Synthesis and Numerical Analysis of Compliant devices – A Topology Optimization Approach for Mechanisms and Robotic Systems

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Synthesis and Numerical Analysis of Compliant devices – A Topology Optimization Approach for Mechanisms and Robotic Systems

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ABSTRACT

The Topology Optimization design invariably shall be used in various applications like Mechanism and Robotics designs, Aircraft Engineering designs and innovative systems for improving the efficiency of structure. The paper emphasizes more on general Topology Optimization design for a rectangular domain. The domain numerically analyzed with defined geometry setting and defined boundary conditions for finding the Stress and displacement. In this Topology Optimization Design synthesis, the result is suitable volume and mass reduction in the Mechanism and Robotics application parts which further can be taken for Prototype development in 3D printing and experimentally test with safety characteristics and compares Objective functions chosen for design and development. The design can be used for other various automotive and aerospace devices based on deformation level and application of external forces. The Final destination of this design and development ends with passing Fatigue Endurance test cycle test pass condition in Mechanism and Robotic functions in static and dynamic state.

KEYWORDS Topology Optimization methods, Mass Reduction, Compliant Mechanism and Robotics Devices, Design Synthesis, Numerical Analysis.

INTRODUCTION

In the Automotive and Mechanism and Robotics applications Parts, we normally design and adapt for Rigid body mechanisms to achieve greater Fatigue strength and Shelf Life. But Recent design of engineers thought process of reduction of excess mass in all constructive Mechanism and Robotics assembly parts to Improve vehicle efficiency without compromising the safety. In current trend the combinations and comparisons of various materials comes in to picture during design synthesis like Rigid bodies, Flexural devices, reinforce structures with combination of metals and non-metals, Realization of flexible components added in all Mechanism designs of Automotive and Mechanism and Robotics applications, minimizing the joints and links is challenging perspective in design synthesis for Assembly components. Elastoplastic behavior design (Figure 1.0) is chosen for mechanical motion parts design is trending mechanism for précised motions and Accuracy.

As per Shinji nishiwaki et al, Stiffness Structures with allowable deformation design gives better performance, hence they took Optimal compliance is taken as an Objective function [1].

The Kinematic synthesis design is successful in applications because it has combination of both Rigid body Mechanisms and Compliant mechanisms composed of flexible pivots through PRBD models developed by Kyler A. Tolman and Howell [2]
The General Compliant mechanism design involves mainly for mass minimization in Mechanism and Robotics vehicles to improve the vehicle performance. Topology Optimization methods adopted for various components or assembly in tedious shape with reduced parts combined to form as a single continuum part with low risk in design synthesis [5].

Compliance in joints of robot gripper will lead to accuracy in pick and place of objects. Compliance in grippers will reduce contact forces acting on it. Maximize the Stiffness by distributing material available on stress affecting zones is the Primary Objective Function of Topology Optimization. The Optimization techniques decide amount of material and where it gets distributed. Primary Goals to achieve through the Topology Optimization is Maximum stiffness with mass reduction and balance the goals to achieve Optimal solution in Parts design [4].

The Topology optimization and its constraints to develop the part in 3D printing technologies and various methods of constraining topology optimization to obtain superior part functionality with Optimum cost is the current expectations in Mechanism and Robotics Industry. Whereas production vehicles require their components to be less cost with production in large scales, The Car performance is rated through its fuel efficiency and in which the components lesser mass is directly proportionate to that car’s performance[5].

The Motivation for design of Compliant devices in Mechanism and Robotics parts continues from previous research and success on converting Compliant Centrifugal Clutches, Compliant tweels (Tyre and wheel), Compliant Mechanical Brakes and Bicycle, In Compliant Mechanisms designs the Continuum synthesis approach is used here for design of Distributed Compliant mechanism which is purely based on Topology Optimization for structures. In this method the errors are minimized to achieve Geometrical and Mechanical advantage. In this Optimality criteria is based on finding suitable criteria for specialized design conditions and developing iterative procedure to find optimum design. Also, Less Objective Function subjected to Constraints and Convergence is quick compared to Other Optimization methods [6,7].

In many situations the Reverse engineering process is carried out for Study of various Mechanism and Robotics parts for example the Car wiper parts are converted as an Optimized Compliant Wiper through Topology Optimization to get Optimum Compliant design. The final design enables a significant weight reduction 20% obtained. The weight reduction is associated with material economy, coupled with reduced energy consumption in the manufacturing stages, and as a secondary consequence, a significant reduction in fuel consumption of the car [8].

The mass of Engine bracket support topology is Optimally designed and which resulted in effective lowering the mass of engine bracket support of nearly 20% (1243gms→989gms) and NVH result of Natural frequency reduction of 10% (1024Hz→1122Hz), ultimately made the Passenger Comfort [9].

Compliant mechanism-based rotation pointing mechanism is designed with 2 (DOF). Compliance analysis finds the relationship between the applied load and deflection of the mechanism and has been the focus of many researchers [10].

The Motor cycle piston is taken for analysis to reduce the mass by Topology Optimization and Maximize the Stiffness by distributing material available on stress affecting zones is the Primary Objective and Function of Topology Optimization. Topology Optimization is Maximum stiffness with mass reduction and balance the goals to achieve Optimal solution in Parts design. SIMP (Solid Isotropic material with Penalization) is one of the methods to achieve the maximum stiffness with proper material distribution process in Material [11]. Elastoplastic behavior is chosen for mechanical motion parts design is trending mechanism for précised motions and accuracy. Polymers with high fatigue resistance material like Delrin for application requires many Loading cycles [12]. Normality in design involves the property of material which does not deform easily and avoid wear out in all conditions and there is a conflict between two attributes (Flexibility and Stiffness [14]. many of macro and micro-Manipulator design, Single Compliant crank design with Multiple degrees of freedom used in Pumps and Compressors applications parts are analyzed in FEA and design optimized to achieve compliance and accuracy in Manipulator’s displacement [15,16]. Kinetostatic behavior in should be taken into account of design of desired application in which the force on an elastic object causes specific displacement [17].
TOPOLOGY OPTIMIZATION OF RECTANGULAR DOMAIN

The Boundary conditions of a rectangular domain is as shown in Figure 2. Topology optimization can be implemented through the use of finite element methods for the analysis and optimization techniques based on following methods as follows.

Topology Generation - Stress and Material Distribution

The below figures show the topology generation of general domain taken for analysis which is slowly distributed after various Iterations (Figure 3), and final Topology optimized design shows optimum material distribution in blue zones and material voids in red zones (Figure 3).

Figure 3. Stress Distribution after Multiple Iterations

Figure 4. Final Stress Distribution Plot
Objective Functions:

| Total elastic strain energy (J) | Mass Minimization | Output Displacement |
|--------------------------------|-------------------|---------------------|
| 27.682                         | 50%               | 0.066m              |

Table 1 Objective functions

The above table elucidates the Increase in compliance and mass minimizations is achieved through increased strain energy in the rectangular domain (Table 1) the same procedure will be adopted and numerically analyzed in all three following Mechanism and Robotics components.

![Objective function Vs Iteration numbers](image)

**Figure 5. Volume reduction vs Iterations**

**TOPOLOGY OPTIMIZATION DESIGN APPLICATION DEVICES**

Based on General Topology Optimization procedure (Figure 1 to 4) the rectangular domain is optimized and Objective functions also achieved mainly the optimum strain energy with mass minimization (Table 1). Also the volume reduction is converged quickly in components within minimum Iterations (Figure 5).

The major mechanical properties required for the above application are, high in flexibility, strength, durability, fatigue resistance and excellent abrasion resistance hence three materials are chosen for its characteristic study and synthesis. Hence some of the Application parts like L-Seat Plate, Clutch Clamp support plates. Hence Objective Function the Mass minimization with Optimum compliance is considered for taken Mechanism and Robotics devices.

Case – 1: The Numerical Analysis on L-Seat Plate in both Steel and ABS Plastics to find the Objective function after Centric Load application in Domain and Topology Optimization.
The above pictorial images are 2D L-Plate with Solid and Topology Optimized Views, After Optimization we found the mass minimization around 60% from original mass (Table-2).

The Linear Displacement after center force application and corresponding stress and displacement (Figure 6) in both the Materials are analyzed based mass minimization condition (Table-2).

**Figure 6.** Topology Optimized Compliant L-Seat Plate (Mild Steel and ABS Plastics)

The below Tabulation shows the Objective Functions between Steel Optimized Plate and ABS Optimized Plate.

| Description         | Mild Steel                          | ABS Plastic                        |
|---------------------|-------------------------------------|------------------------------------|
| Size                | L-40mm W-60mm H-40mm Thickness: 5 mm| L-40mm W-60mm H-40mm Thickness: 5 mm|
| Mass                | Initial: 0.17 Kg After optimization : 0.071 kg | Initial:0.023 Kg After optimization : 0.009 kg |
| Displacement        | X-Displacement - 0.008mm Y-Displacement – 0.07mm | X-Displacement - 0.75mm Y-Displacement – 8mm |
| Safety factor       | 1.75 min UL                         | 0.17 UL                            |
| Stress              | 118 MPa (Max)                       | 117 MPa (Max)                      |

*Table 2 Objective functions – Steel Plate vs ABS Plastic*
The model design of above L – seat is from the domain of Rectangular domain and in which the solid material is Topology Optimized and voids as shown and stress distribution analyzed numerically in expansion mode (Figure 7).

Case – 2: The Numerical Analysis on Clutch Circular- Clamp Plate in both Steel and ABS Plastics to find the Objective function after Centric Load application in Domain and Topology Optimization (Fig-8)

![C-Clamp Plate - Solid](image1)

![C-Clamp Plate - Topology Optimized](image2)

Figure 8. Topology Optimized Mechanism and Robotics clamp plate Design

The above pictorial images are 2D C Clamp- Plate with Solid and Topology Optimized Views, After Optimization we found the mass minimization around 20% from original mass (Table-3).
The Linear Displacement after center force application and corresponding stress and displacement (Fig-8) in both the Materials are analyzed based mass minimization condition (Table-3)

![Image: Topology Optimized Compliant C-Clamp Plate (Mild Steel and ABS Plastics)]

**Figure 9.** Topology Optimized Compliant C-Clamp Plate (Mild Steel and ABS Plastics)

The below Tabulation shows the C-Clamp Plate Objective Functions between Optimized Steel and ABS Materials

| Description       | Mild Steel                        | ABS Plastic                       |
|-------------------|-----------------------------------|------------------------------------|
| Size              | Diameter (Dia) 1 - 186mm Dia 2 - 126mm Thick-18mm Locating Dia : 44 mm | Dia 1 - 186mm Dia 2 - 126mm Thick-18mm Locating Dia : 44 mm |
| Mass              | Initial: 2.45 Kg                  | Initial: 0.33 Kg                   |
|                   | After optimization: 1.96 kg       | After optimization: 0.26 kg        |
| Displacement      | X-Displacement – 0.000049mm       | X-Displacement - 0.0047mm          |
|                   | Y-Displacement – 0.00032mm        | Y-Displacement – 0.029mm           |
| Safety factor     | 3 min UL                         | 7.27 UL                            |
| Stress            | 2.32 MPa (Max)                    | 2.2 MPa (Max)                      |

**Table 3** Objective functions – Steel Plate vs ABS Plastic
The model design of above C Clamp –Plate is from the domain of Circular domain and in which the solid material is Topology Optimized and voids as shown (Figure 9) and stress distribution analyzed numerically in expansion mode (Figure 10)

**ROBOTIC GRIPPER DEVICES TOPOLOGY OPTIMIZATION:**

The model design of above Gripper Device is from the domain of Trapezium domain and in which the solid material is Topology Optimized and voids as shown (Figure 11) and stress distribution analyzed numerically in expansion mode (Figure 12)
RESULT.

With reference to Figure 5 to 9 and Table 2 and 3 elucidates the three different cases.

Case- 0 Rectangular Domain flexure with maximum deflection where its application is suitable for Support Part in Air jets (Rotors, Disc), Dampers in Cushioning part in Shock absorbers’.

Case- 1 In this condition the L-Seat will deflect inner side due to flexural points in itself with respect to application of external force this can be used in Robotic Gripper applications

Case- 2 Based on specimen mass, reduction clamping clutch plates engagement and disengagement efficiency from clamping position and retain its normal position easily. This can be used in mass clamping and dynamic clutch engagement devices with lesser force applications.

Case- 3 Based on the above 2 cases the Robotic Magnetic Gripper application is Topology Optimized for Considerable volume reduction to handle easily and to achieve accuracy in Pick and Place functions.

All the 3 Cases will Increase the efficiency, Speed and accuracy of the Mechanisms and Robotic Functions by achieving the Considerable mass minimization with acceptable stress load.

DISCUSSION

Topology Optimization and synthesis for general domain and relative applications are analyzed in this paper and based on analysis the surplus volume and mass reduction and in turn efficiency improvement in Mechanism and Robotics devices is fairly possible, Analysis is helpful to Identify the high-stress areas in the compliant devices with various material characteristics to achieve less deformation without fatigue failure. Optimized shape and mechanical advantage of the product is achieved for desirable strength. The desirable volume and mass reduction [Refer Table 2.0] happens with penalization method and following of design synthesis the application parts to be 3D printed through Additive Manufacturing Technology for Compliant flexural Anchor, Compliant gripper and Clutch clamp plate, Further the materialized parts will be experimentally tested and compared with numerical analysis objective functions and relative performance test of characteristics for its stability and rigidity, This formulation and design of topology optimization balances both the compliance and stiffness requirements and withstand the applied Loads in these devices. Future works Numerical analysis comparison of component design with experimental parts testing and part performance under loads. Thus, optimization technology and analysis conducted to achieve desired objective functions without affecting safety.

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DECLARATIONS:

1. ETHICS APPROVAL AND CONSENT TO PARTICIPATE
The Authors Declare that they have no Conflicts of Interest

2. CONSENT FOR PUBLICATION
The Authors Declare that they have no Consent for Publication

3. Conflicts of Interest
The Authors Declare that they have no Conflicts of Interest

4. NOMENCLATURE
   1. L-Length of the Structure
   2. UL - Ultimate Load
   3. Kg-Kilogram,
   4. mm-Millimeter,
   5. Mpa-MegaPascal,
   6. W - Width of the Structure
   7. H – Height of the Structure
   8. Min-Minimum Shear Stress, Equivalent Stress
   9. Max- Maximum Shear Stress, Equivalent Stress
   10. ABS - acrylonitrile butadiene styrene Material
   11. O/P-Output Deflection
   12. 2D- 2Dimensions of the Domains
   13. Fig- Figure of the Stress Diagram

5. AVAILABILITY OF DATA AND MATERIALS
The Data and Materials Used to Find the Research Gaps, Support to Find the Numerical Analysis and Topology Optimization are Included within this Research Article.

COMPETING INTERESTS
Not Applicable

FUNDING
Not Applicable

AUTHORS’ CONTRIBUTIONS
Author -1 – Involved and Contributed in Preparing the Introduction of Compliant devices and Mechanisms, Method of Validation, Analysis of Shear Values comparison with Literatures, Searching relevant references in Literatures and Results discussion and Inference on Research work results.

Author- 2 – Involved and Contributed in General Design Domain development and chosen methods for design and Optimization, Mechanisms Analysis of Shear Values comparison with Literatures, Chosen Components for Topology Analysis.
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In is PhD work his Research activity is in the Field of Mechanical Engineering, Mainly Research scope covers Design and Topology Optimization of Automotive field parts in which identifying and converting Rigid Body Mechanisms in into compliant mechanisms to Improve overall Vehicle efficiency, Reduction of no of Parts and mainly to achieve Mechanical and Geometric advantage on changing to Compliant devices instead of rigid bodies. He applied for membership and registered in Scopus. SERB, His Previous Publication is in International Journal of Mechanical Engineering and Technology (IJMET) Volume 9, Issue 4, April 2018, pp. 748–755, Article ID: IJMET_09_04_083 – Review on design of compliant mechanism for automotive application – a topology optimization approach. Design of Compliant Mechanisms for Engineering Support - A Topology Optimisation Approach | Chapter 16 | Advanced Aspects of Engineering Research Vol. 2, Development and Numerical Experiments of Compliant Anchor Mechanism for Clamping Purpose - A Topology Optimization Method’ was reviewed by experts in this research area and accepted by the board of ‘Blue Eyes Intelligence Engineering and Sciences Publication’ which has published in ‘International Journal of Recent Technology and Engineering (IJRTE)’, ISSN: 2277-3878 (Online), Volume-8 Issue-2, July 2019, Page No.: 1890-1895. The B Impact Factor of IJRTE is 5.92 for the year 2018. Your published paper and Souvenir are available at: https://www.ijrte.org/download/volume-8-issue-2,

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