

Computational design and additive manufacturing of periodic conformal metasurfaces by synthesizing topology optimization with conformal mapping

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Received 26 March 2017; received in revised form 14 July 2017; accepted 8 September 2017

Available online 21 September 2017

Abstract

In this paper, we present a computational framework for computational design and additive manufacturing of free-form periodic metasurfaces. The proposed scheme rests on the level-set-based topology approach and the conformal mapping theory. A metamaterial with pre-specified performance is created using a level-set-based topology optimization method. The achieved unit cell is further mapped to the 3D quad meshes on a free-form surface by applying the conformal mapping method which can preserve the local shape and angle during the mapping. With embedded geometric information, the proposed level-set-based optimization methods not only can act as a motivator for design synthesis, but also can be seamlessly hooked with additive manufacturing without the need of CAD reconstructions. The current computational framework provides a solution to increasing applications involving innovative metamaterial designs on free-form surfaces for different fields of interests. The performance of the proposed scheme is illustrated through two benchmark examples where a negative-Poisson's-ratio unit cell pattern, and a stiff and light inner structure are mapped to 3D free-form surfaces and fabricated through additive manufacturing.

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Keywords: Topology optimization; Level set method; Conformal mapping; Additive manufacturing; Metasurface

1. Introduction

Metamaterials are defined as a group of artificial materials which gain superior effective properties through the inner structures rather than their composition. Metamaterials have been considered as critical attributes and important technology themes by a broad range of applications in telecommunication, aerospace, defense, automotive and medical devices, which may serve as building bricks for constructing more advanced metadevices. Despite recent

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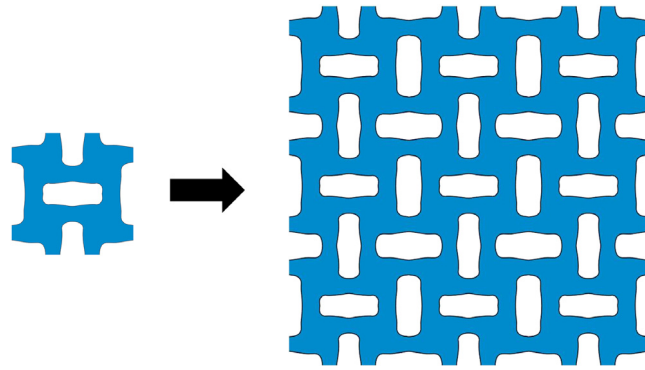


Fig. 1. Planar metastructure with 3×3 unit cells.

advances in metamaterial research [1–4], conventional mechanical metamaterial designs have been executed mainly in the regular Cartesian space, e.g. in a 2D rectangular plane or a 3D cubical space. With the development of additive manufacturing technology, the time has come to think about achieving metamaterials on a free-form surface, also termed conformal metasurface (not to be confused with planar metamaterials found in electromagnetic applications). Such conformal metasurface can result in many new applications, for example, conformal cooling surfaces, orthopedic devices, conformal sensors or antennas, etc.

There is an increasing research on conformal structures and its applications. Wang and Rosen [5] achieved a truss structure conformed to a part's shape using parametric modeling techniques, and Chu et al. [6] proposed an additive manufacturing method including conformal lattice with a unit cell library of different mechanical properties. For radar-cross-section reduction, Jang et al. [7] proposed a conformal metamaterial absorber achieving high absorption rates in different incident angles, by utilizing three different unit cell designs at various zones of a curved surface. In flexible electronics, Bernhard and Lewis's team recently implemented conformal printing of small electrical antennas onto the surfaces of hemispherical glass substrates [8], which was reported to improve the antenna performance by an order of magnitude. Considering additive manufacturing capabilities and constraints, Aremu et al. [9] developed a method to obtain cell-based lattice structures that can conform to an external geometry, and addressed potential trimming problems by generating a surface lattice. The ability to rationally design and efficiently realize artistic or functional metasurfaces is important in both art and science. While research on designing metamaterials has drastically advanced recently, topology optimization of conformal metasurfaces remains untapped. There is a distinct lack of an appropriate method that can be applied to metasurface design.

A common practice in metamaterial design is to obtain a 2D or 3D unit cell, a representative volume element (RVE) under periodic boundary conditions [10]. This constitutive building unit can be later periodically assembled in two or three directions, to build the desired metastructure (Fig. 1). It may also be utilized as a building unit to form a rotational periodic structure, such as a cylinder, by a straightforward transformation from Cartesian to the cylindrical coordinate system. Such an obtained geometry may possess different characteristic behavior compared to the planar metastructure [11]. Mapping a plane unit cell to a free-form surface is nontrivial. A potential solution is conformal mapping, an angle-preserving Riemann mapping that can preserve the local shape. A functional and practical methodology could be useful for developing customizable products in the medical field, where implants, artificial bone structures, and prosthetics have a free-form surface with pre-specified mechanical properties. Large scale applications can also benefit, including wings and fuselages of the aerospace industry, where lightweight structures with extreme thermomechanical properties are desired.

1.1. Pipeline of proposed framework

In this paper, a computational framework is introduced for topology optimization and additive manufacturing of metamaterials on 3D free-form surfaces, which rests on the level-set-based topology optimization approach and the conformal mapping theory. A metamaterial unit cell design with tailored effective properties or prescribed performance is first achieved using the level-set-based topology optimization scheme. After the free-form object

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