Precision Engineering 42 (2015) 113–132

Contents lists available at ScienceDirect

Precision Engineering

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

Modeling and design of planar parallel-connection flexible hinges for in- and out-of-plane mechanism applications

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ARTICLE INFO

Article history:
Received 1 September 2014
Received in revised form 2 April 2015
Accepted 17 April 2015
Available online 24 April 2015

Keywords:
Flexible hinge
Planar
Parallel
Serial
Compliance
Stiffness
Straight
Circular

ABSTRACT

The paper studies the planar parallel-connection, small-deformation flexible hinge chains formed of serially-coupled individual segments with variable cross-sections. It introduces the concept of virtual flexible hinge that is quasi-statically equivalent to the actual parallel-hinge configuration. General compliance and stiffness matrices are formulated for the virtual hinge under in-plane and out-of-plane loads by combining the transformed compliances of the individual hinge segments. Two classes are specifically analyzed: one comprises geometrically parallel, straight-axis hinge designs and the other includes concentric, circular-axis hinge configurations. From each class, particular designs with identical and transversely symmetric hinges of right circularly corner-filleted geometry are further investigated. Specifically, the behavior of parallelogram mechanisms with straight-axis hinges and of stage devices with circular-axis hinges is analyzed. Their elastic responses are validated by finite element analysis and their stiffnesses are subsequently studied in terms of offset geometric parameters.

1. Introduction

Flexible hinges are utilized as elastically-deformable rotation/translation joints in compliant mechanisms that are implemented in a variety of actuation/sensing applications primarily designed for precision motion. Traditionally, the flexible hinge is a single member of straight-axis or of circular-axis connecting two adjacent rigid members, as illustrated in Fig. 1 where $[f]$ and $[u_O]$ are the load and displacement vectors at a point O on the mobile rigid links.

This paper expands upon the traditional concept of flexible hinge as a single member by considering the case where two or more flexible hinges are connected in parallel to two adjacent rigid links—see Fig. 2(a). Using the small-displacement, linear-theory compliances of individual hinge segments, the model proposed herein generates the compliance matrix of a single virtual flexible hinge that is quasi-statically equivalent to the actual multiple parallel hinges, as pictured in Fig. 2(b). Utilizing multiple parallel flexible hinges instead of a single hinge to connect two rigid links enhances the design and performance qualifiers by introducing additional geometry/topology parameters (such as those defining the relative placement of individual members), enabling to alter the connection stiffness or producing motions that are not obtainable by means of a single hinge, such as parallel motion.

Fig. 3 shows photographs of a few devices that use two or more parallel-connection flexible hinges. Fig. 3(a) is a portion of a compliant gripper showing two geometrically-parallel arms in a parallelogram configuration. Considering that each arm is made of three (flexible) segments connected in series, the two arms act as two hinges in parallel. Fig. 3(b) pictures a tunneling microcantilever – [1] – utilized at measuring currents whose out-of-the-plane motion is ensured by the two thin parallel hinges. Fig. 3(c) pictures a micro electro-thermal actuation/suspension unit formed of two parallel pairs, each containing five identical inclined flexible hinges connected in parallel in one pair.

The vast majority of flexible hinges have been designed thus far as straight-axis members per the skeleton representation of Fig. 1(a). Achieving the necessary hinge stiffness/compliance is realized by varying the geometric parameters thereof, particularly the in-plane cross-section thickness when the flexible hinge and the compliant mechanism are machined from plate-like material of constant out-of-plane

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http://dx.doi.org/10.1016/j.precisioneng.2015.04.007
0141-6359/

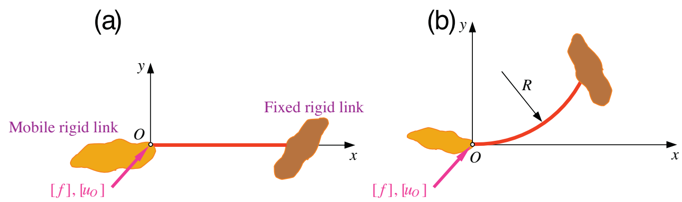

Fig. 1. Single flexible hinge skeleton representation with mobile-end loads/displacements and: (a) straight axis; (b) circular axis.

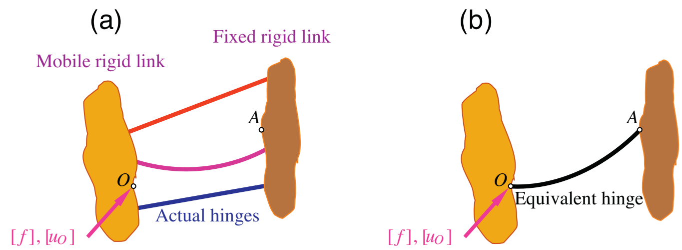

Fig. 2. (a) Skeleton representation of actual parallel-connection flexible hinges with straight and circular axes; (b) virtual equivalent flexible hinge.

width. When the variable thickness is defined as an analytical curve, closed-form compliances are normally derived that enable characterizing the quasi-static response of hinge-based compliant mechanisms. The simplest straight-axis variable-thickness hinge configuration is formed of a single-profile planar curve, such as the right circular design, which was studied in [2–7]. Another single-profile flexible hinge has its in-plane thickness varying elliptically—approximate and full-form compliance equations have been derived for the right elliptical hinge in Refs. [8,4,9]. Other single-profile flexible hinges can be designed by using the parabolic, hyperbolic curves – as in [4] – and the Lamé curves—as presented in [10].

Straight-axis flexible hinges have also been obtained by serially connecting segments with in-plane thicknesses defined by different curves as a means of expanding the number of geometric parameters, which enlarges the elastic properties range. Examples from this category include the right circularly corner-filleted design—[11,12,4], the right elliptically-filleted variant—[13,14], as well as the Bézier-profile configuration—[15], the V-shape design—[16], the polynomial type—[17] or the exponential-sine profile—[18] designs. While all these straight-axis hinge configurations presented transverse and axial symmetry, asymmetric configurations have also been developed as discussed in [19,20] for instance.

More recently, flexible hinge designs with circular axis – see Fig. 1(b) – and variable cross-section have been introduced including the single-profile right circular design – [21] – and the multiple-profile circularly right circularly corner-filleted configuration—[22,23]. Compared to the straight-axis hinges, the circular-axis designs increase the number of geometric parameters and enhance the coupling

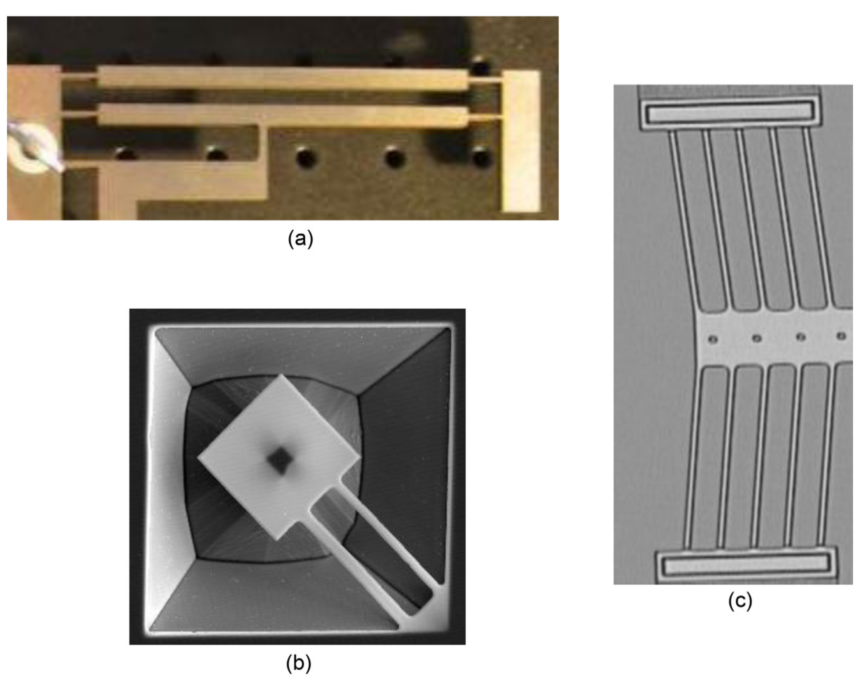

Fig. 3. Photographs of actual devices with parallel-connection flexible hinges: (a) portion of a parallelogram in a gripper; (b) tunneling microcantilever—[1]; (c) electro-thermal micro actuation/suspension unit.