, it can be replaced, *e.g.* following [22,23,38] or other similar concepts cited: the proposed scheme of designing a one–way metasurface, would just need the coupling of a phase array and a non dispersive zero–index metamaterial, regardless of their particular implementations.

2.4. Scattering Abatement (Cloaking)

The term (acoustic) cloaking is commonly used for the ability of a device, the "cloak", to "hide" an obstacle from the incident noise perturbation field, thus preventing scattering from objects that may be embedded in such a domain.

First examples of cloaking were published for Electromagnetic waves in 2006 by Pendry[64] and Leonhardt[65]. Successively, the exploitation of the background idea of coordinate–transformation invariance of the governing equations has been ported to the acoustic domain by Cummer and Schurig[66]. This idea implies that any coordinate transformation based deformation of the space can

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be physically created in real space with appropriate, and typically complex, distributions of acoustic properties of the propagation medium.

Norris [67,68] gave a fundamental contribution to the theoretical development of the acoustic cloaking theory, showing that the first path discovered to obtain this effect, called "inertial cloaking" because it required a material to exhibit anisotropic density and leads to an infinitely massive device, is a subcase of a more general theory: anisotropy can be distributed between density and bulk modulus, the extremes defining inertial and pentamode metafluids, both possessing fluid–like properties which are not found in simple fluids. The first are defined by a tensorial anisotropic mass density and a scalar bulk modulus. The latter represents a solid structure ideally behaving like a fluid, possessing five compliant, soft modes of deformation (connected to vanishing shear stiffness) and only one more rigid mode (linked to the only non-null eigenvalue of the elasticity tensor representing compressibility). Pentamode metafluids may be engineered with a lattice of carefully interconnected solid struts creating a structure that exhibits a quasi vanishing shear stiffness[69,70].

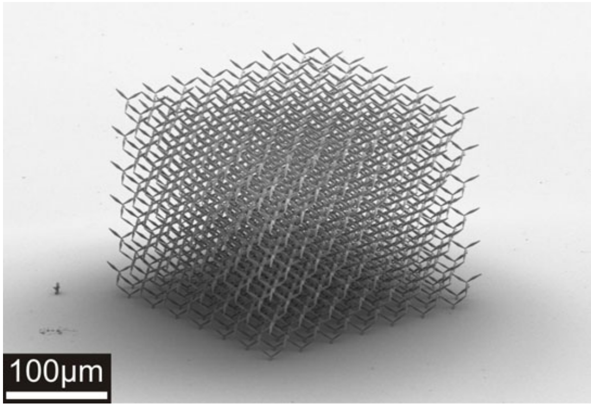

Figure 9. A pentamode material as realized by Kadic[69] with 3D laser lithography. Unit elements are linked to each other with connections 0.55 μm thick

During the last decade, the scientific community has produced a large number of papers on the topic, with numerical, theoretical papers and practical realization of acoustic cloaking[71–78]. Alternative approaches exploiting coordinate transformations have been explored like the so–called carpet cloaking[79–87], *i.e.* making an arbitrary shaped surface acting like a flat wall.

The transformation acoustic cloaking theory is valid only for quiescent media, hence when a moving fluid is present the convective terms make the governing equation no longer formally invariant under a coordinate transformation. Recent studies have tried to extend the existing theory of acoustic cloaking to the aeroacoustic domain, *i.e.* in presence of flow[88–91] with interesting results, even addressing complex turbulent flows via numerical optimization of the cloak design [92], and also exploiting a reinterpretation of the acoustics governing equation in a four dimensional space–time that expose the relativistic structure of the phenomenon [93–98]. However, practical realization are so far limited to the static acoustics and, for the most, intended for carpet cloaking of small objects [83,87] or based on large and/or massive devices [99,100], and maybe the most interesting work is from Mendez[78], who designs a feasible pentamode material for acoustic cloaking by topology optimization, starting from the desired metafluid acoustic characteristics, and numerically tests it.

Although technology is not yet ready, one can think about potential applications of cloaking on aircraft to reduce community noise. For instance, a virtually scarfed nacelle device can take advantage from the adoption of cloaking treatment of the upper side of the nacelle. It is easy to imagine a synergy in reflecting the acoustic energy towards the sky and avoiding further reflection from the upper front part of the nacelle, from the fuselage or from the wing. For this kind of applications, cloaking devices should be able to effectively work in the presence of a mean flow, even turbulent, their usage must

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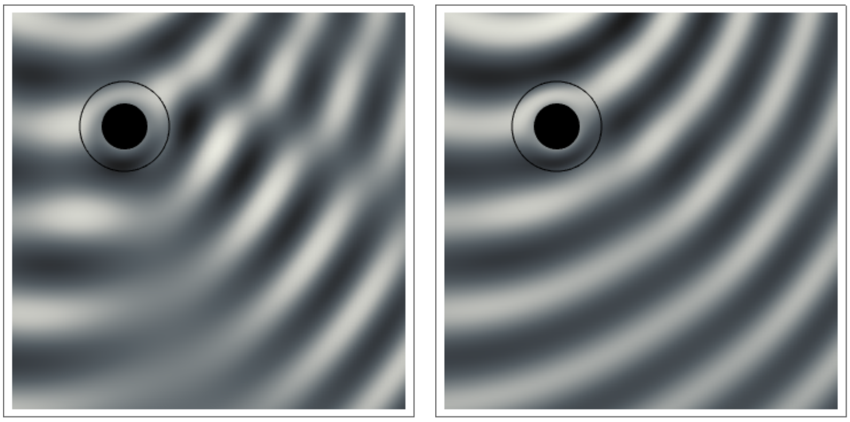

(a) (b)

Figure 10. Acoustic cloaking in presence of flow: the classic transformation acoustic theory defines a metamaterial that fails in abate scattering for $M \neq 0$ (a). A correction of metamaterial parameters as derived in [97] can recover the cloaking effect even for M=0.3 (b).

not imply an excessive weight penalty and their thickness must be smaller than the thickness of the nacelle and not negatively interfere with the overall aerodynamics behaviour.

3. Challenges

During the last decade a great effort has been done by the research community on acoustic metamaterials and the ability to shape the acoustic field. European Union, for instance, financed several projects on the topic, such as DENORMS (Designs for Noise Reducing Materials and Structures), a European Cooperation in Science and Technology (COST) action, started in 2016, or the ACOUTECT consortium, founded in 2017 within the Horizon 2020 program, that focuses on building acoustics.

However, most of the so far presented works, even the concepts selected as most promising for aeronautical applications in section, deal with quiescent hosting media. On the still long road to the application of effective metamaterial concepts in the aeronautical framework for noise reduction, the first issue emerging to be tackled is to include flows in models and simulations. As a moving fluid fundamentally affect the acoustic waves propagation, corrections and modifications in models and concepts that depends on Mach number and/or flow field shape, are expected to make them effective in the aeroacoustic domain. AERIALIST (AdvancEd aicRaft-noIse-AlLeviation devIceS using meTamaterials), another European Horizon 2020 founded project, is addressing the challenge of extending the acoustic metamaterial theory to take into account the effect of realistic aerodynamic flows. Started in 2017, the explicit goal of the project is to contribute to the identification of metamaterial–based breakthrough technologies to achieve the noise reduction targets foreseen by the ACARE (Advisory Council for Aviation Research and Innovation in Europe) Flightpath 2050.

Another challenge to face will be the development of suitable numerical methods to simulate the behavior of acoustic metamaterials in 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, that are not always available, especially for complex geometries and conditions as non uniform complex background flows. Numerical approaches are surely 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 design, and often their behavior rely on acousto–elastic interactions in structures where thermo–viscous losses are not negligible, deeply affecting the solution. A direct

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numerical simulation of such concepts, *e.g.* using FEM on fully detailed geometries, would result in computationally expensive, high resource demanding calculations, due to the fine mesh needed to both accurately reproduce the smallest geometrical details and solve the frequency of interest. This, often, does not allow for a performance optimizations in which simulations should be 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 [101] for meta poro–elastic laminates with thin coatings, that couples the Finite Element Method simulating the response in the poro–elastic medium with inclusions, and the Bloch expansion simulating 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 to address the issue when different scales are involved, such as microporous materials in which one is interested in the macroscopic effect due to the microstructure of the system[102] and can be adopted in a metamaterial design process[103,104].

4. Conclusion

A review of metamaterial concepts focusing on future aeronautical applications has been produced. The aeronautical community is concentrating its research efforts on the reduction of community noise produced by aircraft, and the significant potential shown in acoustics by metamaterials can undoubtedly give a contribution in this sense. Despite the huge literature on acoustic metamaterials, this potential still remain undisclosed for applications that involve a moving fluid. Starting from these considerations and bearing in mind the restrictions on weight and size deriving from the specific application field, concepts of acoustic metamaterials have been selected as the most promising for aircraft community noise reduction. Achievable results promised by metamaterials includes, *e.g.* enhanced and/or selective frequency noise absorption, even at low–frequency with subwavelength thickness, that can be exploited for a new generation of acoustic liners; anomalous reflection from the nacelle's internal walls that can create virtual scarfing effects from the intake of engines, and that may also be adopted for cabin noise mitigation. Metamaterials would be, ultimately, able to unlock new degrees of freedom for designers, allowing them to shape the acoustic signature of the aircraft to make them less annoying for the community. Towards an effective implementation of the analyzed metadevices, deeper investigations on the effect of the presence of a background flow must be conducted, but also the effects of metamaterial designs on the flow have to be studied. In fact, another detriment for effective applicability of a metamaterial concept in aeronautics would be, alongside with excessive weight or size, a negative impact on aerodynamic efficiency, that must be carefully avoided. Since metamaterials derive their properties primarily from their structures, complex designs are often adopted and complex visco–thermal losses and acousto–elastic interactions are involved in the generation of the related metabehaviors. To numerically reproduce such phenomena can be hard, resulting in very expensive simulations if standard direct methods, such as FEM, are applied. It is clear that new, fast and reliable tailored numerical tools are needed to tackle the design and optimization process of metamaterial devices, that is necessary to complete the road to highest TRL of this new breakthrough technologies.

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Author Contributions

Giorgio Palma, Huina Mao and Lorenzo Burghignoli performed the literature survey and collected the relevant references for the review. The original draft was prepared by Giorgio Palma

and Huina Mao, who also followed the review & editing process together with Peter Göransson and Umberto Iemma who also supervised the work as principal investigators of the Project AERIALIST.

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