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Research paper

A statically balanced fully compliant power transmission mechanism between parallel rotational axes

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ABSTRACT

This paper presents a fully compliant, potentially monolithic, power transmission mechanism which can rectify a large lateral offset between two parallel rotational axes. The planar nature of the design makes it ideal for manufacturing-limited applications such as micro/meso-scale power transmissions. The proposed compliant transmission is generated based on the Oldham Coupling and its equivalent Pseudo-Rigid-Body Model (PRBM). Normally, a compliant transmission mechanism cannot achieve a high efficiency due to the internal stiffness, i.e. actuation stiffness is not zero. However, in the proposed design, the internal stiffness is removed by static balancing and results in a statically balanced compliant transmission mechanism, i.e. with zero actuation stiffness. Therefore, the monolithic embodiment and static balancing features compensate for backlash, friction, assembly errors and poor mechanical efficiency inherent in conventional Oldham coupling, resulting in a transmission mechanism with high mechanical efficiency. Possible compliant design configurations based on the importance of different design criteria are discussed. Further, a compliant device based on the Paired Double Parallelogram (DP-DP) linear flexure bearing is designed and dimensioned. Moreover, the transmission stiffness, i.e. input-output rotational stiffness within the maximum allowable stress, and the actuation stiffness, i.e. minimum required actuation torque for certain angular displacement, of the designed device are predicted by the theoretical model and finite element modeling. Besides, the result shows the device is providing a constant transmission stiffness through a full cycle rotation. To prove the concept, a macro scale prototype is constructed and evaluated experimentally. It is shown that the results from the experiment are in agreement with the theoretical and finite element models.

1. Introduction

There are different types of applications where a constant velocity transmission coupling, which can transfer a rotational power between parallel axes, can be applied. It can be used in micro/meso scale transmission systems where two gears with the same number of tooth have been used [1,2]. Moreover, such a power transmission coupling can accommodate with lateral alignment errors, parallel misalignment, between rotational axes. This is a need in many applications such as precision measurements, micro engines, laser processing, and etc [3]. In state of the art, several kinds of constant velocity joints

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have been invented to accommodate with alignment errors [4]. However, these are made based on rigid-body mechanisms, and like gears, they are leading to many disadvantages such as wear, friction, backlash, need for assembly, maintenance, and lubrication. Besides, sometimes a precise or expensive assembling process is essential to have a proper transmission or gearing mechanism in micro scale applications [5].

Compliant mechanisms have shown a great potential in affording new solutions, to deal with above-mentioned obstacles, for power transmission mechanisms [6–9]. Compliant mechanisms gain their motion from elastic deformation of flexible members rather than from rigid-body kinematic pairs [10]. These mechanisms are a favorable choice in the field of precision engineering due to the elimination of rigid-body kinematic joints, which eliminates the disadvantages of rigid-body linkages.

Several patents on near-constant velocity flexible couplings, which can accommodate small alignment errors, were found in literature [11,12]. The designers have considered an extra degrees of freedom, either by using wire flexures or an extra flexure, to enable the devices for angular misalignment as well as lateral misalignment. However, this will allow for a non-constant velocity rotation transmission between the input and the output axes due to the asymmetric linkage arrangement with respect to the homokinetic plane [13]. Besides, designs sometimes contain simple compliant four-bar mechanisms to approximate straight-line movement to compensate for lateral misalignments. However, this approximation also leads to a nonuniform velocity transmission [14]. conventional rigid-body pairs offer near zero stiffness around the motion axis and high stiffness along the constrained axes. However, compliant kinematic pairs require significant force and energy due to the elastic deformation of the flexible members. Therefore, a compliant mechanism offers a poor efficiency, and it requires continuous force to hold the mechanism in position [15]. This results in several disadvantages for compliant transmission mechanisms such as nonuniform torque/force transmission, deficient travel range, low speed, and demanding for larger actuators. However, the deformation energy is stored in flexible members. Therefore, the mechanism can be statically balanced as the elastic force is a conservative force. As a result, these mechanisms can be actuated with much less energy as compared to the unbalanced compliant design [15–18].

The aim of this paper is to design a compliant and statically balanced constant velocity power transmission mechanism between two parallel rotational axes with a lateral offset. The design is furthermore required to be planar, making it desired for micro fabrication techniques such as double sided Deep Reactive Ion Etching (DRIE).

The design of the proposed compliant transmission mechanism is described in the following sections. The Pseudo-Rigid-Body model (PRBM) and static balancing are studied and developed in Section 2. The compliant design is illustrated and the torque transmission capability is discussed by the theoretical model in Section 3. The proposed compliant design is then evaluated experimentally in Section 4.

2. Methodology

The compliant transmission mechanism, proposed in this paper, is created by employing conventional kinematic synthesis and corresponding Pseudo-Rigid-Body Model (PRBM). This section describes the rigid-body kinematic of the design, which is based on the rigid-body Oldham coupling. Moreover, the PRBM model is introduced to develop the static balancing and study the torque transmission capability of the equivalent compliant design.

2.1. Rigid-body Oldham coupling

The rigid-body Oldham coupling is a four-bar mechanism, RPPR, for constant velocity rotation transmission between two parallel rotational axes with a lateral offset [14]. There are three mobile links in this mechanism. The first and second links are rotating around the input and the output axes, respectively. The third link, which is a middle component, is then connected to the first and second links by two prismatic joints which their motion axes are perpendicular to each other. The schematic of the Oldham coupling and its simplified geometrical representation are shown in Fig. 1.

When the input axis rotates through some angle, θ_2, the floating disc, link 3, rotates through the same angle. This in turn rotates the output axis, link 4, through the same angle but with 90° phase shift due to the right angle between the two prismatic joints,

$$\theta_4 = \theta_2 + \frac{\pi}{2}. \tag{1}$$

Therefore, there is a uniform, one-to-one, rotational velocity transmission between the input and the output axes, i. e. $\omega_4 = \omega_2$.

The position of the sliders, r_2 and r_4, varies during full cycle movement of the mechanism and for a given input angle, θ_2, can be expressed

$$\begin{aligned} r_2 &= L_1 \cos\theta_2, \\ r_4 &= L_1 \sin\theta_2. \end{aligned} \tag{2}$$

where, L_1 is the offset between the input and the output axes and considered as the length of the ground link.

Therefore, the maximum displacement required at the prismatic joints can be given by

$$\Delta r_2 = \Delta r_4 = 2L_1. \tag{3}$$