Applications of compliant mechanism in today’s world – A review

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Abstract. In the world of globalization & competitive market there is demand of alternative designs with improved quality, economy & safety. Emerging designs of compliant mechanisms making noticeable contribution to economize cost of production. Compliant mechanism derives their mobility through deflection of flexible members opposite to the conventional rigid body mechanism. The integration of functions into fewer parts, compliant mechanisms offer significant advantages such as fewer parts, less wear, noise & backlash. Researchers expects this field will grow enormously due to advances in the compliant mechanism theory, development of materials with superior quality & advancement in 3D printing technology in the recent years. Recently many familiar examples of compliant mechanism are used in transportation, aerospace, micro-mechanism, biomedical, hand held tools, MEMS & robotics industry. The objective of the current work is to study compliant mechanisms & their applications in various fields communicated by various researchers.

Keywords. Compliant Mechanism, Rigid body mechanism, Product Design, Multimaterial Moulding, Design for manufacturing and assembly, Robotics

1. Introduction

If member of mechanism bends to accomplish something useful or what it meant to do then it can be called as compliant. If the flexibility that allows to bend or to transmit motion, force then it is compliant mechanism

Compliant mechanisms achieve their motion from the relative flexibility of its members opposite to the rigid body [1]. A compliant mechanism can be defined as monolithic flexible structure, which uses elastic deformation to accomplish force and motion transmission [2,3].

A human heart is good example of compliant mechanism which is capable of withstanding billions of cycles without failure. Material properties, geometry, loading and boundary conditions are the three primary ways, influences flexibility of compliant mechanisms or its members. For designing something flexible as well as strong for compliant mechanism it is recommended to have a material with high strength and low young’s modulus [1].

Compliant mechanisms offer advantages over rigid body mechanism such as reducing part count, wear, friction, backlash, weight and eliminate need of lubrication. Though compliant mechanism
offers advantages over traditional mechanisms but challenges are also involved in designing of a compliant mechanism such as simulation of design for motion and force behaviour. As compliant mechanism depends on deflection of flexible members and difficulty increases when deflections are non-linear and their motion cannot be adequately defined through simplified linear equations.

Alternating possible designs, proper material selection and multiple trial and error iterations of finite element methods may require to obtain desired deflection, stiffness & performance of compliant mechanism. The main approaches for designing the compliant mechanisms are

1.1. Rigid Body Synthesis

In which partial compliant mechanism designed through rigid body replacement starting from rigid synthesis results obtained from precision position method.

1.2. Continuum synthesis

Where shape and topology optimization are combined with linear & nonlinear finite element analysis.

1.3. Discrete Synthesis

Where mechanism is represented as network of truss or beam elements so that topological synthesis can be first solved by discrete algorithm then several sizing methods are applied for each enumerated topology [4].

Flexural joints have their own limitations such as low fatigue life, difficulty in fabrication and high stress concentration [25]. For most of the compliant mechanism it is necessary to address issue of fatigue life of flexural pivots as compliant mechanisms derive their motion from bending of flexible parts and they experience high stress concentration at those locations. Proper care & testing is required while designing compliant mechanism to achieve the adequate fatigue life & appearance as consumer may have perception that flexible members are weak. As compared to conventional rigid link mechanism motion of compliant mechanism is limited. Consider example of rigid body shaft and bearing mechanism can undergo continuous revolution whereas compliant components are restricted by their deflection they can achieve within the elastic limit of material [5].

2. Various Compliant Mechanisms Application

In the world of globalization & competitive market there is demand of alternative designs with improved quality, economy & safety. Advances in the compliant mechanism theory, development of materials with superior quality & advancement in 3D printing technology in the recent years, resulted into rapid growth in compliant mechanism applications. Many designs of monolithic or single piece compliant mechanism which replaced rigid body mechanisms used in day to day life applications are as shown in figure 1. Various compliant mechanism application in different industry are communicated below.

![Figure 1. Compliant mechanism applications in day to day life](image-url)
3. Hand Held Tools
L.L Howell, A. Midha [7], presented the methodology for design of compliant plier as shown in figure 2. wherein flexural pivots are very small in length as compared to the rigid links. When input levers are operated by user, force gets amplified at output levers & used to grip the objects. It can be noted that compliant plier is monolithic or need only one-part assembly processes is completely eliminated ultimately simplifies design for manufacturing (DFM) & design for assembly (DFA).

Abdulrahman Ibrahim et. al [8] simulated the model of compliant plier to know the stress, strains & displacement behavior & concluded that amongst various polymer materials ABS was the most suitable material for compliant plier application.

![Figure 2. Compliant plier [27]](image_url)

G.K Ananthasuresh, Laxminarayana Saggere [9], demonstrated design of “A one-piece compliant stapler” which achieved its motion through elastic deformation of flexible members opposite to rigid body motion of traditional mechanism and gives performance as good as conventional one. Figure 3. shows monolithic compliant stapler consists of staple loading slot, the compliant segment which holds staple stack tight, plunger that pushes the staple and two flexure joints are integrated into one injection moldable part. To bend the staples around the paper stack die is integrated on the bottom of rigid beam.

![Figure 3. Compliant stapler [4]](image_url)

Most of the traditional pliers & staplers constructed from metallic parts needs assembly processes, tools, material handling & labor work whereas compliant plier & stapler needs to be manufactured from polymers with injection molding process which completely eliminated the assembly process. Compliant gripper [6], can be used in day to day life & also find application for hair gripper for girls. This design replaced traditional metallic torsional spring & pin with multimaterial beam as shown in figure 4. New types design can be made possible by taking the advantage of multimaterial molding of compliant mechanism but it should be noted that multimaterial molding processes has its own benefits & limitations [24]. Additional cost required for special equipment & processes in multimaterial molding can affect the final cost of product.
4. Biomechanics & Robotics

Pietro Bilancia et. al [10] reported about bio inspired compliant wrist, whose mobility has been achieved by employing two pairs of contact aided cross axial flexural pivots (CAFP) actuated via remotely placed servo motor & tendon transmission. The proposed device achieves motion capabilities via the deflection of two pairs of CAFPs. Figure 5. shows design of compliant wrist.

There are plenty of other application in the field of biomechanics can be manufactured from single piece such as robotic finger. Many problems exist with majority of fingers with conventional rigid links such as lack of adaptability & this problem solved by design of a fully compliant under actuated prosthetic finger. Authors claimed compliant finger shown in figure 6. have promising characteristics such as under-actuated, one-piece structure, small single actuation force, lightweight and adaptable. Compliant mechanisms have great potential for further development in the field of prosthetics, robotics and grasper [11].
Dong Il Park et. al [12] proposed a new type of the passive compliant device shown in figure 7, which can measure its deformation, composed of the passive compliance module, the gripping module, the displacement measurement module and the controller module. Proposed device and the proposed assembly strategy are proved to be very useful for automatic assembly of the precision parts.

Electric & Electronics

Bistable mechanism have two stable position within their motion range, which is necessary part for the variety of applications such as switches, closure valves, circuit breakers & clasps. External energy requires to move from position 1 to position 2 but holding energy requires to keep the mechanism in either positions. It can be observed that compliant bistable switch shown in figure 8, is consists of only one part which reduces the complexity and cost of assembly. Authors used mechanism synthesis technique to retain the aesthetics and feel of traditional light switch for the consumer market [13].
6. MEMS (Micro Electro Mechanical Systems)
In the design of micromechanical structures for MEMS application compliant mechanisms play an important role. To perform complex mechanical functions monolithic mechanical structures can be designed with the help of compliant mechanism theory & these structures can be fabricated within the restrictions of micromachining processes [25].

Shannon A. Zirbel et. Al [15] described a fully compliant constant-force micromechanism that enables dual-stage motion for Nano injection. Together with this dual-stage motion, the device exploits the advantages of compliant mechanisms and constant-force mechanisms on the micro-scale to perform the complex motion required to introduce DNA into mouse zygotes [24].

7. Aerospace
Zeng W. et.al. [15] disclosed compliant variable diameter mechanism shown in figure 9. useful in variable diameter wheels. Mechanism proposed by authors allows the rover wheels to transforms its structure using contraction expansion-retraction motion & gives excellent running performance to it. It is claimed by the authors that compliant variable diameter mechanism prevents backlash, wear, need of lubrication, simplifies assembly, makes mechanism more lightweight as well as compact compared to the conventional rigid body mechanism hence this compliant variable diameter mechanism useful for creating variable diameter wheels for the application of lunar rover.

M.S Parancheervilakkathil et. al [16] disclosed compliant polymorphing wing (figure 10) for small UAV’s capable of cord & camber morphing. The result of aerodynamic analysis showed compliant cord morphing & camber morphing improved the aerodynamic efficiency.
R. M. Fowler et. al [17] proposed to merge of the fields of compliant mechanisms and space mechanisms as a future direction of research in compliant mechanisms & addressed the key factors of applying compliant mechanism technology to space mechanisms.

For the space applications like switches relays or latches compliant mechanism proposed by Zirbel S. A et. al [18]. Compliant mechanism proposed by authors improve reliability, precision & eliminates friction. Disclosed bistable mechanism could also be employed as non-explosive release mechanisms. Camera covers, deployable structures, launch locks, maximum load sensors, force sensors and shutter mechanism are the flight applications for compliant mechanism.

8. Transportation

Roach G. M. et. al [19] compared compliant overrunning clutch to traditional overrunning clutch. Over-running clutches are useful in applications where torque transmission require in only one direction. Over running clutches mainly useful in three common applications: backstop ping, indexing and unidirectional operation [10]. This compliant overrunning clutch shown in figure 11 can reduce cost of manufacturing, assembly & material handling. To manufacture the compliant overrunning clutch, polymer remain attractive choice because of their inexpensiveness & can be mass manufactured using methods like injection moulding. But one of the limitation of polymers is loss of strength. For the compliant over running clutch, Polypropylene material used by authors.

Brian M. Olsen et. Al [20] developed design of compliant road bicycle brake (figure 12) through rigid body replacement synthesis & type synthesis which has performance in line with conventional brake. It is claimed that proposed compliant bicycle brake has potential to reduce the weight &
assembly by eliminating accessory components. The weight reduction potential comes from the elimination of material by removing the cam and cam follower surface of the benchmark.

![Compliant bicycle brake](image)

**Figure 12. Compliant bicycle brake [20]**

9. **Adaptive Structures**

K.W.A. Schreurs et. al [21] presented a design of compliant Shape preserving mechanism shown in figure 13. which essentially acts as sealing mechanism, compliant gripper or it can be used in medical applications. Shape preserving mechanism are expanding mechanism & maintain its shape upon expansion. It is claimed that presented design of shape preserving mechanisms retain their shape up to 99% for their full range of motion. It is disclosed that prototype developed from material PETG (Polyethylene Terephthalate Glycol-modified). Compliant mechanical amplifiers are used for piezoelectric actuators to increase effective stroke of the actuator [22,23].

![Top views compliant shape preserving ring in the three sequential state of expansion](image)

**Figure 13. Top views compliant shape preserving ring in the three sequential state of expansion [21]**

10. **Findings of The Study**

- The Compliant mechanisms are making notable contribution to the design of various fields such as transportation, aerospace, robotics, biomedical, MEMS etc.
- A review of most used compliant mechanism shows that they offer many benefits such as simplify manufacturing, reduce weight, assembly time, eliminate wear, noise, backlash and need of lubrication
- Compliant mechanism can integrate design to eliminate assembly by integrating springs, fulcrum pins, into one piece which leads to reduction in manufacturing cost & material handling cost.
A close review of compliant mechanism design shows that, they can be used where limited degree of motion or small displacements are involved & it is a limitation of a compliant mechanism.

Since many compliant mechanisms undergo large deflection and linear differential equation may not be valid & nonlinear equation may need to be used to account geometric non linearity caused by large deflection.

New types design can be made possible by taking the advantage of multimaterial moulding of compliant mechanism but it should be noted that multimaterial mouldings processes has its own benefits & limitations. Additional cost required for special equipment & processes in multimaterial moulding can affect the final cost of product.

For most of the compliant mechanism it is necessary to address issue of fatigue life of flexural pivots as compliant mechanisms derive their motion from bending of flexible parts and they experience high stress concentration at those locations.

Constraining motion of compliant mechanisms in desired direction or range is very important, unconstrained motion may lead to loss of function ability or failure of compliant member of mechanism.

When flexible components are visible to consumers this can be area of concern for designer because consumers may have perception that flexible components are weak or flimsy. Compliant mechanism requires special care while designing for their aesthetics & to achieve adequate life.

Acknowledgement.
Authors are grateful to Mechanical Engineering Department of Walchand Institute of Technology, Solapur & College of Engineering Pune, for the support.

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