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# Design and Analysis of Compliant Mechanism using Topology

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***Abstract- This study focuses on the design and analysis of compliant mechanisms using topology optimization techniques. Compliant mechanisms, known for their flexibility and lack of traditional joints, offer advantages in various engineering applications. Through topology optimization, we aim to enhance the performance of these mechanisms by systematically redistributing material to achieve optimal structural layouts. The study employs finite element analysis and optimization algorithms to explore efficient designs that exhibit desired mechanical behaviours. The outcomes provide insights into the potential for improved compliant mechanism performance, offering valuable contributions to the field of innovative and optimized mechanical systems.***

**Key Words : Compliant Mechanism. Topology, Optimization, Flexibility, Finite Element Analysis**

## 1.0 Introduction

The concept of using flexible members to store energy and createmotion has been used for millennia. Archaeological evidence suggests that bows have been in use since before 8000 B.C. and was the primary weapon and hunting tool in the most cultures. Such a longbow is illustrated in Figure 1.1. Early bows were constructed of relatively flexible material such as wood and animal sinew. Strain energy in the bow is transformed to kinetic energy of the arrow.

Catapults serve as an early example of compliant members employed by the Greeks dating back to the fourth century B.C. These early catapults utilized wooden components that underwent deflection to store and subsequently release energy, propelling projectiles. Compliant members have historically simulated turning joint motion, exemplified by the flexural hinges of book covers, achieved through altering material composition and thickness at specific flexure points. Methods such as the single-axis cross flexure pivot emerged in the early twentieth century for similar applications. The utilization of living hinges, especially in injection-molded plastics, became prominent, contributing significantly to various product designs. Flexible members also found extensive applications in measurement, illustrated by Bourdon tubes in pressure gauges. The proliferation of products relying on flexible members for functionality has substantially increased in recent decades, thanks in part to the development of stronger and more reliable materials.

The use of compliant mechanisms will probably continue to increase with time as materials and design methodologies are on focus. The demand for increased product quality and decreased cost also pressurizes manufacturers to use compliant mechanisms. A flexible structure that elastically deforms without joints toproduce a desired force or displacement.

**Compliant Mechanism and its Nature:**Humans and nature often hold divergent perspectives on mechanical design. While humans typically favour stiff structures, associating stiffness with strength, nature exhibits a different philosophy. Although humans often construct devices with multiple stiff components for motion, stiffness and strength are distinct attributes. Stiffness measures deflection under load, whereas strength gauges the load-bearing capacity before failure

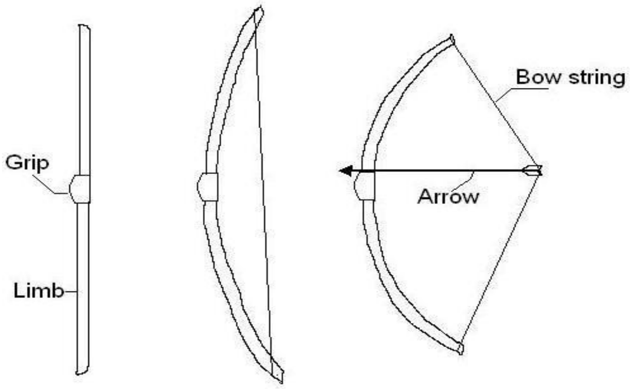


**Figure 1 Longbow in its unstrung, strung, and drawn positions**

. Despite human inclinations, it is feasible to create objects that are both flexible and robust. In nature, stiff structures like tree trunks and bones are used strategically, but living organisms frequently leverage flexibility. Examples include bee wings, bird wings, tree branches, leaf stems, and the adaptive compliance observed in fish and single-celled organisms.

## 2, Literature Review:

A literature review is a critical and comprehensive analysis of existing scholarly literature, research studies, and other relevant sources on a specific topic or research question. It serves to provide an overview and synthesis of the current state of knowledge in a particular field, helping researchers and scholars understand the existing literature's key findings, methodologies, and gaps. A literature review is not merely a summary of individual studies but involves an evaluative process that identifies patterns, trends, contradictions, and areas where further research is needed. It plays a crucial role in shaping the context for new research and contributing to the theoretical framework of a study. Literature reviews are common in academic research papers, theses, dissertations, and scholarly articles.

**JunwenLiyanget. al. (2023)**This article introduces a modified evolutionary topology optimization method for designing compliant constant force mechanisms (CFMs). The method focuses on maintaining a constant force range by adjusting design variables incrementally, addressing nonlinearity with an additive hyper elasticity technique. Numerical examples demonstrate the effectiveness, and 3D-printed prototypes validate the constant force output with minimal variation (less than 2%) across a substantial force range (56.7%).[1]

**Kaixian Liang et.al. (2023)**This paper introduces a macro-microscale topology optimization method for deterministic compliant mechanism design. The macroscopic level utilizes the flexibility matrix and an Augmented Lagrangian approach, while the microscopic level refines individual microstructures for specific mechanical properties. The method allows for the creation of compliant mechanisms with desired characteristics. Numerical examples validate the approach, offering a solution for quantitative design of compliant mechanism properties, applicable to various fields.[2]

**S. Premanand et.al (2022)**This research explores general topology optimization for a rectangular domain, applicable to diverse mechanical systems like four-bar mechanisms, robotics, and aircraft engineering. The study emphasizes stress analysis, safety factor, output deflection, and mass reduction. It compares different materials for optimal volume and mass reduction, with potential applications in various robotic devices. Future work includes experimental validation and endurance testing of the topology-optimized device under static and dynamic conditions.[3]

**Shuang Zhanget. al. (2022)**This study introduces a novel compliant mechanism with RPR degrees of freedom (rotation, translation, universal pairs). Derived from dimension synthesizing a 2-RPU-UPR rigid parallel mechanism, optimization is applied for motion/force transfer characteristics. The design involves inverse kinematics, Jacobian matrix analysis, and optimization of flexure joints. A compliant model is obtained by replacing rigid elements, and FEA simulation validates DOF and design effectiveness, with a focus on suppressing rotation axis drift through motion/force transfer characteristic optimization.[4]

**Jincheng and Huaping Tang (2021)**This paper introduces a stiffness-oriented topology optimization method for designing continuous, hinge-free compliant mechanisms. The approach maximizes the mechanism's mutual potential energy to achieve flexibility while emphasizing desired stiffness in a specified direction. Unlike general methods, this approach focuses on guiding the optimization process by weighting eigen-frequencies, allowing for effective use of material in micro-level compliant mechanism designs. The method addresses and prevents the occurrence of single-node connected hinges in optimized designs, demonstrating validity and robustness in obtaining hinge-free compliant mechanisms.[5]

**Nadim Diab and Farah Jouni (2021)**This study focuses on designing miniature compliant displacement amplifiers using Ant Colony Optimization in topology optimization of two-node frame elements. Stiffness matrices considering varying cross-section dimensions are formulated, and design variables (width, thickness, and material density) are optimized. Three case studies prioritize amplification ratio, output displacement, and a combination of both. The resulting micro-compliant amplifiers outperform constant cross-section counterparts in compactness, amplification ratio, and output displacement with low internal stresses, verified through ANSYS.[6]

**Behzad Majdi et.al (2020)**This study employs the SIMP approach for topology optimization of multi-material compliant mechanisms, specifically gripper, invertor, and cruncher designs. The alternating active-phase algorithm is used to determine material distribution, addressing the multiphase topology optimization problem. Validation against ANSYS Workbench finite element simulations demonstrates the accuracy of the SIMP method in optimizing multi-material compliant mechanisms.[7]

**Chih-Hsing Liuet. al. (2020)**This study introduces an optimal design procedure, integrating topology and geometry optimization, for a compliant constant-force mechanism. The mechanism aims to produce a consistent output force across various input displacements, serving applications like precision manipulation and overload protection. Material and geometric nonlinearities are considered in the optimization process. To address manufacturing challenges posed by low-stiffness elements, a helical compression spring is introduced and optimized. The prototype, 3D-printed using flexible thermoplastic elastomer, demonstrates a nearly constant output force in the 3–6 mm input displacement range. The mechanism is successfully applied in a robotic picking and placing application for handling size-varied fragile objects.[8]

**Lin Cao et. al. (2019)**This paper proposes a topology optimization framework to design compliant mechanisms with a mixed mesh of both beams and flexure hinges for the design domain. Further, a new type of finite element, i.e., super flexure hinge element, was developed to model flexure hinges. Then, an investigation into the effects of the location and size of a flexure hinge in a compliant lever explains why the point-flexure problem often occurs in the resulting design via topology optimization. Two design examples were presented to verify the proposed technique. The effects of link widths and hinge radii were also investigated. The results demonstrated that the proposed meshing scheme and topology optimization technique facilitate the rational decision on the locations and sizes of beams and flexure hinges in compliant mechanisms.[9]

**Deepak Sharma et. al. (2019)**This study introduces a methodology for evolving multiple topologies of compliant mechanisms that generate user-defined paths. The objective is to minimize weight and input energy simultaneously, achieving functional compliance by imposing constraints on precision points. The optimization formulation ensures adherence to the prescribed path with a user-defined allowable deviation parameter. Sensitivity analysis is conducted for different deviation values. The customized evolutionary algorithm (NSGA-II) efficiently addresses the constraint bi-objective, non-linear, and discrete nature of the problem. Non-dominated solutions are refined through a binary-variable-based local search. This work provides designers with insights into topological changes and the flexibility to choose compliant mechanism designs from the non-dominated set of solutions.[10]

**Sonali S. Patil et. al. (2017)**In precision engineering, biomechanics, MEMS, and nanotechnology, special standards are vital for drive and motion systems. Backlash is a significant issue in high-precision positioning stages using conventional rigid body mechanisms at the micro- scale. Compliant mechanisms offer advantages by utilizing elastic deformation for force and motion transmission, eliminating problems like wear, lubrication, and backlash associated with rigid body mechanisms.

This research explores the use of compliant mechanisms in linear displacement applications, optimizing the mechanism's topology and calculating total deformation with ANSYS software. Experimental validation confirms the effectiveness of the compliant retractor mechanism in addressing precision positioning challenges.[11]

## 2,1Objective of Research Work:

- Topology Optimization
- Increasing the Performance Enhancement
- Innovative Material Utilizations

## 3, Material and Methodology:

This methodology provides a structured and iterative approach to designing compliant mechanisms using topology optimization, ensuring a balance between theoretical insights, simulation accuracy, and real-world applicability.Conduct a comprehensive review of existing literature on compliant mechanisms, topology optimization methods, and related design approaches. Identify key challenges, recent advancements, and established methodologies in compliant mechanism design.Clearly define the design objectives, considering factors such as desired mechanical characteristics, application-specific requirements, and constraints.Utilize topology optimization techniques to systematically redistribute material within the compliant mechanism. Apply optimization algorithms to achieve optimal structural layouts that meet predefined design objectives. Create a detailed 3D model of the compliant mechanism using CAD software. Integrate the optimized topology into finite element analysis (FEA) software to simulate the mechanical behaviours under various loading conditions. Explore the use of different materials suitable for compliant mechanisms, considering factors like elasticity, durability, and manufacturing feasibility. Optimize material selection to enhance the overall performance of the compliant mechanism.Perform experimental tests on the prototypes to validate the compliance, stiffness, and other mechanical characteristics. Gather data on actual performance and compare it with simulation and optimization results.

## 4. Result and Discussion:

The compliant mechanism has been designed bytopology optimization with rectangular geometry as the basic geometry. the work has been extended to taper and hexagonal basic geometries. In these studies, for the given input conditions, maximizing the GA and MA have been kept as the objectives.

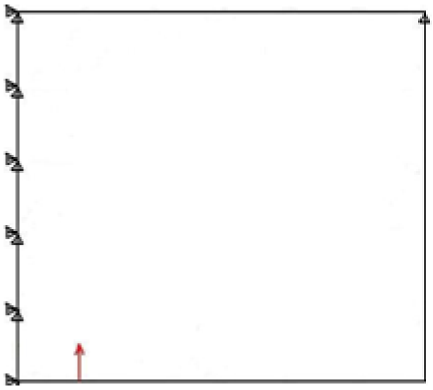
However, in many real-life applications, we need to obtain a specified output displacement at a given location for the given input conditions. Such an attempt has been attempted in this chapter. Using ANSYS, such a study can be done using a trial-and-error approach.

**Table-1 Input conditions for the rectangular design domain**

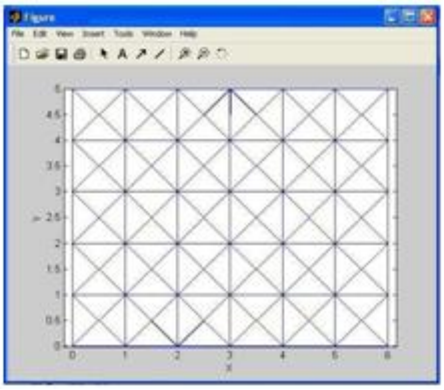
| | |
|---|---|
| Maximum Input force from PZT | 10 N |
| Upper limit of design variable<br>(Cross sectional area of the element) | 25 $mm^2$ |
| Lower limit of design variable<br>(Cross sectional area of the element) | 0.1 $mm^2$ |

**Table-2 Problem specifications for the rectangular design domain**

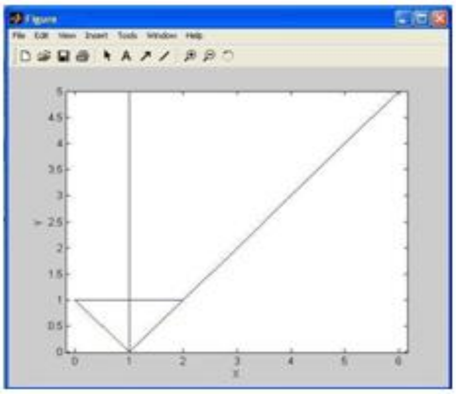
| | |
|---|---|
| Basic design domain (Rectangular domain) | 600 mm u 500 mm |
| Young's modulus | 200 GPa |
| Poisson's ratio | 0.30 |
| Maximum input force | 10 N |
| Upper limit of design variable | 25 $mm^2$ |
| Lower Limit of design variable | 0.1 $mm^2$ |
| Output displacement at output port | 8.0 mm |



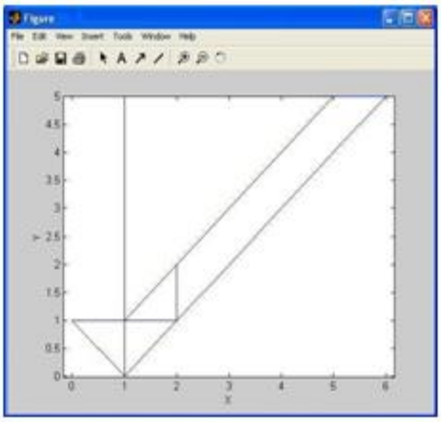
**(a) Design domain**



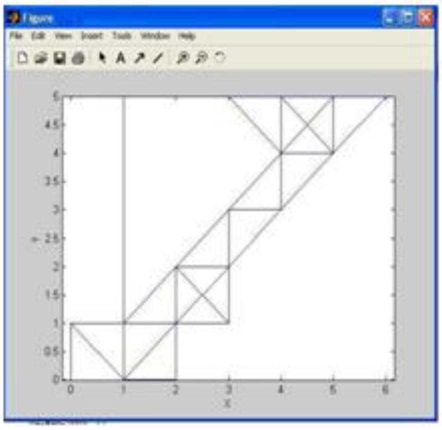
**(b) Meshed design domain**



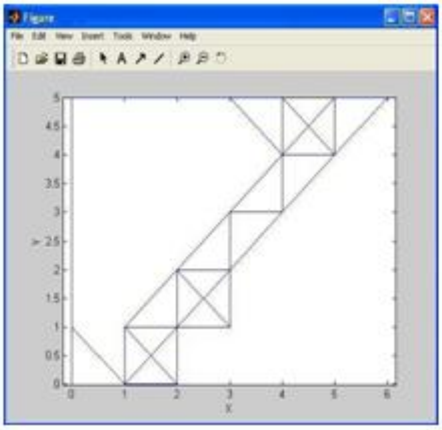
**(c) Topology after 20 iterations**



(d) Topology after 40 iterations



(e) Topology after 60 iterations



(f) Topology after 80 iterations

## 5. Conclusions:

- The input location that gives highest displacement by keeping other conditions constant is $X_i$ = 0.5 for the rectangular and hexagonal geometries and is 0.55 with taper geometry. At these input locations the GA and MA obtained are also the highest.
- Keeping all other conditions constant, the output locations $X_0$ = 0.5, 0.5, and 0.55 give the highest displacement for rectangular, hexagonal and taper geometries respectively.
- With the increase in input force, the output displacements increase almost linearly for the three geometries. However, the rate of increase is lowest with hexagonal geometry, moderate for rectangular geometry and highest for taper geometry.
- With the increase in aspect ratio of the rectangular and taper domains, output displacement increases. However, the magnitudes of displacements are higher for the taper domain when compared to the rectangular one.
- With the increase in thickness of the compliant mechanism, steep reduction in output displacements is noticed for all the three domains.

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