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Designing compliant mechanisms

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Abstract

There are many differences between nature's designs and those of man. One is in the way they are "manufactured." Nature does not assemble its artifacts--it almost always prefers to grow the entire system as a single entity. Undoubtedly, this is the most efficient way of creating new products. In contrast, human engineers assemble different parts fabricated separately. It is true that people don't (at least not yet) have biological manufacturing processes at their disposal. However, there is plenty of opportunity for innovation by imitating the no-assembly designs of the natural world. In fact, it is possible to design some mechanical artifacts as single-piece entities that do not require assembly.

Full text

Headnote
Nature offers a manufacturing paradigm in which elastic deformation generates desired motion and forces for such applications as micromechanical systems. By G" K. Ananthasuresh and Sridhar Kota

THERE ARE MANY differences between nature's designs and those of man. One is in the way they are "manufactured." Nature docs not assemble its artifacts-it almost always prefers to grow the entire system as a single entity. Undoubtedly, this is the most efficient way of creating new products. In contrast, human engineers assemble different parts fabricated separately. It is true that we don't (at least not yet) have biological manufacturing processes at our disposal. However, there is plenty of opportunity for innovation by imitating the no-assembly designs of the natural world. In fact, it is possible to design some mechanical artifacts as singlepiece entities that do not require assembly.

Compliance vs. Rigidity

The crucial difference in the way nature and human designers manufacture artifacts is not entirely that nature can biologically grow things. The main difference, at least to some extent, is due to a different design paradigm. Traditionally, engineered artifacts are designed to be strong and rigid. Designs in nature, on the other hand, are strong and compliant. Nature is limited by the sorts of mechanisms that can be developed because the organism must be one connected whole. Use of compliance to convert available

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energy into useful and sophisticated movements can be seen in many living organisms. For instance, the muscles of a flea simply would not be able to release energy quickly enough to jump if it were not for the specialized compliant design of its legs. The flea converts muscular work to strain energy stored in a compliant joint, which can be released quickly. Centipedes and millipedes depend on distributed compliance for burrowing and other functions. Many insects rely upon compliance to flap their wings.

Although nature thrives on the use of compliance, the engineering world has traditionally limited itself to rigid structures and mechanisms. Even in cases where the compliance or adaptability of a structure is needed, rigid elements and actuators are employed to simulate compliance.

The effects of compliance can be used by the scientific and engineering community at large, and much can be learned from nature. Compliance in design generally leads to simplicity in manufacturing, and in some cases it eliminates the need for assembly operations altogether. Using elastic deformation as a preferred effect is not entirely new to the engineering community: the ancient longbow and the catapult are simple but effective examples. Examples of compliant mechanisms can be found in everyday products, such as the shampoo-bottle lids and milk carton spouts. These mechanisms are integrated so well with their surrounding structures that they are not even seen as mechanisms at all.

Design for No Assembly

Studies have indicated that in a wide variety of industries, assembly costs account for about 40 to 50 percent of the total product cost. Designers, therefore, are always trying to reduce the part count to keep assembly costs down and improve product quality. Design for assembly (DFA) methods have been proven to reduce the part count and incrementally improve quality and cost. One DFA guideline for reducing the part count is to promote part consolidation, unless there is relative motion between the parts. In design for no assembly (DFNA), parts with relative motion between one another can be consolidated into monolithic mechanical devices by using jointless compliant mechanisms, provided the relative motion is small.

Product designs that have a relatively small range of motion can reap quantum benefits from DFNA. For example, a stapler can be designed as a single-piece compliant mechanism. One of the lessons learned from DFA is that as the part count decreases, the complexity and the manufacturing cost of the integrated design increase. DFNA, however, opens doors to new methods of manufacture and thereby circumvents the potential dangers of increased manufacturing cost. For instance, application of DFA methods suggests replacing threaded fasteners with snap fits within the framework of current manufacturing methods. The DFNA method might suggest injection molding the entire assembly as a one-piece flexible structure. The DFNA concept is not a cure-all, of course, but it could be a very cost-effective alternative for certain applications.

Compliant Mechanisms

Besides the manufacturing advantage of no-assembly, the use of compliance has other benefits. In real-life working conditions, elastic deformation is inevitable, even in supposedly rigid mechanisms. The ensuing inaccuracies in design, manufacture, control, and maintenance, all of which result in additional costs, must be accounted for.

The designer's foe (elastic deformation) can be turned into an ally by exploiting compliance to achieve force transmission and motion generation. This concept ot using compliance has been revived at Purdue University, in West Lafayette, Ind. A group at the University of Michigan, in Ann Arbor, has introduced the concept of distributed compliance and is focusing on exploring new applications, including microelcctromechanical systems (see "Compliant MEMS," page 96) monolithic products, and adaptive and smart structures for automotive, medical, and aerospace uses.

Compliant mechanisms are flexible structures that deliver a desired motion by undergoing clastic deformation, as opposed to the rigid body motions of conventional mechanisms. The definition of compliant mechanisms encompasses those designs where elastic elements are used merely as springs, as well as those in which the primary source of motion is due to elastic deformation to achieve a wide variety of force-deflection characteristics with the least mechanical complexity.

The reduced number of parts, most of which are flexible, make compliant mechanisms lightweight devices. Fewer rigid body joints help reduce friction, wear, backlash, and noise. Finally, a compliant mechanism's components are flexible, which enable it to absorb overloads without structural failure.

Adaptive structures can also benefit from the use of compliant mechanisms. Many applications of adaptive structures require the underlying structure to reconfigure itself to effect a desired change in the shape of some attached entity. The current trend in the design of adaptive structures is to inundate an otherwise rigid structure with numerous actuators, sensors, and feedback controls to simulate the compliance needed to geometrically adapt the shape to different operating conditions. The resulting designs are

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generally cumbersome, energy inefficient, expensive, and unreliable. However, if the underlying structure were designed to be inherently adaptive (or compliant), the final design would not only require fewer actuators, but it would afford precise control over force and motion. Current research lays down a theoretical foundation that allows designers to synthesize an energy-efficient, simple, and reliable compliant structure before adding electronic smarts.

As flexure is permitted in these mechanisms, they can be equipped for nonmechanical actuation using the techniques of transduction. This feature lends itself to the design of smart materials and structures where the "deformable structure" is composed of a compliant mechanism (see "Smart Skis and Other Adaptive Structures," page 76). Thus, compliant mechanisms can significantly benefit the development of smart structures, for they provide a simple and cost-effective way to accomplish controlled motion and force generation.

Lumped vs. Distributed Compliance

The main feature of fully compliant mechanisms is that no assembly is required for their construction. Flexible joints (also called living hinges) emulate the function ot a conventional hinge by concentrating flexion to just a few regions. A compliant mechanism with a discrete number of flexural pivots possesses lumped compliance. The drawbacks to flexural joints include high stress concentrations, low static and fatigue strength, and difficulty in manufacturing very thin and thick sections.

By incorporating torsional and linear springs to simulate compliance, lumped compliant mechanisms can be interpreted as rigid link mechanisms. With this as a premise, researchers at Purdue and Brigham Young University, in Provo, Utah, have offered the concept of pseudorigid-body models and have developed syn- thesis techniques by using a substantially enhanced kinematic approach. The researchers initiate the design process with a known or predetermined topology and transform it into a pseudo-rigid-body model. They then determine its link lengths and spring constants simultaneously. The spring constants determine the lumped compliant regions. In distributed compliant mechanisms, flexibility is distributed relatively equally through the entire mechanism-no one portion is much thinner than another. The mechanism as a whole, therefore, is flexible (that is, it possesses distributed compliance). Distributed compliance offers versatility and superior performance and reliability compared with lumped compliance because the flexion is not concentrated to just a few regions. Thus, stress concentrations are avoided.

The notion of distributed compliance blurs the distinction between a structure that resists loads and a mechanism that transmits motion and forces. The traditional methods of designing structures and mechanisms are very different. In the field of kinematics, mechanisms have traditionally been designed for desired displacement to gain a high mechanical advantage. On the other hand, structural design methods have traditionally dealt with designing structures for maximum stiffness (minimal deflection) with minimum weight. Designing for strength is a consideration in both. Compliant mechanisms should be compliant enough to generate motion yet rigid and strong enough to resist loads with a high mechanical advantage-all with minimal weight. Therefore, these designs call for a synergistic treatment of kinematics and continuum mechanics.

A Systematic Synthesis Method

Compliant mechanisms are immovable without their deformation capability. For such structures to serve as mechanisms, they must have suitable topology, shape, and size. These three characteristics together enable a structure to deform under the action of external loads and deliver required motion and force transmission. Topology here refers to the material connection among different portions of the structures, such as fixed region, load application region, output port, and so forth. The topology defines the skeletal structure. The shape and size of individual segments, therefore, completely specify the configuration of a compliant mechanism. Synthesis thus entails determining these three characteristics for a given set of problem specifications.

The method used at the Design Laboratory at the Department of Mechanical Engineering & Applied Mechanics at the University of Michigan, in Ann Arbor, requires nominal input, namely the outline of the design domain, input forces, output loads, and output deflection. The outcome is the complete description of the topology, shape, and size.

The function is abstracted in terms of applied forces, output deformations, and loads, all of which constitute the input-output behavior of a compliant mechanism. Thus, function (or intended behavior) means that a certain portion of the structure should deform in a prescribed direction under the application of specified external forces. In addition to achieving the desired deformation, an optimum solution is sought for minimizing weight or work done in deforming the structure for a given application.

The group at the University of Michigan's Design Laboratory adapted a formal structural optimization technique called the homogenization method. This method was originally developed by M. P. Bendsoe of the Technical University of Denmark, in Lyngby, and Noboru Kikuchi of the University of Michigan. Their objective was to design the stiftest structure for withstanding external loads. However, because the goal at the Design Laboratory was to design compliant mechanisms (or flexible structures), the underlying mathematical formulations had to be modified to capture the desired compliant behavior in the resulting design.

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A rectangular cell-based microstructure is created in the design domain. Each cell has a hole in it. The parameters ii and b determine the size of the hole (or void), while в determines the orientation of the cell. It is then obvious from this that if a = b = 0, then the cell gets completely filled with the material, and if <i and b are equal to the width and height of the cell, an empty space is created. The intermediate values give rise to a porous structure. It is thus possible to generate any topology and shape, within the limits enforced by the fineness of the mesh.

Using the above parameters as a basis, an optimization problem is formulated by taking a, b, and в for each cell as design variables to minimize an objective function and satisfy certain constraints of the design requirements. The optimized values of a, b, and в are converted to a density-like measure depending on the fraction of area occupied by the hole within the cell. Such a density measure is used to portray the optimal layout as an image on a color scale, which is called the homogenized image.

Starting from user-defined, input-output, force-deflection requirements, the synthesis program generates optimal topolog)' of a compliant mechanism needed to produce the desired motions. In designing a microcompliant crimping mechanism using this systematic design procedure, the applied forces (hand forces) and the deflection needed to close the gap of a crimping mechanism were specified. The program converged after 15 iterations, and the final design was derived by interpreting the converged homogenized image. The microcompliant mechanism designed systematically using this method was fabricated using the boron-doped bulk silicon technique at the University of Michigan's microfabrication facility.

The synthesis procedure described above has much practical value because generating even a feasible design (determining topolog)', shape, and size), let alone an optimal design, of a compliant mechanism by the trial-anderror method is very difficult. Furthermore, there are no other methods of synthesizing distributed compliant mechanisms. Future efforts will be directed toward a hybrid approach that uses kinematics more effectively in the context of the continuum approach.

Compliance by Design

In the May issue of Discover, Steven Vogel gives a detailed account of the amazing ways in which nature uses compliance. He then asks a very pertinent question: Why don't we make more use of flexible materials and structures? Human designers have yet to fully embark upon the compliant world in designing machines that are flexible and strong rather than rigid and strong. This transition calls for the use of new materials, new manufacturing processes, [and new design methods. Research in materials science is! making possible the availability of a variety of superior materials intended to be as good as the biological ones. Recent trends in manufacturing technology point to growthlike processes (for example, layered manufacturing, an adaptation of rapid prototyping techniques). However, there is no need to wait for such developments to move onto compliant mechanisms in the DFNA paradigm. What has been lacking are methods to design compliant mechanisms. The development of protocols may encourage designers to consider designs that are flexible and strong. Indeed, emerging technologies such as MEMS, adaptive structures, and smart structures call for such a change. The important thing is that increased use of compliance in design reduces the need for assembly, takes designs closer to true optimum design, and makes them adaptive, smart, and increasingly more like nature's. *

Sidebar
Compliant MEMS

THE ORIGINAL IMPETUS toward compliant micromechanisms came from research on microelectromechanical systems (MEMS) conducted at the University of Michigan's Design Laboratory. MEMS is a rapidly growing field in which micron-size mechanical structures are actuated and controlled using a variety of methods such as mechanical, electrostatic, electromagnetic, optical, fluidic, and thermal energy. Silicon-based MEMS are fabricated using enhanced VLSI (very large scale integration) microfabrication techniques and newly devised micromachining processes. The microfabrication techniques do not accommodate assembly because there are no microtools. MEMS are manufactured using deposition and etching of layers of materials without further assembly. There is a dire need for designs that do not require assembly in their manufacture. Instead of designing microprecision tools for MEMS, the Design Laboratory researchers began investigating ways in which assembly operations could be minimized, if not eliminated. This led to the concept of distributed compliance. As a result, the need for systematic synthesis tools for creating compliant mechanisms was immediately recognized. Compliant mechanisms, in addition to being a perfect fit for MEMS in view of design and manufacture, are best suited for reliability and accuracy because problems caused by wear, backlash, and lack of lubrication are alleviated in monolithic compliant micromechanical devices. Compliant mechanisms offer greater versatility and scope than simple beams and membranes currently used in many microsensors and actuators.

Nature has realized the pivotal role that compliance plays at smaller scales. Nearly 90 percent of living creatures are invertebrates (lacking rigid skeletal structures), and the percentage of invertebrates increases as we go down the dimension scale. At the realm of microorganisms, the level at which MEMS fit in, the compliant structures reign. Thus, nature provides justification for MEMS to shift to the design for no assembly paradigm.

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IPR Petition - USP 10,036,154

Nature's predilection for compliant designs at the micro scale is no mere happenstance. The scaling effects change many things. Setting aside how biochemical processes are influenced by scale, consider for the moment how ordinary physical phenomena lead to unusual effects, as can be seen in MEMS. The small scale and high aspect ratios of micromechanical structures (thickness is usually much smaller than lateral dimensions) makes them inherently flexible. They often curl up because of the residual stresses induced in the fabrication process. Their size makes them susceptible to elastic deformation under electrostatic forces-a phenomenon not evidenced in the macro domain. A flap in a microvalve does not just pivot about a hinge, even if a micro hinge is fabricated. Rather, it gives in to fluidic forces and bends. In essence, it is often hard to make MEMS behave rigidly.

Thus, on the one hand, micromechanical structures do not comply with rigidity, and on the other hand, their manufacture decrees production without assembly. Hence, in MEMS, a compliant design that needs no assembly is not merely a smart choice, it is a necessity.

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