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Compliant folded beam suspension mechanism control for rotational dwell function generation using the state feedback linearization scheme

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ABSTRACT

The control of a slider–crank mechanism driven by a compliant, folded beam mechanism is investigated in this study. The compliant folded beam mechanism, also called the compliant double arm mechanism, has application areas at both the micro and macro levels. The compliant folded beam mechanism control in micro dimensions, driven by a force actuator is investigated here. The kinematic synthesis of the mechanism has been studied using mathematically exact nonlinear Elastica theory. The equivalent stiffness of the large deflecting fixed-free flexible beam, the single arm beam and the complete folded beam mechanism (double arm mechanism) are computed and, the complete mechanism stiffness is represented by a polynomial function that is curve fitted to the nonlinear inextensible exact beam theory solution. The dynamic response of the mechanism is obtained by solving the nonlinear equation of motion numerically using Runge–Kutta methods. *The emphasis of the paper is placed on the subject of control of compliant mechanisms incorporating nonlinear stiffness (having large deflections) for function generation.* The trajectory control of double cranks is achieved by considering linearization by the state feedback since the compliant folded beam mechanism (the double parallel arm mechanism) has a nonlinear stiffness. A PD controller is then applied to the feedback linearized system. The controller coefficients are determined to satisfy desired specifications on the output of the system.

1. Introduction

The concept of compliant mechanisms started with the challenge to exploit the flexibility of linkages for beneficial purposes. Instead of avoiding linkage flexibility problems of mechanisms, employing the flexibility itself to one's benefit leads to advantages over rigid body mechanisms. A compliant mechanism can exploit the flexibility of its components for the creation of motion which can be very difficult and expensive to generate by rigid body mechanisms.

A controller design for function generation of a parallel arm mechanism is presented in this paper. The mechanism employs flexible members undergoing large deflections. Modeling of such mechanisms draws on a broad range of knowledge in several areas including: compliant mechanisms, function generation, and control of nonlinear systems for the desired motion.

A compliant mechanism is called fully or partially compliant [1] depending on the existence of traditional links and joints. Fig. 1 shows a fully compliant five-bar mechanism designed using the traditional rigid links and the elastic joints. A fully compliant mechanism shown in Fig. 1 does not require the assembly of its parts.

Compliant joints have certain disadvantages such as a decreased fatigue life and increased geometric stress concentration factor [1,2]. The use of flexible members can make a mechanism comparatively lighter, thus enhancing its use in applications requiring low weight. The design of a compliant mechanism [3] is more complicated than the design of a rigid mechanism as it

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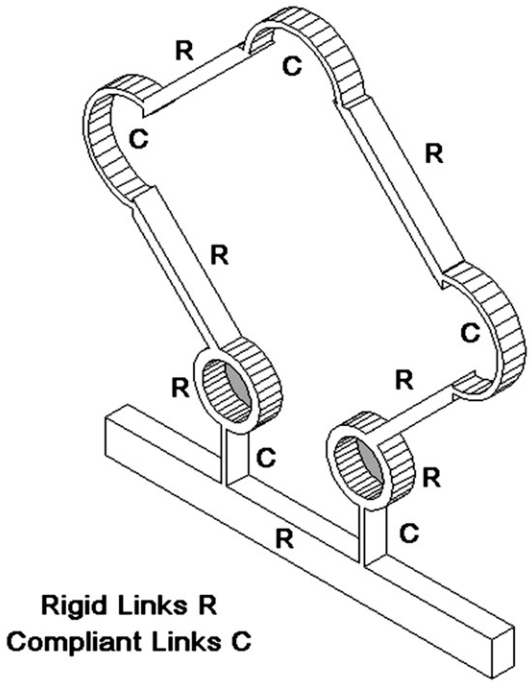

Fig. 1. A fully compliant five-bar mechanism design (made from one piece).

requires large deflection analysis, consideration of the stored strain energy and the solution of transcendental loop closure equations.

It is common in compliant mechanism design to explore the flexible member deflection to its outmost limit, thus requiring a large deflection analysis. The large deflection analysis of compliant mechanisms might be achieved using one of the three methods of; 1) using a Pseudo Rigid Body Model, 2) using a nonlinear FEM software package, and 3) using the Elastica theory. These methods are summarized as follows:

- A compliant mechanism might be modeled with a Pseudo Rigid Body Model (PRBM), which is a rigid body equivalent of the flexible linkage having equivalent torsional springs at its joints [4]. PRBM [5] makes the compliant mechanism analysis relatively easier. Compliant mechanisms are usually designed for simple motion requirements and the trial and the error method are commonly used to design novel compliant mechanisms. Once a desired designed is found, the structural properties of a compliant mechanism might be checked and revised according to the required load and flexible beam maximum bending stress [3].
- Another efficient analysis tool of compliant mechanisms is to use nonlinear FEM. Numerical techniques for large deflection analysis of structures are available in the literature. These techniques address geometric and material nonlinearities of structures. Most of these techniques use Finite Element Methods (FEMs) of different kinds. There are mainly two kinds of incremental nonlinear FEMs considering geometric nonlinearities, the total Lagrangian [6] and the updated Lagrangian [7,8] methods. Material nonlinearities have also been considered in compliant mechanism design. Jung and Gea [9] presented compliant mechanism design with nonlinear materials using topology optimization, for example. They used a general displacement functional with a nonlinear material model in the topology optimization formulation to maximize the mechanical advantage of a force inverter mechanism.
- Elastica theory is another commonly used compliant mechanism analysis tool. Elastica theory provides a closed form of the solution. In other words, the functional solution relation between the applied load and the deflection cannot be expressed explicitly in the form of $y = y(x)$. The mathematical exact equations need to be solved first to express such explicit $y = y(x)$ relationship, then the exact solution might be represented by an accurate polynomial [10]. The only disadvantage of the Elastica theory is that its application is restricted to simple geometries and simple loading conditions. Therefore compliant mechanism designs that can be investigated using the Elastica theory consist of simple flexible members and simple loading conditions.

In this investigation, the Elastica theory is used since the solution of a large deflection, fixed-free cantilever beam (which makes one half of the compliant mechanism arm considered here) is available in literature [11]. Magnetic actuation is frequently used in precision instruments. As an example, a pin actuator for a printer mechanism [12] is shown in Fig. 2. In this printing device, a hammerhead attached to a flexible link is accelerated by a magnetic force. The hammerhead's kinetic energy is used to push ink from a ribbon onto paper.

Dynamics of compliant mechanisms started to appear in literature since the early 90s. Snyder and Wilson [13] studied the dynamics of a single limb compliant robot arm with a payload at the tip. They derived and simulated the nonlinear equations of