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Modeling and Generating New Flexure Constraint Elements

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Abstract

This work introduces the principles necessary to model and generate new flexure constraint elements that may be used to synthesize next-generation precision flexure systems. These flexure constraint elements are modelled using sets of constraint lines, which represent the axes of pure force wrench vectors. All possible sets of constraint lines have been derived and represented as geometric shapes called constraint spaces, which enable designers to visualize and rapidly generate a host of new flexure constraint elements. Systematic steps for appropriately combining these new flexure constraint elements have been created for guiding designers in synthesizing next-generation precision flexure systems, which possess desired degrees of freedom while achieving a large range of stiffness and dynamic characteristics.

1 Introduction

Currently most precision flexure systems are constrained by the common variety of wire, blade, and notch flexures like those shown in Fig. 1A. The wide-spread use of these standard constraint elements is due to the fact that they *(i)* possess well understood degrees of freedom, which are easy to visualize, *(ii)* are relatively easy to fabricate, and *(iii)* are often the only flexure constraint options to which designers have been exposed. The demand, however, for precision flexure systems that possess greater kinematic, dynamic, and elastomechanic versatility is growing as flexure-based applications are becoming more sophisticated. This paper provides the theory necessary to model and generate new flexure constraint elements like those shown in Fig. 1B that satisfy the requirements of these sophisticated applications. Such applications include the use of flexure systems as *(i)* compliant microstructures for new materials that possess properties that are superior to those of naturally occurring materials, *(ii)* devices used to pattern nano-features onto irregularly contoured surfaces, and *(iii)* multi-axis three-dimensional submicron manipulation and assembly stages. As progress towards high-resolution multi-material additive fabrication technology advances, flexure system designs for these and other applications will be driven more by performance requirements and less by fabrication limitations.

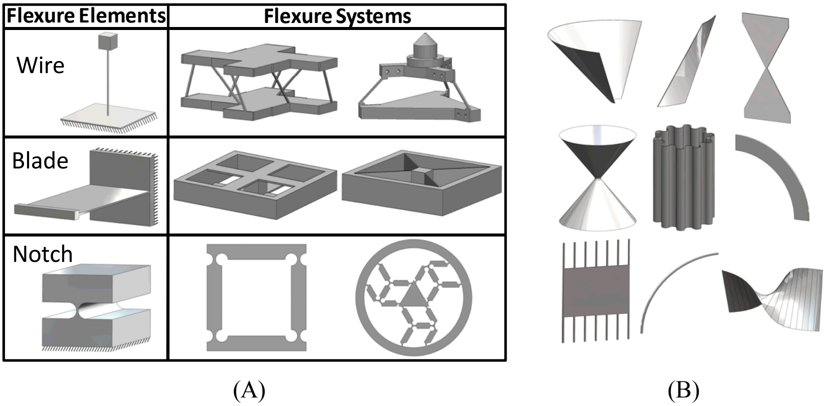


Figure 1: Common flexure elements (A) and new flexure elements (B).

2 Modeling Flexure Constraint Elements

Dependent on its geometry, a flexure constraint element imparts certain combinations of forces on the system that it constrains. The axes of these forces may be represented by lines, called constraint lines, which may be modeled using pure force wrench vectors from screw theory [1]. Any flexure constraint element may, therefore, be modeled using every constraint line that *(i)* fits inside the element's geometry and *(ii)* directly connects the system's stage to its ground. For a wire flexure, like the one shown in Fig. 1A, the only constraint line that satisfies these two conditions is the line that passes through the axis of the wire. For a blade flexure, the only constraint lines that satisfy these conditions are the lines that lie on the plane of the blade as shown in Fig. 2A. For a notch flexure, the only constraint lines that satisfy these conditions are the lines that lie on the surfaces of intersecting planes as shown in Fig. 2B. Each of these geometric shapes, called constraint spaces [2], uniquely link to a complementary freedom space [2], which represents the kinematics permitted by the flexure constriant element. The blade flexure's freedom space shown in Fig. 2C, for instance, is a plane of rotation lines and an orthogonal translation arrow. In other words, the blade flexure permits any rotational motion about any axis that lies on its plane and any translation that is perpendicular to it. The notch flexure's freedom space, shown in Fig. 2D, is a single rotation line. In other words, the notch flexure permits a single rotational motion about the axis of the intersecting planes , which are shown in Fig. 2B.

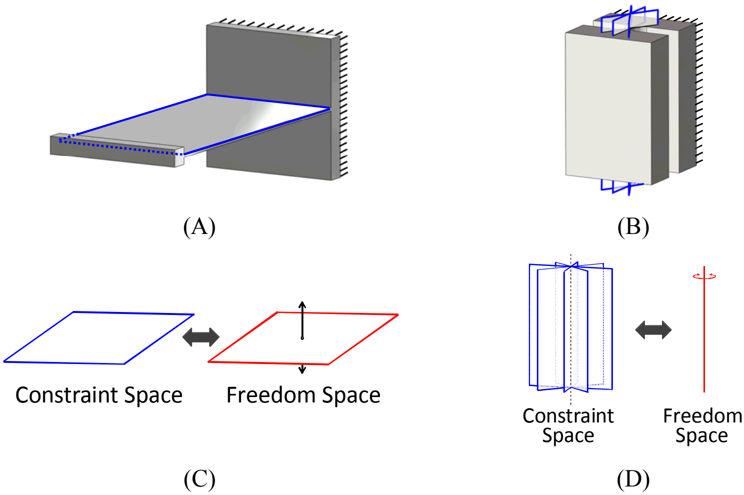
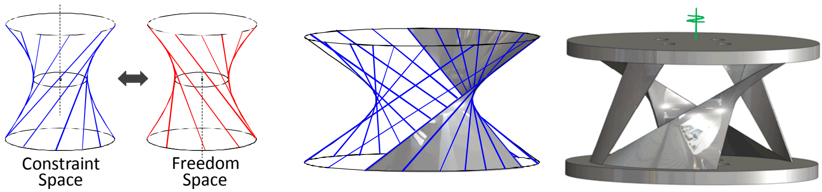


Figure 2: Modelling a flexure blade (A) and a notch flexure (B) using constraint lines. The constraint and freedom spaces of the blade (C) and notch (D) flexures.

3 Generating New Flexure Constraint Elements

The freedom and constraint space pairs shown in Figs. 2C-D are only two of 26 pairs from which flexure constraint elements may be generated. All of these spaces have been derived and described in detail in Hopkins [2]. Using these spaces, designers may generate a host of new flexure constraint elements like those shown in Fig. 1B. Consider the constraint and freedom space pair shown in Fig. 3A. The constraint space consists of a single set of constraint lines that lie on the surface of a circular hyperboloid. The complementary freedom space consists of another set of rotation lines that also lie on the surface of the same circular hyperboloid but point in different directions (The freedom space also contains other screw lines that are not shown in the figure). The flexure constraint element shown in Fig. 3B would permit the desired kinematics of this freedom space because the only lines that lie within its geometry and directly connect the system's stage to its ground belong to the constraint space of Fig. 3A. Using this flexure constraint element and other similar elements from other circular hyperboloids with different parameters, a flexure system may be synthesized that possesses a single screw degree of freedom as shown in Fig. 3C. The stage of this system is constrained to translate as it rotates along and about the screw line shown in the figure with a particular pitch value.



(A) (B) (C)

Figure 3: Using a circular hyperboloid constraint space (A) to generate a new flexure constraint element (B) that may be use to synthesize a new screw flexure system (C).

Conclusion

An approach for modeling and generating new flexure constraint elements has been introduced. This approach enables designers to visualize every new flexure constraint element that lies within a comprehensive body of geometric shapes called constraint spaces. The kinematics of these new elements may be determined using their constraint space's complementary freedom space. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-CONF-XXXXXX.

References:

[1] Ball, R.S., A Treatise on the Theory of Screws. Cambridge, UK: The University Press; 1900.

[2] Hopkins, J.B., Culpepper, M.L., 2010, "Synthesis of Multi-degree of Freedom, Parallel Flexure System Concepts via Freedom and Constraint Topology (FACT)—Part I: Principles," Precision Engineering, 34(2): pp. 259-270.