DESIGN, ANALYSIS & OPTIMIZATION OF COMPLIANT MECHANISMS

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ABSTRACT

The project revolves around how the compliant mechanisms are redefining the design of our products which we use in our day to day life. All these years we have been building our products by combining or joining separately manufactured components to make a single component that satisfies our purpose.

In this type of manufacturing we often compromise on efficiency and performance due to incapability, cost of manufacturing. The rise in the industry of additive manufacturing due to 3D printing has a major contribution in helping the manufacturing of compliant mechanism. Compliant mechanisms gain some or all of their motion from the relative flexibility of their joints rather than rigid body only. Our project elaborates on how different materials affect the performance of the fully compliant plier like the force, stress, deformation, torque and their mathematical calculations are also shown. The topological path model and the finite element analysis carried out also speaks about how the mechanism will be better than the conventional plier.

KEYWORDS: *Compliant Mechanisms, Efficiency, 3D Printing, Joints, Flexible-Link Mechanism, Finite Element Analysis*

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1. INTRODUCTION

In a reciprocating engine, the linear input is transformed into an output rotation, and the input force is transformed to an output force. Considering vice grip, its mechanism transfers energy from your hand (input) to the gripper teeth (output). If friction losses are to be neglected we can say that the energy is conserved between the input and output, where the output might be much larger than the input force, at the same time displacement taking place at output is very small as compared to the displacement taking place at input. In most of the everyday things we use, we see that their structures mostly consist of rigid links which are connected at the joints and as a result, relative motion hardly takes place or does not take place between the links. The major difference between a structure and a mechanism is that structure does not offer mobility or a structure which is rigid cannot be termed as a mechanism. We are surrounded by mechanisms. Automobiles, sports equipment's, furniture, construction equipment's, robotics and almost anything that has mobility is an example of a mechanism.

Compliant mechanisms can be simply explained as mechanism with only a single link which has mobility. These mechanisms are developed in order to increase the efficiency and in general the performance of a product which is manufactured as a compliant mechanism. But due to manufacturing constraints like cost, material availability, availability of technology these kinds of mechanism are not seen in the market as a product. It will be just a matter of time until significant research is carried out and we will be using compliant mechanisms in our day to day life frequently.

2. LITERATURE REVIEW

The authors of this paper went about with the literature search focused mainly on the topics related to the compliant mechanisms. Extensive research on compliant mechanisms and its design was carried out by the authors of the paper. The first step in the design of a compliant mechanism was to establish a kinematically functional design that generates the desired output motion when subjected to prescribed input forces. This is called topological synthesis. As the topology is determined, the shape and size of individual elements can only be optimized to a certain extent in this early stage of analysis. After the required topology is achieved, constraints which hamper the performance which are usually in the design domain can be worked upon. These constraints are mainly minimization of energy loss in the given mechanism, amplifying geometric advantages such as motion or mobility of links or amplifying mechanical advantages such as increasing the force output with decreasing the input and making the mechanism buckle free under applications of external loads or forces.

I.Her, A.Midha^[1] gives the basic concept of compliant mechanism, a compliance number and type of synthesis. The purpose of this paper is to identify and discuss some important kinematic properties of compliant mechanism. In this paper, degree of freedom concept for rigid mechanism is briefly explained. Synthesis of rigid mechanism depends upon mechanism type and number of links and joints, but synthesis of compliant mechanism depends upon instances (i.e. compliance of joints and links). Compliance content of a link, Degree of compliance concept is clearly explained with respect to rigid and elastic counterparts.

Even though the authors of this paper had carried out a vast and varied research with the help of going through some papers published on designing compliant mechanisms they also had some valuable inputs from Prof. G.D Korwar who is himself doing a PhD in compliant mechanisms. According to him the aim of the paper should be to determine the limits of mobility of different kinds of the compliant joints in order to aid in the design of the compliant mechanisms. This is exactly what the authors then tried to work. After some more research the authors then concluded that a single link or compliant mechanism with film joint has greater mobility than beam or notch joint. Compliant mechanism with silicone joints has greater mobility than plastic joints but compliant mechanism with plastic joint can be built in one piece is what was concluded.

3. METHODOLOGY

The authors of the paper went on to design a compliant plier using Solidworks. The dimensions of the plier were taken from STP file provided by BYU University. Ansys analysis of the plier was also performed by the authors for stress analysis and total deformation as these are the major factors that decide the life span of plier and gives more clarity about selection of material for manufacturing. Ansys analysis is done for four different kind of material and the based on the analysis authors have suggested one best suited material for 3-D printing of pliers. Four materials chosen by the authors are Polylactic Acid(PLA), Acrylonitrile Butadiene Styrene (ABS), Thermoplastic Polyurethane (TPU) and Polyethylene Terephthalate Glycol (PETG). A path Model diagram is also proposed by authors that actually helps to understand the energy transfer sequence within the plier. some theoretical design and formula for torque calculation is also given by the authors which they would be able to apply later practically. The following methodology is explained in details as below-

3.1 Designing of plier

3.2 Ansys analysis

3.3 Torque calculations (force muscle calculation)

3.4 Topological path model of compliant plier

3.1 Designing of Plier

The gripper has been modelled according to the original dimensions on the SOLIDWORKS 19 software. The same model has been used for the analysis purpose.

Table 1: Properties of Plier

PROPERTIES	
Volume	1.189e+005 mm ³
Mass	0.1403 kg
Centroid X	83.125 mm
Centroid Y	29.616 mm
Centroid Z	12.504 mm
Moment of Inertia Ip1	185.72 kg·mm ²
Moment of Inertia Ip2	339.9 kg·mm ²
Moment of Inertia Ip3	511.04 kg·mm ²

Figure 1: Cad model of complaint plier

3.2 ANSYS Analysis

Static structural Analysis is a branch of ANSYS that deals with numerical simulation methods and makes use of different algorithms to solve and analyze the problems that involves various kinds of forces. Static structural requires various settings like pressure, force, and various other factors.

3.2.1 Properties Selection

As the all the four materials chosen by authors are not available in the default library of ansys .so the author of the paper went on to read data sheets of various 3-D printing Companies and then calculated the average values and those same values are used for ansys analysis.

3.2.1 Properties of All the Four Materials Taken for Analysis are as Follows

Table 2: Properties of all the four materials

SR.NO	PROPERTY	PLA	ABS	TPU	PETG	UNITS
1.	Density	1.12e-006	1.18e-006	1.26e-006	1.38e-006	kg mm ⁻³
2.	Tensile Yield Strength	35	38	42	45.8	MPa
3.	Tensile Ultimate Strength	41.83	44.8	48	53	MPa

4.	Young's Modulus	2700	2900	3100	3600	MPa
5.	Poisson's Ratio	0.35	0.35	0.3897	0.421	-
6.	Bulk Modulus	3000	3222.2	4684.2	7594.9	MPa
7.	Shear Modulus	1000	1074.1	1115.3	1266.7	MPa
8.	Compressive Yield Strength	40	42	46	55	MPa

3.2.2 Meshing

The partial differential equations that govern fluid flow and heat transfer are not usually amenable to analytical solutions, except for very simple cases. Therefore, in order to analyze fluid flows, flow domains are split into smaller subdomains (made up of geometric primitives like hexahedra and tetrahedra in 3D and quadrilaterals and triangles in 2D). The physical and mechanical properties required for the analysis were specified in the software. ANSYS software is based on Finite Element Analysis (FEA) method so it divides the model in small finite elements for analysis, this process is called as meshing. After the meshing, forces have been applied on the required surfaces. The magnitude and direction of the forces has been specified. Certain surfaces are given fixed constraints according to the placement of forces. Later the analysis was done for maximum equivalent stress and total deformation for all the four material.

3.2.3 Properties of Meshing for Plier (Static Structural Analysis)

Table 3: Meshing Details of compliant plier

DISPLAY	
Display Style	Body Color
SIZING	
Size Function	Adaptive
Relevance Center	Fine
Element Size	Default
Mesh Defeaturing	Yes
Defeature Size	Default
Transition	Fast
Initial Size Seed	Assembly
Span Angle Center	Coarse
Bounding Box Diagonal	215.860 mm
Minimum Edge Length	9.5227e-002 mm
STATISTICS	
Nodes	23728
Elements	4344

Figure 2: mesh model of plier

NOTE-For all the four materials the meshing details are same as described above.

3.2.4 Application of Force

Figure 3: Application of forces

Table 4: Application of forces

OBJECT NAME	FORCE	FIXED SUPPORT	FORCE 2	FORCE 3
State	Fully Defined			
SCOPE				
Scoping Method	Geometry Selection			
Geometry	1 Face			
DEFINITION				
Type	Force	Fixed Support	Force	
Define By	Vector		Vector	
Magnitude	8. N (ramped)		15. N (ramped)	
Direction	Defined		Defined	
Suppressed	No			

For all the four materials the application of force is at the same points and with same magnitude and direction so as to get a uniform result.

For taking various other readings the author of the paper have only altered one value of force i.e. force 1.

3.2.5 Result Table for Maximum Stress

Table 5: Result (maximum Stress)

SR.NO	FORCES(N)			STRESS(MPa)			
	FORCE 1	FORCE 2	FORCE 3	PLA	ABS	TPU	PETG
1.	6	15	15	55.387	55.00	54.612	53.897
2.	8	15	15	85.654	84.892	84.458	83.355
3.	10	15	15	115.93	115.230	114.31	112.82
4.	12	15	15	146.2	146.00	144.16	142.28

Figure 4: Stress analysis PLA Figure 5: Stress analysis ABS

Figure 6: Stress analysis TPU Figure 7: Stress analysis PETG

3.2.6 Result Table for Total Deformation

Table 6: Result (Total Deformation)

SR.NO	FORCES(N)			DEFORMATION(mm)			
	FORCE 1	FORCE 2	FORCE 3	PLA	ABS	TPU	PETG
1.	6	15	15	22.695	21.13	19.29	16.255
2.	8	15	15	42.414	39.489	36.069	30.405
3.	10	15	15	62.143	57.857	52.856	44.563
4.	12	15	15	81.874	76.228	69.645	58.723

Figure 8: Total Deformation PLA Figure 9: Total Deformation ABS

Figure 10: Total Deformation TPU Figure 11: Total Deformation PETG

3.2.7 Stress Comparison Graph for all the Four Material

Figure 12: Graph (Stress VS Force)

3.2.8 Deformation Comparison for All the Four Material

Figure 13: Graph (Force VS Total Deformation)

3.2.9 Force Muscle Calculation

Figure 14: Torque Calculation

Figure 15 : Force muscle (Drafting)

Rivet- a point from where applied force on gripper passes on to output jaw.

ΣM about Rivet =0

$F(L.HAND)*F(R.HAND)=F(CUTTING\ EDGES)*(MAX\ DISTANCE\ BETWEEN\ JAWS)$

$F(CUTTING\ EDGES)= \frac{F(L.HAND)*F(R.HAND)}{(MAX\ DISTANCE\ BETWEEN\ JAWS)}$

As the system is in equilibrium about rivet .

as we can see max distance between jaws is less in complaint mechanisms so force output for same input will be more in case of Complaint mechanisms

For example - $F(L.HAND)*F(R.HAND)=8*8(N)$

$(MAX\ DISTANCE\ BETWEEN\ JAWS)= 1.89cm(\text{for complaint})$

$=2.5cm (\text{for convectional})$

$F(CUTTING\ EDGES)_{complaint}=8*8/1.89=33.86\text{ N/cm (force of muscle)}$

$F(CUTTING\ EDGES)_{convectional}=8*8/2.5=25.6\text{N/cm(force of muscle)}$

We can observe that for 8N of force complaint mechanism gives more output.

3.3 Torque Calculations

Figure 16: Torque Calculation

Figure 17: Force muscle (Drafting)

As we know that torque =force * perpendicular distance

As the perpendicular distance we'll take between one end of output jaw and to rivet.

Now as the distance (r)=5.49cm(compliant)

5.016cm(convectional)

$T(\text{compliant})=8*0.0549= 0.4392\text{ N-m}$

$T(\text{convectional})=8*0.05016= 0.40128\text{ N-m}$

3.3.1 Result Table

Table 7: Result (Mathematical Calculations)

Sr.no	Property/calculated value	Convectional mechanisms	Compliant mechanisms	Percentage increase in complaint
1.	Muscle force (JAWS)	25.6N/cm	33.86 N/cm	24.39%
2.	TORQUE	0.40128 N-m	0.4392 N-m	8.633%

3.4 Topological Path Model Diagram

Figure 16: Topological path Model

Both the above figures show the topological path model diagram. Basically it shows the path which the applied force or input follows until it reaches output jaws. The force in compliant mechanism follows a simple path whereas path followed by input force in convectional plier is complex.

The authors suggest that this might be the reason why for same amount of input force convectional compliant mechanisms gives less output force as compared to compliant mechanism.

As in convectional plier it passes through many joints and as no joint converts 100% energy due to friction, so it gives less output.

Table 8: Topological sequence

SR.NO	NAME OF MECHANISMS	TOPOLOGICAL SEQUENCE	NO OF JOINTS
1.	COMPLIANT	(IN) 1-2-4 (OUT)	1
		(IN) 1-2-3-4 (OUT)	1
2.	CONVECTIONAL	(IN) 1-2-3-4 (OUT)	3
		(IN) 1-2-3-5 (OUT)	3

4. CONCLUSIONS

In this project we have conducted a comparative analysis of different flexible materials used to make a fully compliant plier. This project has tried to convey that mechanisms that bend can also perform as better as the conventional mechanisms. We have seen that within the four materials [PETG, TPU, ABS, PLA] the PETG is better at handling deformations than all the other materials. The flexibility of PETG helps the hinges to bend to give the required motion and output of a plier.

Also from the graphs we can observe that as the force increases, stress and total deformation also increases.

But comparing within the four materials for all forces, least deformation and least total stress is shown by PETG. This is due to the fact that PETG has emerged as a most appropriate and attractive alternative to ABS and PLA. Some of the qualities that make PETG more reliable advanced filament material than other three are:

1. Excellent layer adhesion
2. Warp resistance
3. Reduced shrinkage
4. Higher density
5. Shows Chemical resistance to both acidic and basic compounds.
6. Shows Flexible nature of printing on glass, acrylic, glass.

As the 3D printing industry is growing, finished prints are pliable and more impact-resistant. In fact, PETG is flexible enough that it is virtually unbreakable and this characteristic makes PETG suitable material for complaint plier as pliers are used repetitively. Also it has Excellent layer of adhesion that converts it into improved surface finishes. It has Low shrinkage it means it is often a good choice for printing larger items.

Hence we can conclude that material properties also shows that PETG is ultimate choice over other three materials for manufacturing of complaint plier majorly due to its flexible nature and low total deformation.

From mathematical calculations and Topological Path model it has been proved that both analytically and mathematically Compliant mechanisms are better than Convectional Plier in terms of torque generation and energy conversions from one link to another.

Hence Authors Conclude that Compliant Pliers 3-D printed in PETG are best for use instead of convectional pliers.

5. ADVANTAGES

There are several reasons why a compliant mechanism may be considered for use in a particular application. The major reason behind this is the ease of use of compliant mechanisms in certain applications for example the plier we have 3D printed. One advantage of compliant mechanisms is the potential for a reduction in the total number of parts required to manufacture a specific component. The part count is less in compliant mechanism as it is made up of only one part or 2-3 parts in case of pseudo compliant mechanisms. The number of components required for a compliant mechanism are considerably less than for a rigid version of the same mechanism. Compliant mechanisms are relatively easy to manufacture because they can be manufactured from various manufacturing processes. Compliant mechanisms can be manufactured using many methods such as machining, stamping, laser cutting, and 3D printing. In our case we have used 3D printing which is a little time consuming but an effective method to manufacture compliant mechanisms. Because compliant have fewer parts and simple manufacturing processes, compliant mechanism manufacturing is cheap as compared to normal. The reduction in part count simplifies manufacturing and reduce both the manufacturing and assembly time and cost.

Traditional mechanisms sometimes lose its precision due to backlash error and wear and tear of certain parts. Compliant mechanisms allow precise motion by reducing or eliminating backlash and wear. Rigid-body mechanisms get

their motion from physical motion between two different parts or links, which can lead to Mechanical wear. This leads to failure of component and changes geometry and movement of the mechanism these kinds of problems can be solved by using compliant mechanisms. As backlash is caused by interconnected links so it can easily be resolved in case of compliant mechanisms. The fact that it can reduce various errors leads it to design of various instruments. Vibration and noise are caused by the turning and sliding joints of rigid-body mechanisms are also reduced in some applications by using compliant mechanisms.

Compliant mechanisms have a smaller number of movable joints, such as pin (turning) and sliding joints. This results in reduction of friction and reduction in need for lubrication. This is very important characteristic for those components which are not easily available and gets wear because of friction. It is very useful in space application as the lubricant evaporates in low gravity environment.

Another advantage of compliant mechanisms is that they can be scaled down easily as they are made up of lesser number of parts. The reduction in the total number of parts and joints offered by compliant mechanisms is a significant advantage in the manufacturing of micro mechanisms. We can also see a significant reduction in weight for the component that is being manufactured in compliant as compared to rigid body. This weight reduction also plays an important role in space parts and in shipping industry.

As we know that energy in complaint mechanisms gets stored in flexible links in the same way as in spring. This stored energy can be easily used to transform energy or use that energy at later time in a different manner.

6. DISADVANTAGES

As the material used in complaint mechanisms are mostly flexible which creates restriction in motion and hence no compliant mechanisms can achieve continuous motion that we achieve in rigid body motion.

Also, due this flexible nature the amount of load the mechanism can withstand is limited and force greater than its limit can cause fatigue and eventually the failure of material which is not the case in rigid bossy mechanisms.

As discussed in advantages energy is being stored in mechanism, not all of this energy is released as it is and hence there can be some losses in energy.

Design are made by taking considerations of manufacturing processes which can sometimes lead to premature failures and can ultimately reduce the confidence of consumers. Also, as they are manufactured using 3D printing, so their life span is less as compared to rigid body mechanisms.

During its analysis using any software such as ANSYS, CERO software is unable to recreate the motion exactly that is been made by the mechanism. This further leads to incorrect analysis of mechanisms. Because if fatigue or stress analysis is wrong in initial stages that can lead to wrong material choice for the mechanism as well as can reduce the life span of mechanism.

As the manufacturing requires 3-D printing so it increases the amount of product being manufactured and hence cost of manufacturing sometime becomes high.

Selection of material that from which our mechanism should be made is sometimes very difficult what happens is sometimes we don't get material that are exactly required by and matches with the characteristics of product.so selection of material is tiresome job.

Strength of the material, though they will work perfectly only within the given working parameters.

Flexible links cannot achieve 180-degree angular rotation with same precision as rigid linkages, but still can be achieved with better designing.

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