Acoustic Metamaterials

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Acoustic metamaterials are large-scale materials with small-scale structures. These structures allow for unusual interaction with propagating sound and endow the large-scale material with exceptional acoustic properties not found in normal materials. However, their multi-scale nature means that the manufacture of these materials is not trivial, often requiring micron-scale resolution over centimetre length scales.

acoustic metamaterials additive manufacturing acoustics ultrasonics

1. Introduction

Acoustic metamaterials (AMMs) have been studied extensively [1][2][3][4][5][6] and can be described as a structure composed of (often) periodically repeated acoustic elements that can manipulate sound waves to produce novel and interesting effects. For example, they can achieve a negative effective bulk modulus and negative effective density [1][3]. Unlike natural materials, AMMs derive their unique properties from their structure rather than their innate material composition. The size of their periodic resonant units, also called “meta-atoms”, are closely linked to the operational wavelength. There is substantial interest in creating AMM devices at sub-wavelength scales [2], as when the resonant units are significantly smaller than the wavelength (typically 1/10 the size) [6], the elements can behave as one effective continuous medium—waves do not see the granularity of the medium. Early forms of AMMs have dimensions similar to their operational wavelength [7], and their properties derive from scattering. As such, the upper wavelength limit, and corresponding largest possible meta-atom size, in the ultrasonic regime (i.e., >20 kHz in air) is 17.25 millimetres, demonstrating the need for the development of smaller-scale AMMs. Acoustic wavelengths, with air as the transmission medium, range from 17.25 millimetres (at 20 kHz) to 17.25 metres (at 20 Hz)—this poses an issue to commercializing audio-range technologies with wavelength equivalent sizing, due to their unfeasible dimensions. Devices operating in a fluid medium [8] or mechanical capacity [9] also present similar issues. AMMs using local resonances can be subwavelength and are thus more attractive and applicable. Developing 3D printing technology with finer resolutions is vital to miniaturize AMM designs to a practical size and enable their use in potential applications. To manufacture AMMs that can operate at higher ultrasonic frequencies, or sub-wavelength devices at audio frequencies, there is a demand for printing technologies with resolution in the micro (or even nano) scale.

A noteworthy area of AMM research is active structures, whose material properties and/or physical geometries can be changed by external stimuli. Parameters of particular interest are tuneable bulk modulus and effective density [10][11][12][13][14][15]. In the context of this review, an active AMM indicates an AMM system whose acoustic properties and/or geometric structure can be modified using an external interaction. This external input could involve an applied magnetic field [16], electric current, mechanical energy [17], temperature, chemical energy, fluid filling [18], hydration [19], or various other energy inputs/outputs [18]. Active AMMs can be broadly separated into non-Hermitian (involving acoustic gain) or externally biased (where there is no transfer of energy with acoustic waves) [4]. A common trend in active AMMs is to incorporate piezo-electric elements that allow tuning via an applied electric field [20][21]. In traditional (or passive) AMMs, the material properties cannot be altered after fabrication, and the operational bandwidth is fixed and often narrow. One limitation of this is their unsuitability for potentially transformative applications requiring a broader range of frequencies. However, AMM structures with a tuneable bandwidth present a potential opportunity to surpass this limitation. Active AMMs often incorporate many materials, due to their novel modulation systems; therefore, progressing multi-material 3D printing would greatly benefit the production of active AMMs.

2. Additive Manufacture of Small-Scale Metamaterial Structures for Acoustic and Ultrasonic Applications

The field of acoustic metamaterials holds much promise for the future, with novel solutions to acoustic problems becoming increasingly close to real-world applications. While the field of AMMs covers such problems as earthquake engineering, building acoustics and underwater applications, we have chosen to focus on the potential uses of acoustic metamaterials on airborne systems for audio and ultrasonic applications.

With airborne sound covering wavelengths from metres to millimetres, the scale of materials that interact with these sounds is similar, so not only are novel subwavelength meta-atom designs important, but also the ability to create them is crucial. Additive manufacturing has proved to be the most promising out of existing technologies, exceeding its subtractive counterparts, to build up complex materials from their constituent meta-atoms. However, the outlook is challenging for translating this academic research into fully-realized devices for industrial and consumer applications. Rapid prototyping, while cheap for everyday use, still becomes expensive with scale, particularly techniques requiring custom materials. Additive technologies working at multiple scales is not feasible, so obtaining micron resolution over scales in excess of a centimetre is close to impossible. Complex shapes are challenging, and aspects of temperature dependence or curing/annealing mechanisms of raw materials can mean that it is difficult to print with adequate accuracy and reliability. For example, the printing of membranes—commonly used to provide mechanical behaviour to a meta-atom—is challenging, where at a small scale the raw materials can have post-production tension and warping that is difficult to compensate for. In addition, each technique has production requirements unique to itself. As mentioned, vat polymerization techniques cannot print voids or inclusions directly, instead requiring vents or other ways to leak out the original liquid polymer. Designs of AMMs need to account for that, providing another barrier to production.

Clearly, for a practical and realisable AMMs, we need to be able to create large-scale materials (and ultimately devices) with small-scale features. Additive manufacturing is the best candidate for both rapid prototyping and bulk manufacture, but limitations on specific fabrication characteristics act as a barrier to AMM research, constraining printable ideas and restricting its potential. Given that metamaterials typically derive their properties from repeating units of local resonators or geometrical features, a key issue in their manufacture is consistency and reproducibility across length scales. A material in which some of the meta-atoms failed to print correctly could alter the acoustic properties and potentially disrupt the predicted acoustic behaviour. This high dependency on uniformity, or reliability of shape, across meta-atoms means that AMMs are still very challenging to create, even with additive manufacturing, and especially at smaller scales. The robustness of metamaterials to meta-atom failure could be a key area of research to progress AMMs to commonplace use.

MPP was found to have the smallest printable feature size, followed by DIW, jetting systems and DLP, with the highest resolution of these methods well within the nanoscale. This result is supported by similar findings in the literature [22][23]. For structures requiring varied material options, like active AMMs, DIW and jetting systems were found to have the widest material range—from ceramics and metals to live cells—and a minimal risk of cross-contamination of materials, unlike vat polymerisation and powder bed methods. Additionally, extrusion/deposition methods are regarded as comparatively fast additive manufacture techniques, further demonstrating the significant potential of DIW and jetting systems as extremely effective and well-rounded techniques for AMM manufacture.

Other noteworthy techniques include SLM and EBM, which excel at fabricating metallic parts with microscale resolution without the use of support structures. Vat polymerisation and ink deposition methods are the set of techniques best suited to printing hydrogels—a key material for the fabrication of some active metamaterial designs. Vat polymerisation shows strong potential for AMM fabrication, with SLA, DLP and MPP all being robust techniques with individual benefits; however, their main limitation lies in their material restrictions and post-processing requirements. Further development to overcome these challenges would be beneficial for their application in AMM construction.

Over the following 10 years, the next generation of practical AMMs will need to come from either significant progress in rapid prototyping and manufacturing technology, or the discovery of meta-atom designs that have complex physical behaviour while being sufficiently simple enough to be printed. Active acoustic metamaterials promise to push development forward, compensating for manufacturing challenges by adding complexity through controlled actuation rather than static structure, but they are also difficult to produce beyond very basic systems at the smallest scale. Nevertheless, it will be exciting to monitor which of these two strands of research will succeed first.

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