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Methodology of Compliant Mechanisms and its Current Developments in Applications: A Review

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Abstract: Traditional rigid-body mechanisms consist of a number of components to implement their functions. Therefore they face problems such as backlash, wear, increase in part-count, weight, assembly cost and time, regular maintenance. Reducing these problems will help in increasing mechanism performance and cost reduction. Recently, there are several examples of compliant mechanisms that have been designed and widely used in various fields such as for adaptive structures, biomedical, hand-held tools, components in transportations, MEMS and robotics. However, the largest challenge was relative difficulty in analyzing and designing compliant mechanisms. Two approaches known in the literature for the systematic synthesis of compliant mechanisms are the kinematics-based approach and the structural optimisation based approach.

Key words: Compliant mechanisms, rigid-body mechanisms, kinematics and structural optimisation based approach

INTRODUCTION

A compliant mechanism can be defined as single-piece flexible structure, which uses elastic deformation to achieve force and motion transmission[1,2]. It gains some or all of its motion from the relativeflexibility of its members rather than from rigid body joints alone[3]. Such mechanism, with built-in flexible segments, is simpler and replaces multiple rigid parts, pin joints and add-on springs. Hence, it can often save space and reduce costs of parts, materials and assembly labor. Other possible benefits of designing compliance into devices may be reductions in weight, friction, noise, wear, backlash and importantly, maintenance.

There are many familiar examples of compliant mechanisms designed in single-piece that replaced rigid-link mechanisms, which will be highlighted in other section in this study. Figure 1, shows examples of compliant mechanisms used commonly.

We can simply manufacture a single-piece fully compliant mechanism via injection molding, extrusion and rapid prototyping for medium size devices[4], or using silicon surface micromachining[5] and electroplating techniques[6] for compliant micromechanisms. Although a compliant mechanism gives numerous advantages, it is difficult to design and analyze. Much of the current compliant mechanism design, however, must be performed without the aid of a formal synthesis method and is based on designer's intuition and experience[7-9]. Several trial and error iterations using finite element models are often required to obtain the desired mechanism performance.

Typically, there are two approaches known in the literature for the systematic syntheses of compliant mechanisms are the kinematics based approach[10] and the structural optimization based approach[11-14].

Fig. 1: Common compliant devices. A binder clip, paper clip, backpack latch, lid, eyelash curler and nail clippers are shown[3]

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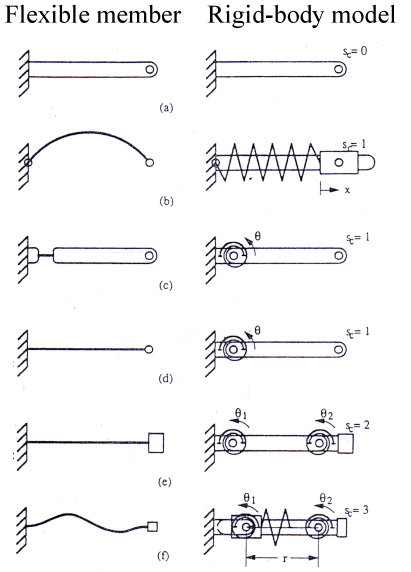


Fig. 2: Various flexible segments and their pseudo-rigid-body models[15]

Kinematics-based approach: In kinematics approach, compliant segments are illustrated as several rigid links connected together by pin joints and torsional springs are added to resist torsion. The value of spring constants and where to place it to the model are calculated differently depending on types of segments.

There are several familiar segments assigned by Howell and Midha[10], i.e., small-length flexural pivots, cantilever beam with force at the free end (fixed-pinned), fixed-guided flexible segment, initially curved cantilever beam and pinned-pinned segment. Different types of segments require different models, see Fig. 2 and in[3], Howell discussed briefly how they might be applied to compliant mechanisms.

Although this method is easier to analyze compare to its compliant counterpart, however, mechanism's force-deflection relationships are still difficult to be determined. Typically, there are two approaches introduced to determine that relationship from pseudo-rigid-body models. The first method uses conventional Newtonian methods i.e., each links are analyzed to obtain static equilibrium. Thus, the force system for the entire mechanism is established. On the other hand, principle of virtual work is also can be selected to determine force-deflection relationship. The approach views the system entirely and does not include all the reaction forces[3].

Typically, kinematics-based approach is well suited with mechanisms that undergo large, nonlinear deflections. Besides, this approach requires starting with a known rigid-links mechanism.

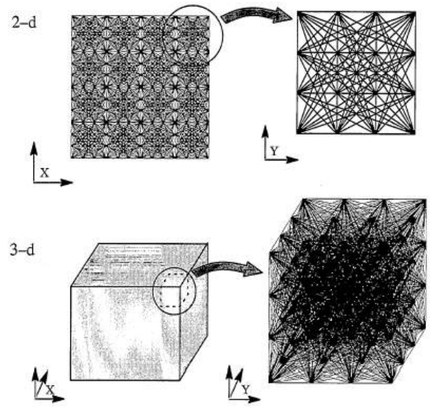


Fig. 3: Composite materials composed of truss or thin frame modelled microstructures in 2 and 3 dimensions[25]

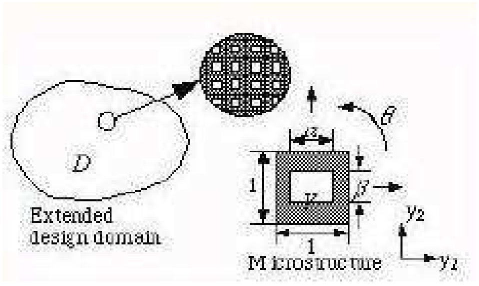


Fig. 4: Design parameterization in homogenization method[28]

Structural optimisation based approach: In this approach it is not required to begin with a known rigid-link mechanism. It focuses on the determination of the topology, shape and size of the mechanism[16]. A numerical approach of topology optimisation starts with a domain of material to which the external loads and supports are applied[17]. The objective function is often the compliance, that is, the flexibility of the structure under the given loads, subject to a volume constraint. In general, there are two types of design domains i.e., ground structure[8,18-20] and continuum structures[21-24].

Ground structure uses an exhaustive set of truss or beam/frame elements in the design domain. The individual cross-section is defined as design variables. When the cross sectional area of an element goes to zero, that element will be removed. Thus after the optimisation procedure converges, some elements will be removed from the original exhaustive set. The remaining elements will define the topology for the compliant mechanism[1,16]. Figure 3 shows examples of initial guess in 2 and 3 dimensions, which is full ground structure with a uniform distribution of cross sectional areas.

In the continuum structures, design domain is typically divided into appropriate finite elements where every element has intrinsic structural properties[26]. In solving topology optimisation problems using this kind of domain (continuum), three major approaches are used. One is the homogenization method, which is based on the assumption of microstructure in which the properties are homogenized[21,22,27]. There are three design variables associated with each finite element. Two of them represent the dimensions of the rectangular hole in the element and the last one is for the orientation of the hole as illustrated in Fig. 4. The element is considered anisotropic due to the hole.

Another approach is the density method which the material density of each element is selected as the design variables. The density method assumes the material to be isotropic and each design variables varies between zero and one and the intermediate values should be penalized to obtain a "black and white" (zero-one) design[29,30]. Several penalization techniques have been suggested. In the SIMP approach (Solid Isotropic Microstructure with Penalization), a power-law model is used, where intermediate densities give very little stiffness in comparison to the amount of material used. Another approach is to add a concave penalty function that suppresses intermediate values to the objective function[31,32].

The third approach is the evolutionary structural optimisation (ESO). The original idea of this method is to gradually remove lowly stressed elements to achieve the optimal design[33,34].

Solution techniques: Several programming techniques may be used in order to solve the problem in structural optimisation based approach. For an example, the sequential linear programming (SLP) method is the most popular approximations method for non-linear optimisation problem due to its simplicity[8]. However, there are other sophisticated optimisation methods such as sequential quadratic programming (SQP), convex linearization (CONLIN), method of moving asymptotes (MMA), generalized convex approximation (GCA) and others. The SLP starts with trial design and replaces the objective function and constraints by linear approximations obtained from a Taylor series expansion about this initial design. An easy-to-use evolutionary structural optimisation (ESO) has also been used for solving large structural optimisation problem[3]. Optimisation problems can be stated in the most general form as:

Minimize $f(x),\ x \in R^n$
Such that $g_j(x) \geq 0;\ j = 1,\ldots,p$ (1)
$h_j(x) \geq 0;\ j = 1,\ldots,q$

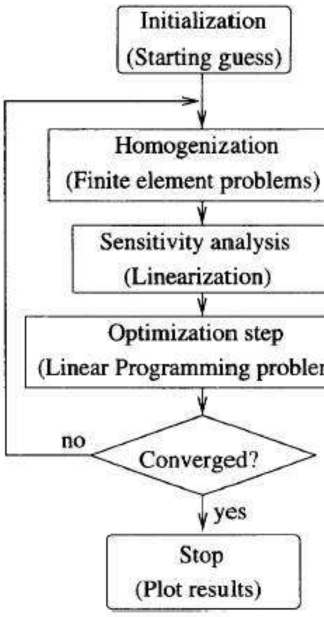


Fig. 5: Example of a flowchart of the design algorithm[35]

Where f, g_j and h_j are function, the inequality and the equality constraints, respectively. They are functions of the n optimisation variables x_i, $i = 1\ldots n$ which are arranged in the vector of variables x. The vector is of dimension n, i.e. $x \in R^n$. Alternative to the above formulation inequality constraints can be written in "greater than" fashion. Arranging the constraints in vectors g and h (1) can be written even shorter:

Minimize $f(x) \mid g(x) \geq 0,\ h(x) = 0;$ (2)
$g: R^n \rightarrow R^p,\ h: R^n \rightarrow R^q$

Actually design objective can be either minimize or maximize. Some designers want to minimize the weight, volume, mean compliance etc. whereas some want to maximize strength to weight ratio, stiffness etc. Figure 5 shows an example a flowchart of the design algorithm.

Highlights in applications: New competitive products must meet the growing demands of the market. They must be light-weighted, resource efficient, durable, stable and have a low noise emission. At the same time, the products must be introduced quickly into the market. For the fulfilment of these demands it is necessary to use the advantages of compliant mechanisms. Compliant mechanisms are applicable in various fields such as for adaptive structures, components in transportations, hand-held tools, electronics, robotics, medical, etc for numerous reasons.

Adaptive structures: Compliant cable technology was developed by National Aeronautics and Space Administration (NASA) Goddard Space Flight Center. In structural connections, these mechanisms provide compliance and dampening. They permit motion in the primary direction and selective motion in other directions. This provides subtle cushioning, twisting and realignment, which allows mating and contact surfaces to conform to each other. The essential functional element-the bending element-of NASA Goddard's compliant mechanism consists of a short cable section. The configuration and material are varied according to the specific application requirements[36]. The bending element is constrained at each end in cantilever fashion (Fig. 6a).

A snap-fit mechanism can be engaged by simply pushing the two counter parts together. However, it is not a favored choice in design for disassembly since it is often difficult to disengage without making any destruction to the components. Li *et al.*[21] have demonstrated the design of reversible snap-fit compliant mechanism, which actuated with localized thermal expansion of materials through time transient heat transfer within the structure.

Compliant mechanical amplifiers are used for piezoelectric actuators to increase effective stroke of the actuator[18,37]. Furthermore, the actuators designed may be used in smart structures applications such as helicopter rotor blade control.

Components in transportations: An aircraft wing based on a compliant mechanism would bend and twist as a single piece to control flight, eliminating separate control surfaces such as ailerons, spoilers and flaps. This, in turn, simplifies construction and yields potentially much higher performance[38]. This design modification provides the following benefits:

* Reduces radar cross-section thereby improving stealth characteristics; Reduces weight and complexity; and Increases aircraft maneuverability.
* Over-running pawl clutches[39,40,41], with or without centrifugal throw out, provide torque in one direction but freewheel in the other. They are used for one- and two-way rotation, as in pull-starts for small engines, bicycle and “Big Wheel®” free wheels, fishing reels, gear drives, winches, conveyors, elevators, counters, collators, feed mechanisms and many other machines[42] (Fig. 6b).
* Centrifugal clutches made as compliant mechanisms eliminate numerous segments, springs, pins, rivets, etc. Flexible segments are designed into the single moving part so that when the hub (driven by a motor) spins the clutch up to speed, centrifugal force causes the heavy segments to engage the drum and drive the machinery. Small and medium horsepower applications include go-karts, mini-bikes, trimmers, tillers, chain saws, chippers, amusement rides, agriculture and industrial machine couplings[43].
* Bicycle brakes of compliant design provide absolute parallel motion, have visual appeal and are preferred by experts for their strength, superior control, even wear and reduced noise[44]. Example is in Fig. 6c.

Hand-held tools: Monolithic stapler helps in simplifying the design for assembly (DFA) and designs for manufacture (DFM) as shown in Fig. 6d[45].

Vibration damping for power tools: Reciprocating tools such as jackhammers, rivet guns and hammer drills can cause repetitive motion injuries such as nerve damage and carpal tunnel syndrome. The vibration transmitted from the tool while it is operating causes the damage. Cable compliance technology can effectively reduce this vibration through shock isolation. Because it is small this NASA technology can also be applied to hand tools[36].

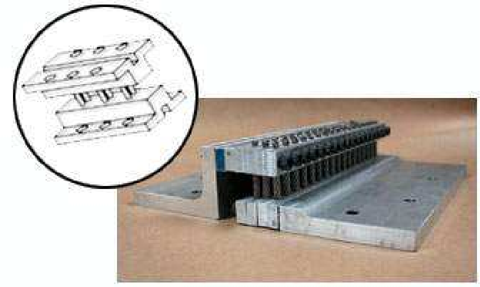
Electric and electronic (EE): Microelectromechanical Systems (MEMS) are small, compliant devices for mechanical and electrical applications. MEMS are fabricated using techniques developed for the production of computer chips. Most MEMS devices are barely visible to the human eye with many features 1/50 the diameter of a human hair. However, they can perform micromanipulation tasks by converting thermal, electrostatic, mechanical, optical, electromagnetic or electrical energy to some form of controlled motion. Examples of MEMS application are medical instruments for in-body surgery, hearing aids, air-bag sensors, micro pumps and optics and tilting mirrors for projection devices[7].

Near-constant-force (NCF) electrical connectors use compliant technology to maintain constant connection between electrical connections over long periods of time. The majority of computer hardware and automotive electrical problems arise from faulty electrical contact integrity. The NCF electrical connector improves connections and reliability[43].

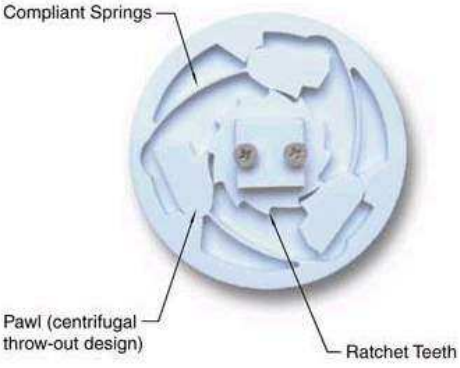
Bistable (2-position) mechanisms move between two stable conditions (Open and Close positions, as in Fig. 6e) and are useful as switches, circuit breakers, clamps, snap hinges, closures, positioning devices, etc. Though they require external force to move from position 1 to 2, no holding energy is required to remain in either position. Plastic prototypes have exceeded a million cycles in durability tests[43].

Robotics: NCF compression mechanism use compliant technology to achieve near-constant pressure with a deviation of only 2% in the compression forces. Several configurations have been designed to work over a range of travel patterns. No NCF compression mechanism is known on the market yet, so the opportunities are great. Uses of NCF compression mechanisms might include fitness products, robot end effectors, tool holder, motor brush holder, wear test apparatus and safety devices[43].

Medical: Joint prosthesis: Prosthetic devices are typically expensive and short-lived and only the most expensive provide “human-like” response. The compliant joint provides resistance similar to a human limb because of its nonlinear nature: as the cable in the joint bends the stiffness increases whereas standard mechanical devices have constant stiffness[47]. Figure 6f presents the compliant technology applied to a knee joint.



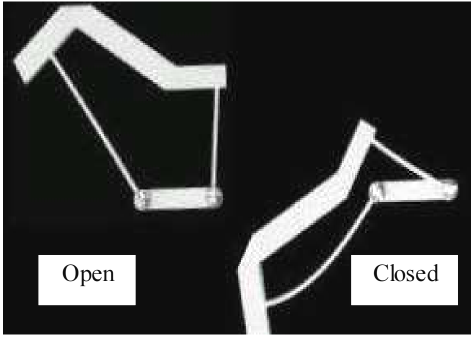
(a)



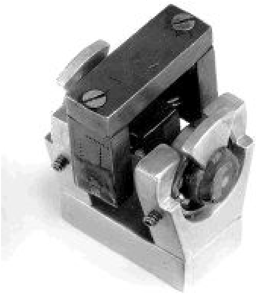
(b)

(c)

(d)



(e)



(f)

Fig. 6: (a) Compliant cable technology[36], (b) Over-running pawl clutches[42], (c) Bicycle brakes[44], (d) The number of separated parts in previous stapler (right) monolithic stapler (left)[45], (e) Bistable (2- position) mechanisms[46] and (f) 2-Knee-joint engineering prototype[47]

1. Physical therapy: A walker that uses NASA‘s cable compliance technology enables patients with limited use of their legs and lower backs to be supported for walking therapy[47].
2. Compliant end-effector[48] and piezoelectric actuator[49] for Minimally Invasive Surgery (MIS): A new compliant suture needle grasper has been designed for use in (MIS) procedures. This design eases the sterilization over current MIS tool designs.

3. Compliant mechanisms must tolerate between flexibility and stiffness: In compliant mechanism, adequate flexibility is essential to afford the required displacement at the point of interest. But in the same time, a compliant mechanism should be stiff enough to be able to sustain external forces. Thus, there are two complementary design objectives to be met simultaneously when designing a compliant mechanism i.e. flexibility and stiffness. For a compliant mechanism with additional flexibility may not uphold large external force otherwise too stiff will limit its displacement. Hence, an optimum balance between these two requirements is required in the synthesis of compliant mechanisms[16].

Geometrical nonlinear: When considering nonlinear displacements in topology optimisation, there are lot of problems and possibilities arises. The problems may consist in the finite element modelling, buckling behavior and the need for introducing additional constraints to present ill behavior and the new possibilities may include path-generating mechanism. Elements stiffness matrices for low-density elements become excessively distorted resulting in negative definite stiffness matrices[50].

Fabrication

Micro fabrication: Fabrication of microstructures can be done using silicon surface micromachining in thin-film materials. Currently, two-dimensional (2-D) fabrication procedures are well developed, but effort is devoted to the development of fabrication methods for two-and-a-half and fully three-dimensional (3-D) micro mechanisms[5]. However, there are relatively few "of those machines existing in the world to fabricate MEMS in the quantities that are needed[51]."

Macro fabrication: Using traditional machining methods to fabricate the flexible members of compliant mechanisms give a lot of challenges. But, since many new methods of fabrication have been developed recently, such as the use of 3-axis computer numeric controlled (CNC) milling, laser cutting, wire electrical discharge machining (EDM), abrasive water jet and rapid prototyping which make it possible to develop a prototype of compliant mechanisms[4]. However, in each of those methods, there is still having a limitation either from the machine itself or the material that will be used. Therefore, before proceeding into the drawing and machining phase, it is important to familiarize with the machine and material. For an instance, care must taken to ensure that there is enough space for the cutter to pass through the mechanisms or to design a mechanism with possible minimum radii and thickness that can be cut[4].

Fatigue failure analysis: For some compliant structures the desired motion may occur once and the static failure theory may be enough for analysis. But for compliant mechanisms, usually, it is desired that the mechanism be capable of undergoing the motion many times and design requirements may be many million of cycles or "infinite" life[3]. Premature or unexpected failure in the device can result in unsafe design, or it may reduce consumer confidence in products that fail prematurely. Hence, for these reasons it is critical that the fatigue life of a compliant mechanism be analyzed and determined experimentally. However, to the author's knowledge, there are too little of previous results on analysis of fatigue failure in the compliant mechanisms.

Biomechanics: Biomechanics is the area that specializes in cardiovascular, orthopaedic, rehabilitation engineering and simulation. There are plenty of potential devices which can be simplified into single-piece component such as joint at knee, hip, pelvic etc. or to make the components to be more compliance with the natural flow of blood such as artificial heart valve.

MEMS: As the future application of MEMSs, researchers are developing techniques to store information by moving atoms from one position to another on a microchip. In this way, it will be possible to store information that currently requires a large hard disk on a few square millimetres storage device. Thus, jobs such as reading and writing from this small area will be done by a miniature robot arm[17].

CONCLUSION

Compliant mechanisms have made an enormous contribution in the design process of various fields such as for adaptive structures, components in transportations, hand-held tools, electronics, medical, etc. The use of compliant mechanisms will help in reducing the number of components which therefore decrease manufacturing cost and additionally increase the performance. However, due to fundamental difference from conventional mechanisms, the methods used while designing rigid-link mechanisms are inadequate for the design of compliant mechanisms. Hence, lots of researches have been carried out to overcome these problems by using and introducing numerous techniques. In future, there should be the analysis of fatigue failure to prevent premature failure in the device. Besides, the implementation of compliant mechanisms in important areas such as in biomechanics, MEMS, sensors and aerospace will be assumed to be more interesting in future agenda.

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