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Research paper

Design of fully decoupled compliant mechanisms with multiple degrees of freedom using topology optimization

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ABSTRACT

Compliant mechanism-based microdevices with multiple inputs and multiple outputs have a wide range of applications in precision mechanics, e.g., cell manipulation, electronic microscopy and MEMS (Micro-Electro-Mechanical Systems). In designing this kind of microdevice, the movement coupling among the microdevices becomes critical because many inputs and outputs are involved. This paper presents a systematic method for designing fully decoupled compliant mechanisms with multiple degrees of freedom by using topology optimization. An optimization formulation is posed by considering both output coupling and input coupling issues to achieve fully decoupled motion. The SIMP (Solid Isotropic Material with Penalization) and MMA (Method of Moving Asymptotes) methods are adopted to identify the optimized material distribution in the design domain. Several numerical examples are presented to demonstrate the validity of the proposed method.

1. Introduction

A compliant mechanism, i.e., a monolithic or jointless structure that can transfer an input force or displacement through its elastic body deformation, offers unique possibilities in a wide range of application fields [1,2]. For example, in biological cell manipulation [3,4], optical fiber alignment [5,6], and scanning probe microscopes [7,8], compliant mechanism-based micromanipulators have been extensively used to achieve ultrahigh precision accuracy.

Over the past several decades, substantial research has been conducted on the synthesis of compliant mechanisms, and several approaches have been developed. These approaches typically follow two directions. The first is the so-called kinematic-based approach, which is also known as the pseudo-rigid-body model [9–13]. In this method, the design process often begins with a known rigid-link mechanism. A compliant mechanism can be obtained by replacing the conventional joints with flexural hinges, and it can thus be modeled as a rigid-link mechanism with torsional springs at the joint areas. Therefore, the existing analytical methods for a rigid body mechanism can be directly adopted. This convenience makes the pseudo-rigid-body model highly suitable and widely utilized in designing mechanisms that are used in precision-positioning engineering [14,15]. A shortcoming of this method is that one must begin with a known rigid-link mechanism, which makes the design highly dependent on the designers' institution and experience.

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The other method for the design of compliant mechanisms uses topology optimization methods. Topology optimization is regarded as an approach that is able to seek the optimum distribution of material in a given design domain that minimizes a given cost function while satisfying a series of constraints [16–20]. To date, topology optimization has been exhaustively explored, and several methods have been developed, such as the SIMP method [21,22], ESO method [23,24] and level set method [25,26]. Among them, the SIMP method is the most popular because of its simple concepts and ease of use. A comprehensive review of established topology optimization methods can be found in [27–29]. The seminal work on designing compliant mechanisms using continuum topology optimization can be found in [30], in which a multi-objective formulation based on the weighted sums of the flexibility and stiffness is developed. Various subsequent studies have been conducted to explore the design of compliant mechanisms by using continuum topology optimization methods. Recently, methods for topological synthesis of compliant mechanisms have been extended to include geometrical non-linearity [31,32], design of supports [33], multiple materials and physics [34,35].

Despite these significant advances, a fundamental issue is that most studies have been conducted on designing compliant mechanisms with single input and single output behavior. Only a few approaches have been presented on a topological design of single input and multiple output compliant mechanisms. The seminal work can be found in [36], in which the weighted sum method was employed to develop a valid optimization formulation for designing compliant mechanisms with a single input and multiple outputs. However, a shortcoming is that it is very difficult to choose the weighting factors such that all of the outputs can be considered equally in the solution [37]. Later developments in this area can be found in [37–41], in which the design objective was often developed by simultaneously considering mutual potential and strain energies. Alonso et al. [41] presented a generalized formulation to design multi-input-multi-output compliant mechanisms in which the design objective is to maximize the summation of the mutual potential energy due to each input load.

However, in the aforementioned studies, the coupling issue of the outputs was neglected; thus, they often resulted in a mechanism with coupled outputs. Generally, a decoupled mechanism means that one input produces only one output motion along the specified direction without affecting the motions of other axes. Therefore, the term “decoupled” often refers to output decoupling. However, despite its importance, input decoupling, which emphasizes the isolation of the input motion, is rarely considered [42]. When the mechanism is driven by one actuator at the input port, the actuators at other input ports may suffer from unwanted loading due to the movement of the output platform. To overcome these issues, it is useful to develop a fully decoupled mechanism by considering both input and output decoupling properties. The most early developed decoupled compliant positioning stages were designed based on the kinematic-based approach, which often resulted in a decoupled mechanism at the expense of complicated structures [43–47]. In practice, to benefit the control implementation and prototype fabrication, methods for designing a fully decoupled compliant positioning stage with a simple structure are desirable.

For this reason, a topology optimization method for designing fully decoupled compliant mechanisms is proposed in this study. A layout design of the compliant mechanisms with multiple inputs and multiple outputs is performed wherein displacements at all output ports are maximized along the desired directions. A weighted sum method is used to establish an adequate objective function. Then, several constraints are developed, aiming to achieve both the input and output decoupled requirements. An optimization model is developed and solved using the SIMP method and the method of moving asymptotes. Several numerical examples are presented to demonstrate the validity of the proposed method.

The remainder of the paper is organized as follows. In Section 2, an optimization model that can be used to design fully decoupled compliant mechanisms with multiple inputs and multiple outputs is proposed. In Section 3, the proposed optimization model is rewritten by incorporating it with the SIMP method. Sensitivity analysis is also addressed. In Section 4, numerical implementations that need to be considered when using the SIMP method are addressed. In Section 5, several numerical examples are shown to demonstrate the validity of the proposed method. Conclusions and future works are provided in Section 6.

2. Problem formulation

2.1. Continuum topology optimization

The continuum topology optimization approach is considered a distributed material optimization method. In this method, the candidate design domain is discretized and modeled by using finite elements. The material property of each element is controlled such that removing a certain region can be achieved by forcing the material properties of a certain number of elements to approach zero. We adopted the SIMP method due to its concept simplicity and ease of use. Considering linear isotropic materials, the SIMP method provides a connection between Young’s modulus and the density of an element by

$$E(\rho_e) = E_{\min} + \rho_e^p (E_0 - E_{\min}) \tag{1}$$

where the element density $\rho_e \in [0, 1]$ is the design variable, $E_{\min} > 0$ represents the stiffness of void material, E_0 is the stiffness of the given isotropic material, and $p > 1$ is the penalty [48].