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Substructure compliance matrix model of planar branched flexure-hinge mechanisms: Design, testing and characterization of a gripper

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ABSTRACT

This paper proposes an analytical compliance-based matrix method to model the quasi-static, small-displacement response of planar branched flexure-hinge over-constrained mechanisms. It studies structurally- and kinematically-branched flexible mechanisms comprising several chains that are connected in complex series-parallel configurations and that are acted upon by multiple external/reaction loads. These architectures are substructured or decomposed into simpler chains whose compliances are evaluated from known individual segment compliances. The substructured-chain compliances are subsequently combined with external loads to solve for unknown displacements and reactions and to further evaluate parameters relevant to the mechanism behavior. The method is applied to the design and analysis of a novel displacement-amplified gripper with right circularly corner-filleted flexure hinges. The mechanism's mechanical amplification, stiffness, and grip force are evaluated when either full or partial compliance (flexure-based only) is assumed. The analytical model predictions are confirmed by finite element analysis and by experimental testing of a proof-of-concept prototype. Subsequent analytical-model simulation highlights the relationships between the main geometric parameters and the gripper's performance qualifiers.

1. Introduction

Planar mechanisms with flexure-hinge joints connecting the rigid links have been used widely in precision positioning and piezoelectric actuation [1–20] or gripping/manipulation applications [21–35] that involve small displacements to be performed in an often-times controlled environment. In order to predict and/or control the direct or inverse kinematics of these mechanisms with reasonable accuracy, relationships between input and output are necessary which are based on the elastic and geometric properties of the specific flexure hinges (compliances or stiffnesses) and on the overall mechanism configuration.

While finite element modeling of flexible-hinge mechanisms with dedicated codes is highly popular due to the method's accuracy and high productivity associated with relatively small modeling/computation time, this technique is also confined to specified sets of design variables. As such, each time design variable needs to change, a separate finite element modeling and analysis needs to be carried out to evaluate, for instance, the stiffness of a new design. Similarly, unless a comprehensive set of finite element analyses is performed, it is not possible to assess the scaling of a compliant mechanism design performance with its relevant parameters. In such cases, analytical models are necessary actually offering the operational/algorithmic tools to easily (re)evaluate input–output

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relationships that mathematically incorporate the design variables and parameters, to assess design performance, and to enable optimization avenues. Obviously, analytical models come with various simplifying assumptions that lead to inherent errors, but in many instances, their accuracy (that can be checked numerically/experimentally) is quite satisfactory.

To achieve their tasks, planar mechanisms utilize flexible hinges and rigid links that are combined in series and/or parallel and the corresponding load-displacement analytical models are based on either series – [4–9,36–38] – or parallel connection models – [38]. Because purely parallel mechanisms are relatively rare, the majority of these devices incorporate serial chains that are connected in parallel – [9–19,36,39–43] – such as the symmetric displacement-amplification mechanism of Fig. 1(a). This device is formed of two serial chains that are connected in parallel – the chain *AFK* to the left of the symmetry line and the chain *AF′K* to the right of it. Each chain is a series connection of several flexible and rigid links.

The procedure of determining the displacement at point *K*, for instance, would evaluate the load acting on each of the two mirrored half portions at *K* by taking into account that both portions undergo the same displacement at that point. Once the load acting on, say, the *KFA* half-portion is determined, the displacement at *K* is simply calculated by linearly superimposing the two load vectors acting at *K* and at *F* on this serial chain *AFK*, which is fixed at *A*.

Consider now the mechanism of Fig. 1(b), which is apparently similar to the device of Fig. 1(a) but comprises chains that are combined in series and parallel in a more complex manner. As it can be seen, it is no longer possible to utilize the algorithm applied previously to determine the output displacement at *M* mainly due to branching that occurs at point *J* where three chains converge. Moreover, the chain *JEA* is not a passive chain as there is loading (the actuation) applied at the internal point *D* and therefore, *JEA* cannot directly be combined in parallel with *HJ*. The two main distinctive features of this mechanism are: (a) it is branched structurally (with the three chains converging at *J*) and (b) it possesses at least two chains (branches) that are acted upon by external/reaction loads. Such flexure-based mechanisms, which we call structurally- and kinematically-branched to emphasize features (a) and (b), have not been studied analytically thus far, to the best of our knowledge.

This paper proposes a general analytical model capable of solving the direct and inverse quasi-static kinematics of planar structurally- and kinematically-branched, overconstrained mechanisms that combine flexible and rigid links in a complex series/parallel fashion and that are subjected to multiple loads. The matrix model proposed here for these designs identifies and evaluates the compliance of passive chains (links that are not acted upon) in a first stage by means of a substructuring process. In a second phase, reactions and displacements are calculated at externally- and internally-constrained points of interest and then, in a third stage, analytic relationships between loads and displacements are determined at other points of interest. With all relevant reaction loads and displacements known, mechanism performance qualifiers such as stiffness or mechanical (geometric) amplification/reduction can eventually be quantified. This paper partially employs the serial-chain compliance model developed in [8], but this is limited to chain portions that are serial. However, the complex, branched flexure-hinge designs presented here are studied by means of a new, comprehensive matrix model that incorporates serial and parallel chains acted upon by multiple loads.

The algorithm developed here is utilized to model, analyze, design, and characterize a novel planar displacement-amplifying gripper with right circularly corner-filleted flexure hinges in order to evaluate the mechanism's mechanical amplification, stiffness, and contact (grip) force. A proof-of-concept piezoelectrically-actuated gripper prototype was fabricated and experimentally tested. For the prototype geometry and material properties, the experimental and finite element results confirmed the analytical model predictions. The analytical model was further utilized in a search-type optimization to study how the gripper's design parameter variation affects the mechanism's performance and to establish configurations that will ensure matching specific performance criteria such as stiffness and displacement/force ratios.

The main contributions of the paper are summarized as follows:

- It introduces the process of substructuring of structurally- and kinematically- branched planar flexure-hinge mechanisms into simpler component serial chains.
- Within this structural approach, an analytical matrix method is developed that formulates the general quasi-static load-displacement relationships resulting from using the component flexible segment compliances in conjunction with the actual load and boundary conditions.
- It presents the design, analysis, testing and characterization of a new planar branched displacement-amplifying gripper whose configuration that matches specified performance criteria can be identified by means of the compliance-based substructuring method.

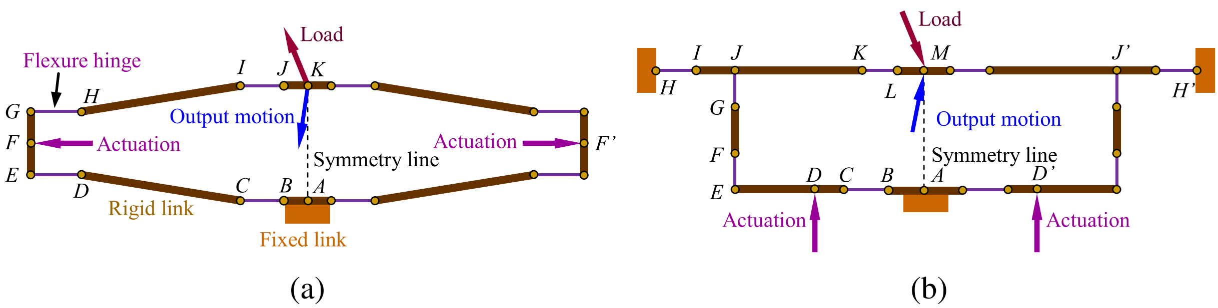

Fig. 1. Skeleton representation of two planar flexible mechanisms: (a) parallel design formed of two serial chains; (b) parallel configuration formed of two branched chains.