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Topology synthesis of Multi-Input–Multi-Output compliant mechanisms

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ABSTRACT

A generalized formulation to design Multi-Input–Multi-Output (MIMO) compliant mechanisms is presented in this work. This formulation also covers the simplified cases of the design of Multi-Input and Multi-Output compliant mechanisms, more commonly used in the literature. A Sequential Element Rejection and Admission (SERA) method is used to obtain the optimum design that converts one or more input works into one or more output displacements in predefined directions. The SERA procedure allows material to flow between two different material models: 'real' and 'virtual'. The method works with two separate criteria for the rejection and admission of elements to efficiently achieve the optimum design. Examples of Multi-Input, Multi-Output and MIMO compliant mechanisms are presented to demonstrate the validity of the proposed procedure to design complex complaint mechanisms.

1. Introduction

A compliant mechanism can be defined as a monolithic structure that relies on its own elastic deformation to achieve force and motion transmission [1]. The most promising application area of these mechanisms is the design of microelectromechanical systems (MEMS). These submillimeter mechanical systems coupled with electronic circuits are manufactured using etching techniques and surface micromachining processes from the semiconductor industry [2]. The use of hinges, bearings and assembly processes are prohibitive due to their small size, and must be built and designed as compliant mechanisms etched out of a single piece of material.

The simplest design of a compliant mechanism is a Single-Input–Single-Output (SISO) device, where an input force is supposed to produce an output displacement elsewhere in the design domain. Originally accomplished by trial and error methods, the research community quickly took an interest in the systematic design of SISO compliant mechanisms by means of topology optimization techniques [3–5]. The main advantage of these optimization techniques was that the optimum designs were automatically suggested for prescribed design domains, boundary conditions and functional specifications. There was no need to pre-determine the number of links or the location of the flexural joints in the device [6].

The optimization methods used to design SISO compliant mechanisms are diverse: the Homogenization method [3,7], the SIMP method [5], the Genetic Algorithms [8], the Level Set methods [9] and, more recently, the SERA method [10].

However, the design of more practical actuators requires the consideration of Multi-Input–Multi-Output (MIMO) compliant mechanisms. These devises are widely used in the fields of micro-manipulation and micro-positioning and consider multiple loading (Multi-Input) and/or multiple displacement (Multi-Output) conditions. In this case, a robust optimization method with a suitable problem formulation is necessary to obtain an optimized mechanism which can fulfil the design requirements of strength and flexibility to withstand the applied loads and produce the specific displacements.

Larsen et al. [11] were the first researchers to design compliant mechanisms with multiple output requirements with a formulation that minimized the error in obtaining prescribed values of the geometrical and mechanical advantages. Topologically complex mechanisms were designed with the use of the SIMP method. This formulation, however, failed to provide the flexibility required for the kinematic function and the rigidity required simultaneously, since the output constraint had to be specified beforehand.

Frecker et al. [12] proposed a different procedure to design mechanisms with multiple output requirements starting from an initial ground structure. The formulation was based on their multi-criteria optimization procedure for single output cases [4]. Two different combinations of the Mutual Potential Energy (MPE) and the Strain Energy (SE) [13] were studied as objective functions so that the two objectives of maximizing the MPE and minimizing

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the SE were simultaneously accomplished: (1) a weighted linear combination of MPE and SE, and (2) the ratio between them. The extension to mechanisms with multiple output ports used a combined virtual load or a weighted sum of objectives of the multi-criteria formulations to achieve the optimum.

After these first approaches, other researchers worked on the design of compliant mechanisms with multiple conditions or constraints. Sigmund [14,15] performed topological synthesis of multiphysic actuators with output constraints together with the SIMP method. Saxena [16] performed topology optimization of compliant mechanisms with multiple output ports. The optimization method used was the Genetic Algorithms and the initial domain a fully connected ground structure. Jouve and Mechkour [17] presented an example of a Multi-Input compliant mechanism obtained with an extension of their Level Set formulation. Liu and Korvink [18] proposed the Artificial Reaction Force (ARF) method as an alternative to implement compliant mechanism design with equality output displacement constraints. More recently, Zhan and Zhang [19] presented preliminary results on MIMO compliant mechanisms using a ground structure approach and the Method of Moving Asymptotes (MMA).

The aim of this paper is to present a generalized formulation for the design of MIMO compliant mechanisms. This work is based upon Alonso Gordoa et al. [20] where the Sequential Element Rejection and Additional (SERA) method was extended to multiple loading conditions in structural optimization problems. The current paper uses the same procedure of the SERA method as basis and develops a general formulation for compliant mechanisms design with multiple input and/or output ports. The formulation is an extension from the one used with SISO compliant mechanisms [10]. In addition, an internal loop is defined in this new algorithm to cover the cases of multiple conditions in the input and output ports. Different examples are presented in this paper to demonstrate the validity of the proposed formulation to design MIMO compliant mechanisms by means of a SERA method.

2. Problem formulation of a MIMO compliant mechanism

A MIMO compliant mechanism is required to meet the flexibility and stiffness requirements in order to withstand the applied loads and produce the predefined displacement transmission. Fig. 1 shows such a MIMO compliant mechanism domain Ω. It is subjected to n forces and m output displacements. For the ith applied force $F_{in,i}$ at the ith input port $P_{in,i}$, the output displacement at the jth output port $P_{out,j}$ is $\Delta_{i,j}$.

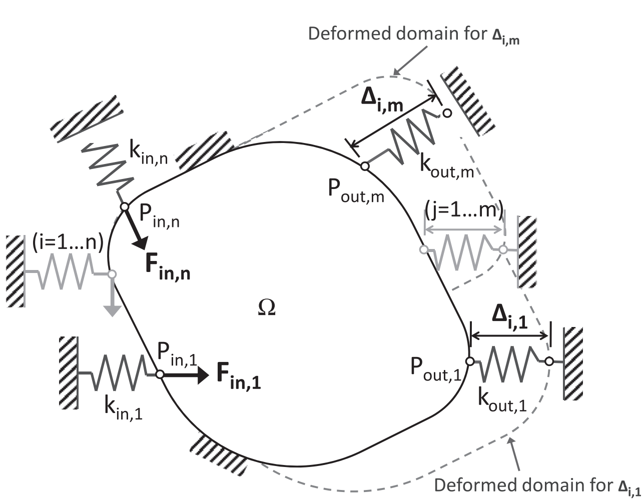

Fig. 1. Problem definition of a MIMO compliant mechanism.

Simplified cases of this generalized definition are: (a) Multi-Input compliant mechanisms with a single output displacement to be produced ($m = 1$), and (b) Multi-Output compliant mechanisms with a single input port where an input load is applied ($n = 1$).

The goal of topology optimization for MIMO compliant mechanisms is to obtain the optimum design that converts one or more input works produced by force vectors into one or more output displacements in predefined directions. The mathematical formulation (1) is expressed as the maximization of the summation of the Mutual Potential Energy (MPE) due to each ith input load producing an jth output displacement.

The MPE was defined by Shield and Prager [13] as the deformation at a prescribed output port in a specified direction. It was defined for single load conditions and implies that the maximization of the MPE is equivalent to the maximization of the output displacement. Generally, the MPE is not a convex function. Solution existence and uniqueness has not been proven mathematically for this formulation. Although it cannot be guaranteed in all cases, experience with the algorithm has demonstrated that the same overall topology can be obtained regardless of the starting point [10,23].

The objective function for a single input load was generalized for multiple conditions as the maximization of a weighted average of the MPE of each case. This approach has already been used with methods such as SIMP [6] or the Level Set [25] methods for other types of multiple criteria problems. The weighting factors $\omega_{i,j}$ relate the i-Input, j-Output cases and their summation is defined to be the unit.

The multi-criteria objective function is subjected to a constraint in the target volume fraction $V^* = [0,1]$. This constraint is generally used in structural optimization algorithms in order to define the fraction of design domain that the optimum design aims to have. The relative volume of the FE is factored in this constraint so that a mesh with different element sizes can be considered (1).

The design variable of the optimization process is the density of every element e in the mesh ρ_e. The design variables are discrete $\rho_e = \{\rho_{\min}, 1\}$ where the material is either present if the eth element density is equal to $\rho_e = 1$ or not present if it equal to the minimum value $\rho_e = \rho_{\min} = 10^{-4} \approx 0$.

$$\max \sum_{i=1}^{n}\sum_{j=1}^{m} \omega_{i,j} \cdot \mathrm{MPE}_{i,j} \tag{1}$$

$$\text{subjected to } \sum_{e=1}^{N} \rho_e \cdot \frac{V_e}{V_{\mathrm{Tot}}} \leqslant V^*, \quad \rho_e = \{\rho_{\min}, 1\}, \quad e = 1, \ldots, N$$

$$\sum_{i=1}^{n}\sum_{j=1}^{m} \omega_{i,j} = 1$$

where ρ_e is the density of the eth finite element, N is the number of finite elements, V_e is the volume of the eth element, V_{Tot} is the total volume for the domain and $\rho_{\min}$ is the minimum density considered, a typical value of which is 10^{-4}.

3. The finite element analysis and sensitivity analysis

To obtain the $\mathrm{MPE}_{i,j}$ (3) that refers to the ith input load applied to produce the jth output case, two load cases need to be calculated: (1) The Input Force Case, where the input force $F_{\mathrm{in},i}$ is applied at the input port $P_{in,i}$, named with the subscript 1,i in (3), (4) and Fig. 2a; and (2) the Pseudo-Force Case, where a unit force is applied at the output port $P_{out,j}$ in the direction of the desired displacement, named with the subscript 2,j in (3), (5) and Fig. 2b. The system