International Journal of Mechanical Sciences 86 (2014) 69–75

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Evolutionary topology optimization of hinge-free compliant mechanisms

Y. Li [a], X. Huang [a,b,*], Y.M. Xie [a], S.W. Zhou [a]

[a] Centre of Innovative Structures and Materials, School of Civil, Environmental and Chemical Engineering, RMIT University, GPO Box 2476, Melbourne, VIC 3001, Australia

[b] Department of Building Engineering, Tongji University, Shanghai 200092, China

ARTICLE INFO

Article history:
Received 3 June 2013
Received in revised form
11 October 2013
Accepted 15 October 2013
Available online 30 October 2013

Keywords:
Topology optimization
Bi-directional evolutionary structural optimization
Compliant mechanisms
Sensitivity analysis

ABSTRACT

This paper develops a bi-directional evolutionary structural optimization (BESO) method for the design of hinge-free compliant mechanisms. A new objective function is proposed to maximize the desirable displacement and preclude the formation of hinges simultaneously. Sensitivity numbers are derived according to the variation of the objective function with respect to the design variables. Based on the resulting sensitivity numbers, the BESO procedure is established by gradually removing and adding elements until an optimal topology is achieved. Several 2D and 3D examples are given to demonstrate the effectiveness of the proposed BESO method for the design of various hinge-free compliant mechanisms.

1. Introduction

Compliant mechanisms are single-piece flexible structures that transfer an input force or displacement to another point through elastic deformation. They consist of fewer parts than rigid-link mechanisms. In other words, some or all of their motions are derived mainly from the relative flexibility of their components instead of rigid body joints [15]. Such non-assembly and monolithic mechanical devices have numerous virtues such as saving space, reducing material costs and avoiding assembly procedures. Therefore, the application of compliant mechanisms has become increasingly prevalent in medical instruments and micro-scale mechanical systems [14].

There are two main approaches in the systematic design of compliant mechanisms, namely the kinematics-based approach and the structural optimization-based approach [6]. The kinematics-based approach takes advantage of kinematic synthesis of a rigid-link mechanism which consists of rigid parts and joints [8]. For designing compliant mechanisms, Her and Midah [5] developed a methodology through a given rigid body kinematic chain, and Howell and Midha [7] proposed an analysis and synthesis method using a pseudo-rigid-body model. However, the resulting designs might not be able to fully reproduce the motion of its rigid-body counterpart [16]. Unlike the kinematics-based approach starting with an assumed rigid-link mechanism, the structural optimization-based approach tackles the problem with topology optimization formulations.

Over the last three decades, various structural topology optimization methods, e.g. the homogenization method [3], Solid Isotropic Material with Penalization (SIMP) [27,19], the level set method [18,22] and Evolutionary Structural Optimization (ESO) [25,26] have been developed. The ESO method is based on a simple concept that inefficient material is gradually removed from the design domain so that the resulting topology evolves towards an optimum. The later version of the ESO method, namely the bi-directional ESO (BESO), allows not only to remove material from the least efficient regions, but also to add material near the most efficient regions simultaneously [9,10]. It has been demonstrated that the current BESO method is capable of generating reliable and practical topologies with high computational efficiency for various structural optimization problems [11].

The design of compliant mechanism is one of many areas to which the topology optimization technology has been applied. Sigmund [23] developed the density method based on the continuum-type topology optimization technique for the optimal design of compliant mechanisms. Nishiwaki et al. [17] adopted the homogenization method for solving optimization problems of compliant mechanisms by introducing a mutual energy concept. Saxena and Ananthasuresh [21] generalized multi-criteria formulations in terms of monotonically increasing functions of the output deformation and the strain energy. An ESO method with

* Corresponding author. Tel.: +61 3 99253320; fax: +61 3 96390138.
E-mail address: huang.xiaodong@rmit.edu.au (X. Huang).

0020-7403/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijmecsci.2013.10.013

an additive strategy was proposed by Ansola et al. [1] and was also applied to 3D compliant mechanisms [2]. Wang [24] quantified mechanical advantage based on a linear elastic structural analysis according to the stiffness elements of compliant mechanisms.

The designs of compliant mechanisms using topology optimization techniques naturally lead to the introduction of hinges into the models, making them function essentially as rigid-body mechanisms [20]. Such hinge zones cause high stress concentration and are difficult to fabricate for micro-scale systems. This paper develops a new BESO algorithm for optimally designing hinge-free compliant mechanisms. The strain energy of the structure is introduced into the formulation of the optimization problem. Based on the finite element analysis and sensitivity analysis, a BESO procedure is established to evolve the compliant mechanism to an optimum. Several examples are presented to demonstrate the effectiveness of the proposed method for designing various hinge-free compliant mechanisms. Different from other density-based topology optimization methods, BESO provides clear topological representation of compliant mechanisms without any 'gray' area.

2. Optimization problem and structural analysis

Consider a general design domain Ω under given loading and boundary conditions as shown in Fig. 1(a). It is assumed that the applied force at the input port i is F_{in} and the reaction force at the output port j is F_{out}. The latter force is acting on a workpiece which is modeled by a spring with a constant stiffness, k_s. The resulting input displacement is Δ_{in} at the input port i and the output displacement Δ_{out} at the output port j. In general, an efficient compliant mechanism should be flexible enough to produce expected kinematic motion under the action of applied loads to satisfy the flexibility requirement [12]. Therefore, the design objective could be maximizing a displacement ratio which is called the geometric advantage $GA=\Delta_{out}/\Delta_{in}$. Meanwhile, the compliant mechanism becomes a structure as shown in Fig. 1(b) when the output port is fixed. Such a structure should possess a certain stiffness to limit the input displacement at the input port. In other words, a compliant mechanism should be flexible enough to produce the expected kinematic motion and stiff enough to resist applied forces [17,13]. The stiffness of the structure can be inversely measured by the mean compliance or total strain energy in the structure. Furthermore, maximizing the structural stiffness or minimizing the total strain energy can also preclude the formation of hinges in the design of compliant mechanism [20]. Considering those factors, we can mathematically formulate an optimization problem for the design of a hinge-free compliant mechanism as follows:

$$\begin{aligned} &\text{Maximize}: \ f(x_e)=\frac{GA}{SE} \\ &\text{Subject to}: \ V^* - \textstyle\sum_{e=1}^{N} V_e x_e = 0 \\ &x_e = x_{min} \ \text{ or } \ 1 \end{aligned} \tag{1}$$

where $SE=\mathbf{u}^{\mathrm{T}}\mathbf{K}\mathbf{u}/2$ is the total strain energy in the structure shown in Fig. 1(b). V_e is the volume of an individual element and V^* is the prescribed total structural volume. The binary design variable x_e denotes the density of eth element. Normally, a small value of x_{min} e.g. 0.001 is used to denote the void elements.

The analysis of the compliant mechanism can be the superposition of two load cases as shown in Fig. 1(c) and (d). The displacements of the compliant mechanism at the input and output ports are

$$\Delta_{in} = \Delta_{11} + c \times \Delta_{12} \tag{2a}$$

$$\Delta_{out} = \Delta_{21} + c \times \Delta_{22} \tag{2b}$$

where Δ_{ij} denotes the displacement at the port i due to the applied force F_j. c is the combination coefficient to be determined. Meanwhile, the forces should satisfy the following relationships:

$$F_{in} = F_1 \tag{3a}$$

$$F_{out} = -cF_2 = k_s \Delta_{out} \tag{3b}$$

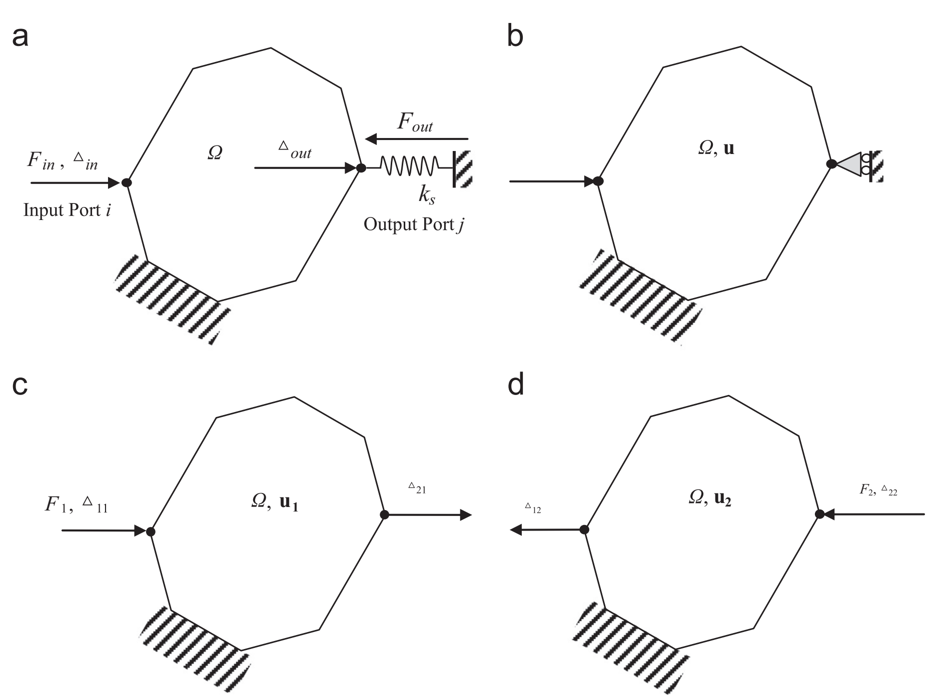

Fig. 1. (a) Compliant mechanism design; (b) output-restrained structure; (c) input load case; and (d) output load case.