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Analysis and design of an underactuated compliant five-bar mechanism

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Generally, the pseudo-rigid-body model of compliant mechanisms is single degree-of-freedom in the literature. In order to obtain more flexibility, compliant mechanisms can also be synthesized from multi degree-of-freedom pseudo-rigid-body models. In this study, analysis and design procedures for such a compliant five-bar mechanism are presented with underactuation. Analysis is performed with different loading scenarios. An approximate method for dead center estimation is introduced. Some results are verified by using finite element analysis. A generalized design procedure for the mechanism is proposed. An advantage of underactuation over constrained mechanisms is presented with an example.

1. Introduction

Compliant mechanisms have been investigated by several researchers because these mechanisms are less expensive, lighter, and easier to manufacture when compared to rigid-link mechanisms [1]. Especially in recent years, much research has been done in the field of compliant mechanisms [2–9]. However, the main disadvantage of compliant mechanisms is the complexity of their analysis and design. In order to simplify the analysis of the compliant mechanisms, the pseudo-rigid-body model (PRBM) technique is frequently used in the literature [1]. This technique is used for the analysis and design of compliant mechanisms whose PRBM is mostly single degree-of-freedom (DOF). Number of small-flexural pivots of a compliant mechanism can be increased so that DOF of its PRBM is more than one. However, in this case design of the resulting mechanism would be more challenging according to well-known rigid-body analysis and design techniques. Moreover, multi DOF PRBM of such mechanisms will be underactuated if the number of input is less than the DOF of the system.

Analysis of underactuated multi DOF mechanisms is not as simple as that of single DOF mechanisms. For such mechanisms, kinematic analysis must be performed together with force analysis. Therefore, the analysis and design of these mechanisms can be performed by assigning a specific output loading condition. There are several studies about the underactuated mechanisms. A mechanical logic element with multi-port lever was investigated by Söylemez and Freudenstein [10]. Laliberte and Gosselin [11] carried out a study on simulation and design of underactuated mechanical hands. Tanık and Söylemez [12] derived a synthesis procedure for variable oscillation mechanisms with underactuation. Mahindakar, Rao, and Banavar [13] presented a study on control of an underactuated manipulator. Cheng, Carbone, and Ceccarelli [14] studied an underactuated finger operation. Tanık and Söylemez [15] studied an underactuated compliant variable stroke mechanism.

In this study, the proposed mechanism is composed from one compliant link and two rigid links as shown in Figs. 1 and 2a. Since there are rigid kinematic pairs available, the mechanism is partially compliant. The compliant link possesses two small

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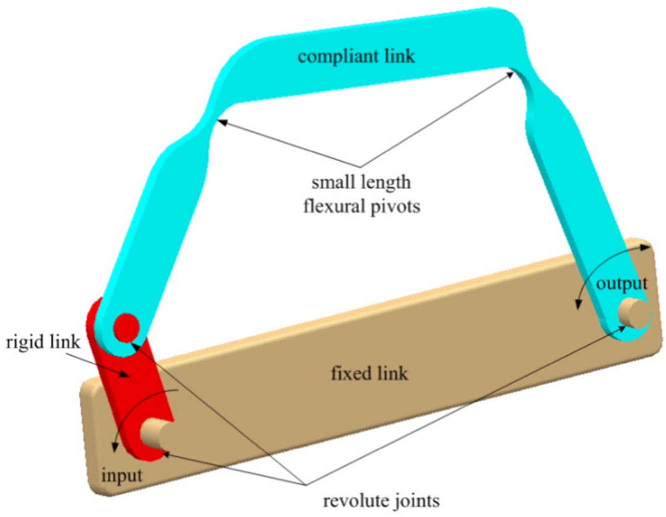

Fig. 1. The partially compliant five-bar mechanism.

length flexural pivots that provide flexibility. The mechanism is considered to be working with one input at the crank and the output is at the rigid segment of the compliant link connected to the fixed link.

The Kutzbach criterion for DOF of a planar mechanism is $N = 3(l - 1) - 2j_1 - j_2$ where j_1 refers to the number of single DOF joints and j_2 refers to the number of two-DOF joints. From the PRBM of the compliant five-bar mechanism given in Fig. 2b, there are five links and five revolute joints. DOF of a revolute joint is one and indicated with R in Fig. 2b. Thus, according to the Kutzbach criterion DOF the mechanism is calculated as $N = 3(5 - 1) - 2(5) - 0 = 2$. Since there is only one input, the mechanism is underactuated.

2. Analysis of the mechanism

Analysis of the compliant five-bar mechanism can be performed by using its PRBM which is given in Fig 2b. The torsional springs on the PRBM represent equivalent stiffness for the small length flexural pivots of the compliant link. As in the vast majority of the compliant mechanisms, it is assumed that masses of the links are negligible [1,9,15] and operating speeds are slow. Therefore, all analyses are based on static equilibrium in this study. We can use the method of virtual work for the equilibrium condition:

From Fig. 2b, virtual works of the active loads are:

$$\delta W_i = T_{1i}\delta\theta_{1i} \; i = 2, 5 \tag{1}$$

Virtual works of the springs are (Fig. 2b)

$$\delta W_{34} = -k_{34}(\theta_{14} - \theta_{13} - c_{34})(\delta\theta_{14} - \delta\theta_{13}) \tag{2}$$

$$\delta W_{45} = -k_{45}(\theta_{15} - \theta_{14} - c_{45})(\delta\theta_{15} - \delta\theta_{14}) \tag{3}$$

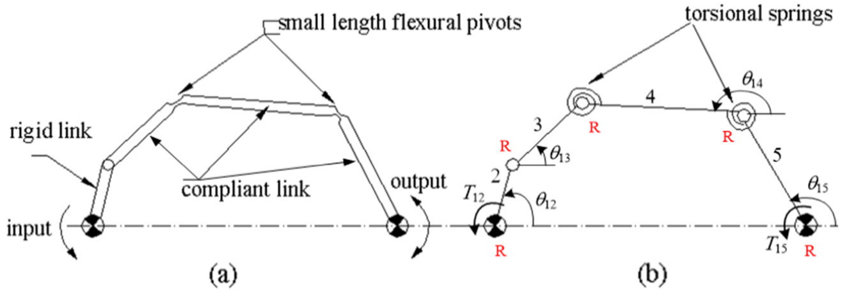

Fig. 2. The compliant five-bar mechanism (a) and its PRBM (b).