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METAMATERIALS IN FLEXIBLE WINGS

A.O. Krushynska
Engineering and Technology Institute Groningen, Faculty of Science and Engineering, University of Groningen, 9747 AG Groningen, the Netherlands
E-mail: a.o.krushynska@rug.nl

Flexible wings of insects can adapt to varying flight conditions, ensure maneuverability, and enable stability of forward, flapping, and backward flights. Yet, the challenging aerodynamics of these wings, from the modeling point of view, and enormous variability in wings' morphology prevent achieving a complete understanding of their dynamics. Until now, researchers have continued discovering new functions of insect wings linked to their structure. For instance, a recent study [*Neil T.R. et al., Proc. Natl. Acad. Sci. 117 (49), 31134-31141 (2020)*] has reported the remarkable ability of moth wings to reduce ultrasonic echoes at a subwavelength scale allowing one to consider these wings as natural acoustic metamaterials. Other researchers have applied the metamaterials concepts to implement morphing and control aerodynamic features in artificial flexible wings. Here, we briefly overview this emerging research direction at the border of the two fields – metamaterials and artificial flexible wings. It still has a very limited number of works but already shows a promising potential of metamaterials in developing advanced micro-flying devices.

Keywords: metamaterial, flexible wings, shape morphing, vein pattern, noise reduction

1. Introduction

Scientists have been fascinated by the dynamics of insect wings for centuries, though their systematic studies began with the advent of numerical methods and high-speed computers due to the high complexity of modeling large deformations and wing-air interactions. Since then, the number of works on nonlinear aeroelasticity, morphing, flexibility, and vibroacoustics of natural wings and their artificial counterparts for small flying devices has exploded and constantly increases.

Many aspects of intricate kinematics and aerodynamics of flexible wings have been clarified. For instance, flexibility [1, 2, 3, 4] and camber [5] were recognized as crucial factors enabling insect flights. Ellington et.al [6] explained the origin of high lift forces and Wang [7] elucidated the lift generation mechanism in flapping wings. Comprehensive overviews on the state-of-the-art flight mechanics of flexible wings can be found elsewhere [1, 8, 9].

Despite the abundant knowledge accumulated, we are still far away from a complete understanding of the dynamics and other (not necessarily flight-related) functions of insect wings. Researchers continue searching for new approaches to analyze insect wings, and simultaneously, to adapt them in the development of artificial flying devices reproducing insect flight [10]. A remarkable example is a recent study by Neil et.al [11] revealing an unexpectedly broadband absorption of ultrasound by moth wings. They have found that intricate scales linked to the wing membrane act as deep-subwavelength resonators and enable synergetic absorption, which delivers acoustic camouflage against echolocating bats. This collective sound attenuation performance allows us to consider moth wings as natural acoustic metamaterials and serves as a source of inspiration for new avenues in the design of flexible artificial wings.

In this paper, we overview the studies that apply metamaterials to develop artificial wings. We start with the definition of mechanical and acoustic metamaterials and their features and continue with reporting the key results for metamaterial-based artificial wings that have morphing functionality, bioinspired designs, and controllable aerodynamic properties. The paper is finalized by conclusions.

2. Metamaterials definition and classification

Metamaterials can be defined as rationally designed – architected – composites with properties exceeding those of their constituents [12]. Nowadays, metamaterials form a separate, very active, and rapidly growing research field at the intersection with Acoustics, Mechanics, Materials Science, Thermodynamics, Condensed Matter Physics, Seismology, Civil Engineering, and other scientific disciplines.

A purposely designed architecture of metamaterials delivers advanced characteristics, which previously were even hard to imagine and currently are responsible for superior performance indispensable for many applications. If the architecture is engineered to manipulate acoustic fields or waves in fluids, one speaks about acoustic metamaterials. Acoustic metamaterials are applied in transformation acoustics and cloaking due to their varying refractive index; membrane-type and space-coiling acoustic metamaterials have been used for acoustic beam shaping, impedance control, sound absorption, etc. [13].

Mechanical metamaterials form another category of metamaterials distinguished by their unprecedented mechanical properties or functionalities. Examples of such properties include extreme or highly anisotropic elastic moduli, auxetic (negative Poisson's ratio) behavior, programmable, adaptable, and tunable mechanical behavior [14].

2.1 Morphing metamaterial wings

An important characteristic of morphing – shape-changing – wings is their aerodynamic adaptability enabling the control of a flying object by generating imbalance in aerodynamic forces via the manipulation of lift-generating surfaces [15]. Furthermore, morphing wings can potentially enlarge flight envelope, maneuverability, and adaptability in dynamic environments [16].

Spanwise morphing delivering in-flight aspect ratio adaptation is beneficial to extend the wings for an efficient loitering mode and retract them to increase a high-speed dash. It has historically been accomplished by using telescoping mechanisms that lead to greater mechanical complexity and increased weight [15]. To overcome these limitations, Boston et.al. [15] have proposed lightweight cellular metamaterials with multiple stable shapes that can enable spanwise morphing by allowing large, elastic deformations while maintaining sufficient load-bearing ability. For this, they studied multistable honeycombs with different unit cells and characterized their in-plane and flexural mechanical properties and structural efficiency analytically and numerically. Promising configurations were selected to develop a beam-like metastructure for a one-directional shape adaptation. The obtained hybrid span-morphing wing with rigid structures and compliant metabeam joints proved the ability to increase lift from spanwise morphing without increasing wing flexural deflection.

Other traditional morphing strategies use post-buckled precompressed actuators, foldable and deployable artificial feathers, macro fiber composites, and soft pneumatic actuators. Such pure mechanical designs involving rigid-flexible coupling or flexible structures can be difficult to realize due to extreme requirements on the dimensional constraints, actuating limits, and weight restriction, especially, in small-scale flying vehicles [16], which further stimulates the search for promising solutions in metamaterials.

Xiao et.al [16] have explored the design freedom of pantographic metastructure to tune the multiaxial stiffness of morphing wings. Specifically, they adopted soft actuators with hyperelastic PneuNets and pantographic metastructures to achieve seamless and continuous deformation in spanwise and chordwise directions during shape-changing. Wind tunnel tests confirmed that this approach is appropriate to induce wing morphing and enables effective tuning of the aerodynamic performance.

Wang et.al [17] proposed active digital metamaterials formed by distributed morphing lattices of variable geometry to achieve a morphing ability. Their designs include three types of fundamental cells with different mechanical properties – rigid, compliant, and auxetic – and three types of active cells derived by combining the fundamental cells and embedded micro-actuators, which enable autonomous extension or contraction. All these cells are assembled in a morphing lattice structure by applying a heuristic optimization algorithm. The numerical results show that the optimized lattice structure can morph its outer surface into a predefined aerodynamic contour. The digital-metamaterial wings can be promising to improve the aerodynamic performance of aircraft wings.

Jha and Dayyani [18] have analyzed the potential of a large strain morphing skin formed by a zero Poisson's ratio (ZPR) Fish-Cells metamaterial. They used a multi-objective genetic algorithm shape optimization to improve the ZPR characteristics of this metamaterial and finite element models to analyze the morphing performance of an optimized design in the regime of large non-linear strains. The results of the conducted analysis suggest that the shape-optimized ZPR metamaterial can be considered as a candidate for a morphing aircraft wing.

2.2 Additively manufactured flexible wings with controlled aerodynamics

Additive manufacturing is a promising and versatile approach to manufacturing flexible (membraneous) wings for small flying vehicles. Recently, several research teams have explored the possibilities of additive manufacturing to develop aerodynamically efficient wings.

Filc et. al [19], inspired by the natural morphology of the rose chafer beetle (*Protaetia cuprea*) wings, have studied the influence of geometric features and modifications of the vein's cross-section on the aerodynamic performance. Their analysis deliberately eliminates the complexity of material heterogeneity in real wings with the aim of focusing on geometrical traits. They found that combining the tapered form (thicker base vs. thinner edge), comparatively thick interconnecting membranes, and camber (chord-wise curvature) deliver crucial structural advantages to flexible flapping wings and proved that fine-tuning these design parameters is paramount for their aerodynamic performance. Such fine-tuning is however a challenge considering hundreds of the design parameters for bio-inspired wings.

A computationally feasible approach to address this challenge implies replacing the natural morphology of veins with a metamaterial pattern, which can be described by only a few geometric parameters. For instance, Zhilyaev et.al [10] have proposed a cambered tapered wing with a metamaterial pattern that can easily be manufactured on a hobbyist 3D printer from a flexible polymer. The balance between the flexibility of membranes and the rigidity of veins was achieved by controlling the number of 3D-printed layers. The structural morphology was tuned by a multi-parameter optimization technique with contradictory requirements – to increase lift and, simultaneously, reduce noise and stresses induced by large deformations during flapping. To fully explore the multi-dimensional design space of patterns for metamaterial wings, it was also proposed to combine AI-based design techniques, such as machine-learning techniques, with the finite-element method [20]. This approach validated on honeycomb and re-entrant metamaterial patterns has demonstrated its computational feasibility to provide systematic insights into the effects of structural parameters in reasonable computation time. Importantly, it was found that the 'best' parametric settings are not limited to single values but to bounded regions offering broad design flexibility. In other words, crucial design parameters, e.g., pattern anisotropy and varying thickness, can vary in specified ranges and, accompanied by variable secondary parameters, deliver 'optimized' aerodynamic performance for a wide range of metamaterial patterned wings. This opens the possibility of developing multiple fine-tuned designs of metamaterial wings with required aerodynamic characteristics resembling the ambiguity of natural patterns.

3. Conclusions

This brief review shows that the application of mechanical and acoustic metamaterials has a strong potential to relax the design limitations and address persisting challenges in the development of artificial flexible wings. We strongly believe that future collaborative efforts of the researchers from the metamaterials and flight dynamics communities will be necessary to reproduce the complexity of different flights of natural flyers and advance the development of artificial (micro-)flying devices to the next, currently unforeseen level.

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