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Analysis of the displacement of distributed compliant parallel-guiding mechanism considering parasitic rotation and deflection on the guiding plate

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A B S T R A C T

Distributed compliant parallel-guiding mechanism (CPGM) is a particular type of compliant mechanisms. This paper establishes a new mathematical model of the distributed-CPGM based on the elastic beam (EB) theory with an increasing precision discussed from three different situations. In situation C, both the parasitic rotation and deflection of the guiding plate are taken into account, which might be tiny but do exist in reality. As for a relatively fair comparison, a more effective pseudo-rigid-body (PRB) model than the simplified traditional PRB model is also established. Then the guiding displacement, parasitic displacement and parasitic angle in the three situations are analyzed at different distances between two compliant beams, which have not been involved by any former researchers. Furthermore, the relations between the displacements and some other structural parameters are analyzed respectively comparing with the finite element method. The results indicate that the EB model in situation C is very effective with a much higher precision than other models, although the computation is more complicated. Our work could be a reference and supplement to the design and manufacture of the current distributed-CPGM.

1. Introduction

As a new type of mechanism, compliant mechanism transfers or transforms force, motion or energy by the deformation of flexible members rather than by movable joints only as traditional rigid-link mechanism [1]. Compliant mechanisms reduce part-count and assembly time, simplify manufacturing processes, increase precision and reliability, reduce wear, weight and maintenance, which have attracted wide attention and made it become a new hot spot in mechanism research [2]. During the last twenty years, researchers have been continuously studying on compliant mechanisms and gained some significant results. As a special method for compliant mechanism analysis, Howell and Midha [3] put forward the pseudo-rigid-body (PRB) model in 1994. In the RPB model, some rigid-link parts with equivalent force–deformation relation are used, to imitate the deformation of flexible members. Then the theories of rigid-link mechanisms can be used in compliant mechanisms analysis. In 2001, Howell introduced the PRB model in detail and systematically established the PRB models of all kinds of beams under different loadings in his book [4]. The theory of the PRB model can make the analysis of compliant mechanisms much simpler, but it has a limited precision as it is just an approximate model. Midha et al. [5] introduced a method for determining the limit positions of compliant mechanisms for which an appropriate PRB model could be created. Pei [6] introduced a new method using a rigid bar with two pin-joints to imitate the behavior of beams, trying to easily establish simple and accurate PRB models for a variety of beam-based compliant mechanisms

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considering the limited accuracy of the traditional PRB model in calculating some precise characteristics such as center-shift of a flexural joint. But the axial force of the beam was neglected that the proposed method was to be improved by the further study. In a word, with the increasing demand of compliant mechanisms working as a key and accurate part in precise measurement, accurate location, MEMS [7], aerospace and biological engineering etc. [1], and how to improve the precision of the analytical model become urgent.

Compliant parallel-guiding mechanism (CPGM) is a particular type of compliant mechanisms. Ideally, the guiding plate will remain parallel to the ground throughout the mechanism's entire motion by the deformations of two compliant beams (Fig. 1). Rigid-link parallel-guiding mechanisms (RPGM) (Fig. 1a) have found use in a variety of practical applications, such as in a high-speed catenaries, positioning of optics, and amusement park rides et al. CPGM can be designed that retains all the advantages associated with compliant mechanisms, including the elimination of joint friction, backlash, and the need for lubrication [4]. The applications of CPGM can be found on an optical lens focusing mechanism used in a compact disc player and on a coining press et al. Classified by the flexible members, there are distributed-CPGM (Fig. 1b) and lumped-CPGM (Fig. 1c). For both types, researchers have shown great interest in their characteristics, especially the displacement, which requires a high accuracy. Compliant double parallel four-bar mechanism (CDPFBM) is one of the classical types of CPGM. Yang et al. [8] analyzed the displacement of CDPFBM and gained some useful results for improving the designs. The model was based on elastic beam theory with a higher precision comparing with the PRB model. More articles [9–11] can be found about the analysis of the output displacement, or the guiding displacement, of compliant single parallel four-bar mechanism (CSPFBM), which is usually called just CPGM. The results discussed in the articles mentioned above were all based on lumped-CPGM and had been compared from the aspects of theory, experiment and the FEM. They all aimed at improving the precision of the analytical models instead of using the PRB model. But there is still an error of 5%–6% between theory and experiment and 1.6%–3% between theory and FEM while they assumed that the deformations of the two beams were the same, as an ideal situation. When the length of the rigid beam of a lumped-CPGM reduces to zero, it degenerates to a parallel leaf-spring mechanism (PLSM), which is a typical type of distributed-CPGM. Compliant mechanisms with evenly distributed stresses have better load-bearing ability and larger range of motion than mechanisms with compliance and stresses lumped at flexural hinges [12]. Christopher et al. [13] reported on the accuracy of the PRB model in predicting the behavior of a nanoscale parallel-guiding mechanism (nPGM) that uses two single-walled carbon nanotubes (CNTs) as the flexural guiding elements. Molecular simulation results of the behavior matched the PRB model predictions of kinematic behavior with an error of 7.3% and elastomechanic behavior with an error of 5.7% because the PRB model does not consider any rotation of the guiding plate, which exists in reality more or less. Aiming at improving the precision of the analytical models, Gregory et al. [14] and Zhang et al. [15] proposed a comprehensive solution based on the elliptic integrals, which is often considered to be the most accurate method for analyzing large deflections of thin beams in compliant mechanisms. Parasitic rotation occurs in the real working situation for many types of compliant mechanisms. But it is ignored by the PRB model, which actually has a great impact on the precision [16]. Ni et al. [17] formulated an analytical method for parasitic rotation and displacement calculations of parallelogram compliant mechanisms for improving the output precision. Zhao et al. [18,19] analyzed the inherent parasitic motion of the generalized cross-spring pivot and developed a novel compliant linear-motion mechanism. Mu et al. [16] took the parasitic rotation into account when they analyzed the guiding displacement of PLSM. From the computational formulas, the influence of some other structural parameters on the guiding errors could be obtained qualitatively, especially the influence of the distance between two leaf springs. Considering more in the real working situation for a higher precision, Brouwer et al. [20] presented new and refined analytic formulas for the stiffness of PLSM in three dimensions taking into account the shear compliance, constrained warping and limited parallel external drive stiffness, which improved the precision significantly and broadened the use of PLSM in precision mechanisms.

As is done by the former researchers, this paper aims at improving the precision of the analytical model of compliant mechanisms, especially the distributed-CPGM. For the first time, both the parasitic rotation and deflection of the guiding plate are taken into our account, although it might be tiny but do exist in reality, and a model with a much higher precision for analysis of the displacement of distributed-CPGM is established.

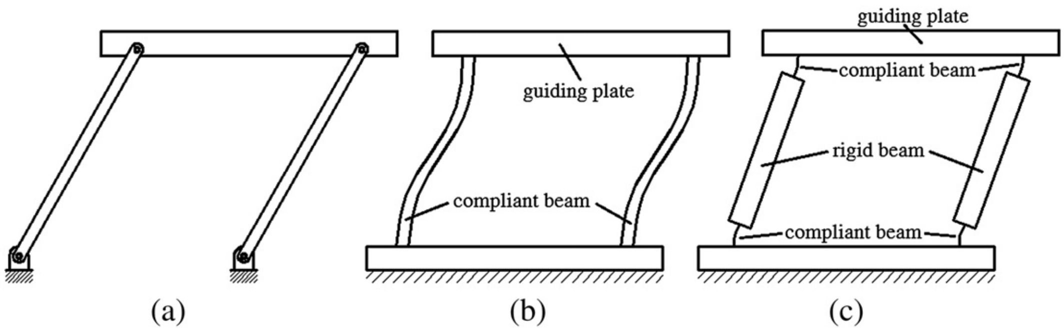

Fig. 1. Parallel-guiding mechanism: (a) RPGM; (b) distributed-CPGM; (c) lumped-CPGM.