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Compliant joint design and flexure finger dynamic analysis using an equivalent pin model

Jiajie Guo [a], Kok-Meng Lee [a,b,*]

[a] State Key Lab of Digital Manufacturing Equipment and Technology, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan, Hubei 430074, PR China

[b] George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0405, United States

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ABSTRACT

Adaptable to nonstructural environment, compliant joints are competent candidates for flexure fingers in humanoid robotic hands. This paper presents an equivalent pin model (EPM), which provides an in-depth understanding on flexure finger dynamics by accounting for the moving rotation center and varying radius of a compliant joint. Distinguished from other lumped-parameter formulations based on constant-axis pin-joint approximation, the large deformation of a compliant joint is characterized by closed-form solutions obtained from a distributed Euler–Bernoulli (E–B) beam model. Modeling tolerance guidelines derived by comparing the E–B model against finite element analysis (FEA) without neglecting shear distortions are provided for designing dimensions of a compliant joint. Design evaluation is illustrated with a flexure finger consisting of three phalanxes by comparing the maximum stress among different configurations. The EPM reveals critical effects of rotational center-offset and varying radius on the dynamic response of a flexure finger, showing that the negligence of these effects yields an out-of-phase prediction in joint rotation. Although presented in the scope of finger manipulation, the method is expected to have potential applications for multi-body dynamics involving compliant mechanisms.

1. Introduction

Robotic hands have been developed in research for amputees or humanoid robots. However, most designs are modified forms of industrial grippers based on typical engineering joints, like pins and hinges, thus could hardly emulate the dexterity of human hands. Traditional robots are designed and built with maximized inertias for the purpose of minimizing vibrations to achieve good position accuracy, in return scarifying fast response, high energy efficiency and low ratio of payload-manipulator weight. Compliant joints distinguish from traditional engineering joints with advantages of light weight, low cost and fine motion, so they are widely used in precision engineering [1] and robotic hands with flexure fingers are thus suitable applications [2–4]. However, this application is limited by joint fatigue and large deflections in dynamics of repetitive motions. To precisely manipulate a robotic hand with minimal joint fatigue, the design and control of a robotic hand require a good understanding of flexure finger dynamics.

It has been known from experiments and model analyses [5] that a non-fixed rotation axis exists in kinematics of biological joints, such as ankles [6], knees [7], elbows [8] and hands [9]. So a biological joint is more dexterous with multiple degrees of freedom (DOFs) than an engineering joint. Flexible beams deform similar to biological joint kinematics with both rotation and

* Corresponding author at: George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0405, United States. Tel.: +1 404 894 7402.

E-mail address: kokmeng.lee@me.gatech.edu (K.-M. Lee).

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translation motions, and they are adaptable to an unstructured environment, thus are competent candidate for compliant joints in robotic hands.

Various models have been developed to capture the nonlinear deformations of flexible beams. Closed-form solutions for a two-dimensional (2-D) beam subjected to large deflection can be found in [10]; however, these solutions are computationally inefficient in practice because they are provided in terms of elliptic integrals. A practical 2-D model that can be readily used for design and control is proposed and validated with experiments on a flexure mobile robot [11]. A 3-D beam model is developed in [12,13] using quaternion, which requires one extra constraint equation for vector normalization. In characterizing curved beam shapes, curvature is a powerful tool since it is a geometry quantity directly related to external moment and stiffness but independent of coordinate frames. [14] provided a review on different approaches using constant curvature for compliant mechanism modeling, and concluded that their results are consistent in a common coordinate frame and notational convention. Piecewise constant curvatures are employed in [15] to obtain a closed-form Jacobian for force sensing. [16] developed a kinematic model based on curvature to control flexion and torsion of a snake-like concentric-tube robot, which is valid for any tube cross section and initial curved shape. Assuming that the bending curvature of a beam can be approximated by a low-order polynomial, a smooth-curvature model is developed for efficient calculation of Jacobians and Hessians with high accuracy [17]. It is noted that most of the beam models adopted in engineering applications are developed based on the Euler–Bernoulli (E–B) beam theory because of its simplicity [18,19]. However, it is assumed in the E–B theory that a plane cross section normal to the undeformed beam referenced axis remains planar and normal to the deformed axis. This assumption indicates negligence of shear distortions, which is not valid for thick short beams. In this way, models based on E–B theory actually have certain limits on the aspect ratios in dimensions. To facilitate compliant joint design for a flexure finger, this paper quantifies the modeling tolerances by comparing a compliant joint model employed from [11] against finite element analysis (FEA), so that certain correction factors can be applied for joint design with thick beams.

To perform delicate manipulation or dexterous grasping, it is necessary to have an accurate dynamic model to design and control robotic hands. However, the characteristics of non-fixed rotation axis in a compliant joint presents a challenge to the forward/inverse dynamic analysis because it complicates the Coriolis force, centrifugal effect, and moment arms, and even gives rise to impulses when a closed-kinematic loop is formed [20]. The robotic systems with compliant components have an infinite number of DOFs and their continuous models are not feasible for controller design. For this reason, discretization is employed with assumed modes, finite elements or lumped parameter methods [21]. A dynamic model through an efficient matrix formulation is obtained based on modal data for suppression of vibration [22]. Fundamental frequency is obtained for an optimized single link flexible manipulator by FEA and comparative study is carried out for dynamic response to various excitations [23]. A feedback controller is designed based on a lumped-parameter model to regulate the contact force on a lightweight single-link flexible manipulator [24]. The pseudo-rigid-body method (PRBM) may fall in the category of lumped-parameter models by regarding a compliant joint as a finite set of revolute joints (connecting rigid links with torsional springs) [25]. Among the key problems in PRBM is to determine the revolute joint positions and the spring stiffness for the purpose of predicting the beam-tip pose. It has been shown in [26] that tip location and slope of a 2-D compliant beam under arbitrary tip loads can be accurately predicted by a 3R PRBM (with three revolute joints). Then, [27] proposes a 2R PRBM to increase the modeling accuracy of 1R PRBM and the computation efficiency of the 3R PRBM. More related work on PRBM and its application to robotic manipulation can be found in [28–30]. Dynamics of compliant mechanisms can be analyzed by finite element methods where the damping ratios are estimated by experiments [31]. However, few efforts have been exerted to apply PRBM for multi-body dynamics with compliant mechanisms. Inspired by the simplicity of PRBM, this paper models a compliant joint in a multi-body system (such as a flexure finger) as a pin joint with a rotational spring; the key issues are to determine its stiffness, rotation center and radius, and to quantify their effects on the finger performance.

Motivated by the need to design and control a flexure finger for robotic hands, this paper presents an equivalent pin model (EPM) based on close-form solutions for a compliant joint with an application illustrating the flexure finger dynamics. The remainder of this paper offers the following:

- A dynamic model for a flexure finger is formulated using Euler–Lagrange equation based on EPM, accounting for the non-fixed rotation center and non-constant rotation radius of compliant joints.
- Design guidelines for compliant joint dimensions are presented by quantifying the modeling tolerance of the E–B beam model.

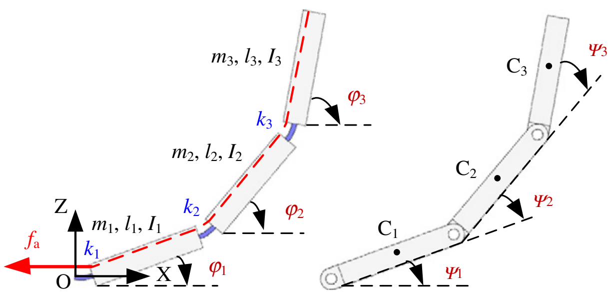

Fig. 1. Schematic of a flexure finger and its equivalent pin joint model.