Mechanism and Machine Theory 49 (2012) 21–39

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

A *compliant mechanism kit* with flexible beams and connectors along with analysis and optimal synthesis procedures ☆

Padmanabh Limaye, G. Ramu, Sindhuja Pamulapati [1], G.K. Ananthasuresh *

Mechanical Engineering, Indian Institute of Science, Bangalore, India

ARTICLE INFO

Article history:
Received 18 December 2010
Received in revised form 9 July 2011
Accepted 14 July 2011
Available online 25 August 2011

Keywords:
Compliant mechanism kit
Beam finite element analysis
Topology optimization
Building blocks
Fillets

ABSTRACT

We present a *compliant mechanism kit* as a parallel to the kits available for rigid-body mechanisms. The kit consists of flexible beams and connectors that can be easily hand-assembled using snap fits. The mechanisms assembled using the kit accurately capture the aspects of the topology, shape, and size of joint-free compliant mechanisms. Thus, the kit enables designers to conceive and design new, practicable, single-piece compliant mechanisms that do not require assembly. The concept of the kit also resolves a discrepancy in the finite element (FE) modeling of beam-based compliant mechanisms. The discrepancy arises when two or more beams are joined at one point and thus leading to increased stiffness. After resolving this discrepancy, this work extends the topology optimization to automatically generate designs that can be assembled with the kit for quick and easy validation instead of time-consuming prototyping. Thus, the kit and the accompanying analysis and optimal synthesis procedures comprise a self-contained educational as well as a research and practice toolset for compliant mechanisms. The paper also illustrates how human creativity finds new ways of using the kit beyond the original intended use and how it enables even a novice to design compliant mechanisms.

1. Introduction

Compliant mechanisms are joint-free mechanisms that transmit or transform motion or force through elastic deformation rather than through hinges and sliders as in their rigid-linked counterparts. The primary advantages of compliant mechanisms are: fewer parts, fewer assembly steps, absence of backlash, and reduced need for lubrication. The absence of hinges makes compliant mechanisms attractive for many applications [1,2] including the emerging areas of micro and nano-scale systems [3]. The twofold motivation for the work presented in this paper is explained next.

In spite of their many advantages, compliant mechanisms are not yet widely used nor are they taught widely in undergraduate engineering courses. A reason for this slow, but gradually increasing, adoption of compliant mechanisms in practice and education may be that designing them is slightly involved because one has to deal with elastic deformations—often geometrically nonlinear. Designing or even analyzing compliant mechanisms usually requires access to finite element analysis (FEA) software. The pre- and

☆ Enhanced version of a paper presented at the 14*th* National Conference on Machines and Mechanisms (NaCoMM-09), NIT, Durgapur, India, December 17–18, 2009.

* Corresponding author. Tel.: +91 80 2293 2334; fax: +91 80 2360 0648.
E-mail address: suresh@mecheng.iisc.ernet.in (G.K. Ananthasuresh).
[1] Summer intern from the Indian Institute of Technology, Hyderabad, India.

0094-114X/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.mechmachtheory.2011.07.008

post-processing involved in FEA, i.e., drawing or modifying the computer model and meshing it and then visualizing its deformation, makes it difficult for the designer to exercise creativity and intuition. Prototyping a compliant mechanism is another difficulty because one needs to machine it usually using a computer-numerically-controlled (CNC) machine because of their not-so-simple geometry. Contrast this situation with rigid-body mechanisms whose motion is more easily visualized. Or, they can be built easily using even cardboard and pins. Furthermore, several kits have been developed as practical toolsets for designing rigid-body mechanisms wherein mechanisms can be realized by simple hand-assembly from the available parts. It is desirable to have such a kit for compliant mechanisms too. Some compliant Lego building blocks are available to work in conjunction with the Lego™ kit [4]. The concept of a stand-alone and general kit with computational support is the focus of this work.

There is a second motivation for developing a *compliant mechanisms kit*. A beam finite element is a popular choice for analysis or topology optimization of compliant mechanisms [5], which have certain advantages over continuum finite elements. Beam finite elements are attractive in analysis because most compliant mechanisms comprise slender beam-like segments. And they are attractive in topology optimization because fewer elements are required and the potential to obtain distributed compliance is better than what can be achieved with continuum element-based methods. However, there is an inconsistency in using beam finite elements for modeling compliant mechanisms. It is due to the modeling of the connections where two or more beams of different widths intersect. Consequently, a prototype of an analyzed or designed mechanism is found to be stiffer than its finite element (FE) beam-model. This is illustrated with an example presented next.

Fig. 1(a) schematically shows a beam connection as it is assumed in the FE model while Fig. 1(b) shows the same beam connection as it appears in the prototype. To accommodate the finite size of the cutting tool and/or to reduce stress concentrations, a fillet is indeed unavoidable. But it adds extra material at the joint. It also reduces the actual deformable lengths of the intersecting beams as opposed to the lengths assumed in the FE model. Hence, the joint becomes stiffer in the prototype than its FE model [6].

When we use beam ground structures in topology optimization [7], there are many beam-to-beam intersections. Hence, the aforementioned problem becomes even more prominent. An example is shown in Fig. 2(a–b). Fig. 2a shows the beam-model of a displacement-amplifying compliant mechanism in its original and deformed configurations while Fig. 2b shows the same for an actual 2D form with fillets. By nonlinear finite element analysis using two-node beam and nine-node 2D continnum elements, it was found out that there was a discrepancy of as much as 109% in the strain energy between the two models. While beam model had strain energy of 13.9E−3 Nm, the continuum model had only 6.65E−3 Nm. This huge discrepancy is not very surprising because the effective lengths of beams decrease because of the junctions and fillets.

While developing the methods to resolve the issue of junction and fillet induced additional stiffness [8], it was realized that a better way is to simply avoid the intersections of flexible beams by having a semi-rigid connector in analysis, design, and the real prototype. This led to the idea of a *compliant mechanisms kit* that enables the design of compliant mechanisms with beams that remain closer to reality. We note that the mechanisms assembled with the kit are only *designs* and not the final mechanisms to be used in practice. This is in the same spirit as any other things designed using a kit.

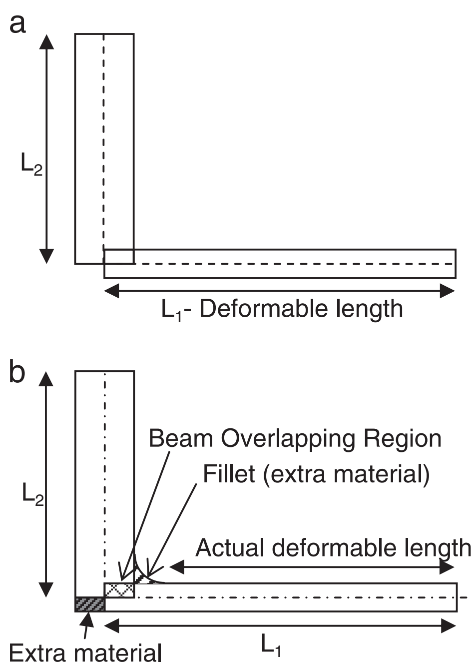

Fig. 1. (a) Ideal beam connection in FE model. (b) Actual beam connection in prototype.