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Introduction

Mechanical Design of Compliant Microsystems—A Perspective and Prospects

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The field of microsystems, or microelectromechanical systems (MEMS) as it is popularly known, is a truly multidisciplinary area of research. It combines a wide variety of physical, chemical, and biological phenomena into an integrated system on a chip [1]. This unprecedented integration naturally calls for new systems design approaches as well as efficient ways to analyze a single system or a component that is governed by many types of partial and ordinary differential equations from different physical and chemical domains [2]. The key component of almost all MEMS devices, with the exception of microfluidic systems, is a movable mechanical structure of micron dimensions. Since the early works in this area dating back to the late sixties of the 20th Century, simple mechanical structures such as beams and diaphragms have dominated MEMS. Thus, the mechanical design in MEMS is mainly concerned with the design of such elastically deforming structures subjected to a variety of forces ranging from electrostatic, thermal, magnetic, piezoelectric, radiation pressure, etc. In addition to these unconventional forces and the accompanying complex equations that govern them, micromachining brings additional difficulties in microsystem design [3].

Micromachining is a set of techniques that are largely adapted from microelectronic fabrication for the purpose of manufacturing micromechanical structures. Significant enhancements beyond the traditional microelectronic processing steps have taken place in the past two decades. Nevertheless, the batch fabrication of many identical components on a single substrate such as a silicon wafer remains the paradigm of choice in micromachining. Assembly of prefabricated components into a system is economically not justifiable in micromachining just as it is in microelectronic fabrication. Consequently, mechanical components too are to be micromanufactured in a batch mode without assembly. The aforementioned simple elastically deforming structures can easily be made this way. As has been shown by many innovative micromachining processes, even multibody jointed mechanical assemblages have been realized using some of these processes. But limited capabilities of micromachining, which is essentially a layered construction of selectively etched planar thin films, continue to impose some restrictions on the mechanical design of MEMS.

As depicted in Fig. 1, mechanical design in MEMS offers new challenges and opportunities for designing micromechanical structures subject to unconventional forces and fabricated using a limited range of micromachining techniques. The choice of materials is also limited to silicon, its compounds, glasses, and some metals, but it is gradually extending to more metals, ceramics, and polymers. The research in the past two decades has led to two types of micromechanical systems: batch-fabricated assembled micromechanisms and assembly-free compliant microsystems.

Batch-Fabricated Micromechanisms

The batch fabrication of rotating gears, electrostatic motors, and in-plane revolute joints [4] marked a significant step in micromachining although their practical applications have not been realized even today. But the underlying sacrificial layer technique has proved to be very useful in the subsequent development of MEMS. Multiuser MEMS foundry processes, such as multi-user MEMS processes (MUMPs) [5] and SUMMiT [6], and other techniques have enabled the fabrication of sophisticated linkages, gear trains, intermittent-motion devices [7], and even cams [8]. Using mechanical ingenuity, even the limited capabilities of a two-layered MUMPs process were used to realize a floating in-plane revolute joint [9]. Novel out-of-plane revolute joints developed by Pister [10] have found practical applications in optical switching [11]. Friction and wear are reported to be significant factors in the failure of MEMS devices that contain surfaces that slide or roll on each other. The clearances in micromachined joints are large leading to imprecise motion due to the backlash error. Thus, in addition to the constrained set of fabrication methods and materials, inherent performance related difficulties are to be overcome in this category of MEMS devices.

Compliant Microsystems

A significantly useful paradigm has emerged in the form of compliant micromechanisms along with systematic methods to design them [12]. Compliant mechanisms rely upon elastic deformation of their flexible structural members to perform mechanical tasks of transferring and transforming energy, force, and motion [13,14]. They have inherent advantages in microsystems because motion in them is obtained from elastic deflection rather than from traditional joints. Therefore, compliant members are able to overcome the limitations of batch-fabricated mechanical joints including binding, clearances which are large compared to device sizes, friction, and wear. Many compliant mechanisms are monolithic and thus facilitate batch fabrication of assembly-free components or even entire devices. They are also well suited for planar fabrication. Complex motions are still possible with these even under micromachining constraints. Deflecting compliant members integrate motion control with energy-storing elements, which would

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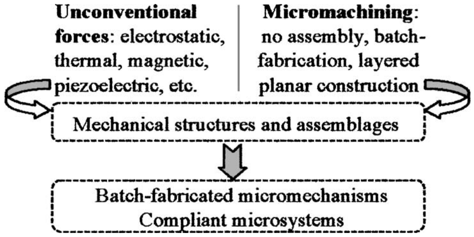

Fig. 1

otherwise be separate components of joints and springs. This makes possible applications such as bistable mechanisms [15,16] and orthoplanar springs [17]. Many commercial MEMS products currently on the market (e.g., accelerometers, pressure sensors, and digital mirror displays) exploit the advantages of compliant mechanisms in their designs.

Besides simple compliant members such as beams and diaphragms that are used widely in MEMS including some commercial applications, compliant micromechanisms are also in use. The suspension of the electrostatic comb-drive actuator is a notable example. This suspension is expected to have high stiffness in one direction and high flexibility in another. The folded beam suspension and some other alternative designs are available for this purpose [18,19]. Microgrippers [20,21], surgical tools [22,23], and manipulators [24,25] also involve considerable mechanical design. Compliant displacement and force amplifiers can enhance the performance of microactuators [26,27] and sensors [28,29]. Compliant micromechanisms are useful for on-chip force gauges [30] and vision-based microforce sensors [31]. Other notable MEMS applications that pose significant challenges for mechanical design are monolithic bistable mechanisms [32,33], high-Q microresonators [34], and radio frequency (RF) switches [35].

The advantages of implementing compliant microsystems are clear, but they do not come without some challenges. The increased complexity of compliant mechanism synthesis over traditional mechanism synthesis is one of these and it has been addressed in several ways, including pseudo-rigid-body models and shape and topology optimization. The pseudo-rigid-body model uses simplified models of pin joints and springs that accurately predict the nonlinear deflection of elastic members [14,36]. The resulting models are equivalent rigid-link mechanisms, thus allowing traditional mechanism analysis and synthesis approaches to be used to analyze and design compliant mechanisms. These pseudo-rigid-body models are particularly useful in initial design. Once a design is determined, it can be translated back to the equivalent compliant mechanism, and a prototype can then be tested or a detailed finite element analysis can be performed. This process is illustrated in Refs. [32,37] in the context of micromachined bistable mechanisms.

Topology optimization methods have also been developed for compliant microsystem devices. These methods enable fully automated approaches to the synthesis of the geometry of flexible structures under a variety of loads including mechanical, thermal, electrostatic, piezoelectric, etc. [38,39]. Shape optimization techniques have also been used for compliant and micromechanisms [40,41]. Another advantage of compliant microsystems becomes apparent in this context when we notice how easy it is to actuate compliant mechanisms with nonmechanical actuations [42] such as the ones noted above. In many instances, the mechanism and actuator are not separate leading to the concept of embedded actuation [43]. Topology synthesis of electro-thermal-compliant mechanisms [44,45] exemplifies this.

It is also worth noting that a reliability study on MEMS devices [46] reported that a prominent failure mode in micromachined structures is the wear in the joints rather than the material failure in compliant members. Hence, it may be expected that the use of compliant microsystems in MEMS applications is likely to increase further making mechanical design an integral part of microsystem design.

Comments on Papers in This Volume

Since the theory of continuum solid mechanics remains valid for micromechanical structures operating within elastic limits, the design of compliant mechanisms is essentially scale independent. Thus, many of the ongoing developments in the design of compliant mechanisms are equally applicable for compliant microsystems. Many papers included in this volume under the subheading of microsystems are thus relevant to MEMS. Their application to MEMS is likely to increase as mechanical manipulation needs grow within the MEMS field. One more important aspect of compliant microsystems is the design and analysis of flexural pivots—narrow elastic hinges that connect two relatively rigid parts—that can be found in many MEMS devices. Despite their widespread use at the macro and microscales, some issues remain open [47], as can be seen in the last four papers included in this volume under the section on microsystems.

Closure

Movable mechanical elements are crucial for the functionality of MEMS. These elements are often very simple deformable structures but the actuation and sensing methods strongly couple mechanical domain with other physical and chemical domains. This and assembly-free batch-mode micromachining techniques make mechanical design of MEMS interesting and challenging. The design of compliant microsystems involving flexible structures and flexural joints plays an important role in the future development of MEMS.

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