DESIGN AND ANALYSIS OF COMPLIANT MECHANISM AND THEIR APPLICATIONS IN AUTOMOTIVE INDUSTRY

Omkar Karlekar[1], Akshay Ghule[2]

[1,2]Mechanical Engineering Student, VIT pune, Maharashtra, India
[3]Professor, Dept. of mechanical Engineering, VIT pune, Maharashtra, India

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Abstract - Engineers routinely design for strength and stiffness. Steel and concrete prevent deflections in buildings, and machines resort to rigid articulation in order to avoid deformations. But although most human design are inspired by Nature, rigidity is a concept foreign to the living world from a kangaroo's legs to the wings of a bat— bones, tendons, and cartilage are the nuts and bolts of organic machines, and deformation is an integral part of the design, crucial for both efficiency and robustness. Unfortunately, designing for flexibility requires deep understanding and precise predictions of finite deformations, which proves to be substantially more difficult than relying on rigidity. Fueled by progress in technology and computation, however, many fields of engineering have started to embrace deformation and to leverage flexibility for better, more elegant, and ultimately more satisfying designs.

Key Words: Compliant Mechanism, Fatigue Analysis, FEA Analysis, Steering Mechanism, Brake Compliant.

1. INTRODUCTION

Complaint mechanisms are mechanical devices that gain some or all of their mobility through the deflection of their flexible members, while transferring or transforming motion, force and/or energy. Figure 1.1 shows an ergonomic modular compliant chair designed by Mett-lachetal using a partially-compliant mechanism. The schematic representation of the partially-compliant mechanism involved in the ergonomic modular compliant chair is shown in Figure 1.2. The reclining feature provided by this chair made

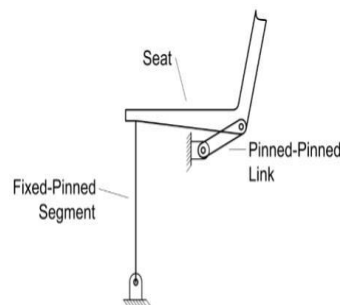**Fig-1.1**   **Fig-1.2**

possible due to the flexibility in the front legs. The reduction in the number of joints also gives the mechanism high

precession. Vibration and noise caused by the turning and sliding joints of rigid body mechanisms can also be eliminated up to some extent using compliant mechanism. It is possible to reduce the weight significantly by using a compliant mechanism over their rigid-body counter parts which is very significant in aerospace technology. Compliant mechanisms gain its mobility from the deflection of flexure joints and the strain energy is stored in them.

2. BACKGROUND AND LITERATURE REVIEW

The first application of compliant mechanism can be dated back to the medieval times, wherein the Romans utilized compliant segments for energy storage in catapults and crossbows. The same property of compliant mechanisms is utilized even today, e.g. the NASA mars rover wheel design. Research in the area of compliant mechanism design that involves transfer of motion, force and energy storage initiated about five decades ago.

The first publication in the area of synthesis of flexible link mechanisms was presented by **Burns and Crossley**. Burns and Crossley provided a graphical technique called as kinetostatic synthesis for synthesis of flexible link mechanisms. The authors considered mechanisms with flexible coupler attached to two fixed- pinned segments. The approach allows performing dimensional synthesis

Recently, **Paul and Midha** provided improved parametric expressions for the PRBM of a fixed and free compliant segment subjected to beam end forces. **Howell** advanced the approach and developed PRBMs for initially curved fixed-pinned segment, and initially-straight fixed-guided segment wherein the beam end angle in the deformed state is the same as in the un-deformed state. **Mettlach** and **Midha** presented a PRBM for a fixed-free compliant beam with multiple characteristic pivots in order to increase the prediction range of the PRBM characteristic deflection domains for simple compliant segment types were derived using the available PRBM parametric equations. The characteristic deflection domain for complex shaped compliant segments was determined using the iterative-incremental finite element analysis procedure developed by **Nahvi**.

2.1 SCOPE OF INVESTIGATION

The objective of this work is to develop synthesis and analysis techniques for compliant segments and compliant mechanisms. This work strives to systematically develop a fundamental understanding of various aspects of compliant mechanism design. The design and analysis methodologies provided herein build on the rigid- body synthesis and analysis techniques for compliant mechanism design. This work provides an efficient method for the analysis of a cantilever compliant beam with force applied on free end using the PRBM concept. To assist a designer in the specification of realistic beam end point characteristics, the concept of characteristic deflection domain is developed. Characteristic deflection domains for various compliant segment types are presented. Pseudo-rigid-body representation of the lower and upper bounding curves of the characteristic deflection domain is evaluated, which are helpful in analysis and synthesis of compliant mechanisms.

A simple and straight-forward approach is presented to evaluate the mechanical advantage of a given compliant mechanism. The formulation utilizes the PRBM approach to derive the mechanical advantage expression for a compliant mechanism. Significant factors affecting the mechanical advantage are studied. Important inferences are derived from the results obtained. The analysis procedure is coupled with the aforementioned improved implementation of synthesis with compliance to design compliant mechanisms with higher mechanical advantage. Finally, experimental investigations are performed to validate the PRBM concept for compliant mechanism design and analysis. Tests are performed on compliant segments, partially-compliant mechanisms and fully-compliant mechanisms.

3. DESIGN OF COMPLIANT STEERING MECHANISM

For converting a rigid steering system into conventional system, firstly the steering system was designed for appropriate length of links in Solidworks and the motion analysis was performed to analyze the results.
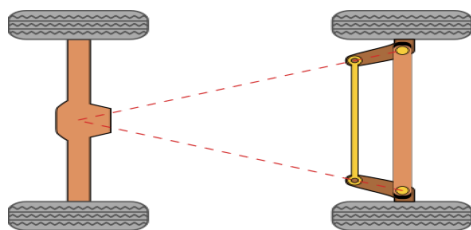

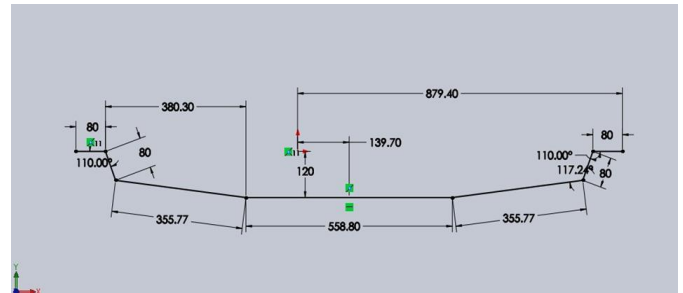**Fig-3.1:** Conventional Steering Mechanism
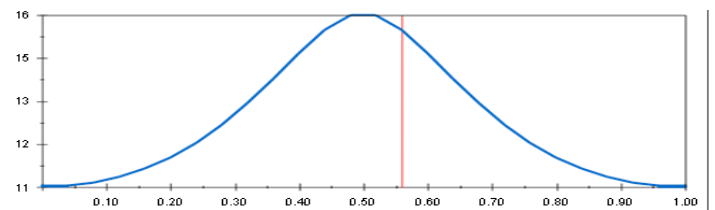

Fig-3.2: Design in Solidworks

Fig-3.3: Motion Analysis Rack Travel Vs Time

3.1 DESIGN OF COMPLIANT COUNTERPART

As per discussed in design of PRBM the different iterations were carried out to find the optimized solution.

Considering that the force is applied in vertical direction the n=0 Thus for value of γ, K_Θ are given by

$$\gamma=0.8517, K_\Theta=2.6548, C_\theta=1.24$$

Thus compliant length is given by

$$\gamma l =(0.8517)(60)$$

$$= 51mm$$

optimized solution was decided for diameter of 8mm and length of 60mm.

Table -1: The final calculations

Length	l	0.057	m		
Diameter	d	0.008	m		
Inertia	I	2.01062E-10	m^4		
Modulus	E	72000000000			
Compliant length	γl	0.0485697	m		
Spring Constant	K	574.5262307	N-m/rad		
Angular Deflection	Fγl/K	0.03381548	rad		
ordinate	l*(1-γ(1-cosθ)	0.056972233	m	56.97223	mm
Abscissa	γl*sinθ	0.001642095	m	1.642095	mm
Stress	Fac/I	453370627	Pa	453.3706	Mpa

3.2 FATIGUE ANALYSIS

Fatigue failure can occur at stresses that are significantly smaller than those causing static failure. Therefore, a fatigue life analysis is essential for all compliant mechanisms. Furthermore, as this mechanism will be used in automotive

applications, the fatigue life is critical. The unmodified endurance limit (for the fatigue test specimen), which is the point where failure will not occur regardless of the number of cycles, for this steel is $S'=0.5S_{ut}$. For aluminium S_{ut}=572Mpa.

$Se=Csurf*Csize*Cload*Creliab*Cmisc*S'$

Now from Howell we know for aluminium of 8mm diameter

$Csurf$=0.9152, $Csize$ =0.9548, $Cload$=1, $Creliab$ =0.702, $Cmisc$=0.71

Thus Se=124Mpa

SF=$Se/\sigma max$

SF=0.24

$$N = \left(\frac{\sigma_{max}}{a}\right)^{\frac{1}{b}},$$
$$a = \frac{(c_f S_{ut})^2}{S_e},$$
$$b = -\frac{1}{3}\log\left(\frac{c_f S_{ut}}{S_e}\right),$$

By calculating we found out that a=2137Mpa, b=-0.02060

N=1.00428x106 thus this indicates infinite life for aluminium in Woehler strength- life diagram.

3.3 MATERIAL SELECTION

In Case scenario of steering mechanism, the applied force is around 400N. For this application aluminium 7075 is used. The modulus of elasticity of aluminium is 72 Gpa and Poisson ratio is 0.3. Which provides good deflection while maintain the stress. As discussed in section 7 the strength-to-modulus ratio of aluminium 7075 is 7.0 which is sufficient enough to provide required deflection while maintaining the stress.

3.4 FEA ANALYSIS

In order to verify the analytical approach, FEA is performed and equivalent stresses on the compliant link are determined. The maximum stress is determined as 533Mpa which is in agreement with analytically calculation.
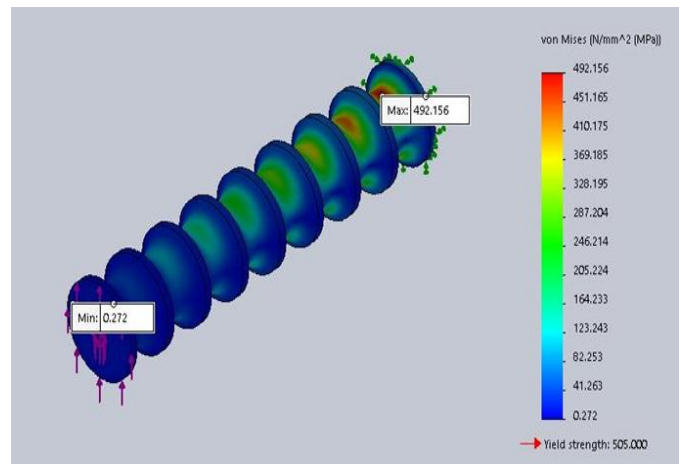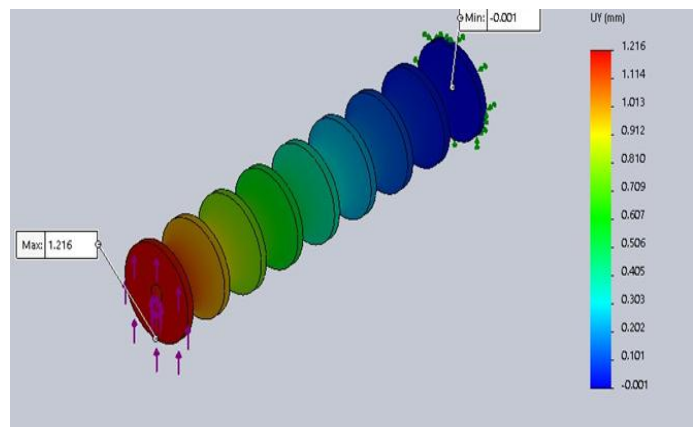

Fig-3.4: Von Mises Stress [MPa]

Fig-3.5: Von Mises Strain [MPa]

3.5 PROTOTYPE

The prototype of steering model was manufactured using 3D printing. The joints were manufactured in form of HDPE i.e. TPU. The final prototype model is shown in Fig 3.5

Fig-3.6: Actual Prototype

4. COMPLIANT BICYCLE BRAKE

A driving factor in the bicycle component industry is to increase device performance and decrease the overall weight. These criteria have led to advanced materials and novel designs. One way to achieve these objectives is to decrease the number of components in the overall design. The purpose of this work is to use the advances in compliant mechanisms theory to develop a bicycle brake with the potential for low weight and high performance (i.e. compact design with a consistent mechanical advantage)

4.1 TYPES OF BRAKES SELECTION

Fig-4.1: Conventional Industry Brake

For designing we have selected the modified single pivot caliper due to following advantages

• Reduced number of parts

• Less expensive to Fabricate

• Mechanical advantage

• High performance

4.2 LINKAGE DESIGN

Free body diagram of modified single pivot of is used to determine the placement of compliant link. From FBD is was deduced that the compliant link needs to be placed between the two links below the pivot point.
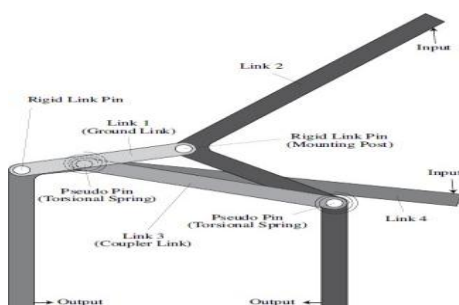
Fig-4.2: Brake Nomenclature

The pseudo rigid body model was developed to create complaint counter part of FBD. In PRBM the compliant link is replaced by rigid link with torsional spring at the pivot point.

4.3 MODEL

The prototype model was developed using SOLIDWORKS and the parts was virtually assembled to check the clearances. The final prototype was developed using 3D printing. The material used for prototyping is ABS. In actual rigorous use the abs compliant link can be replaced by metal one.
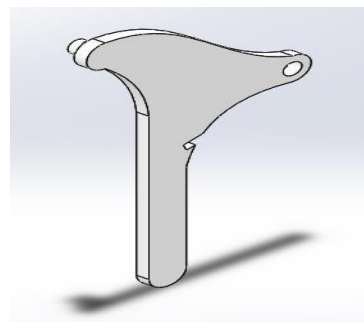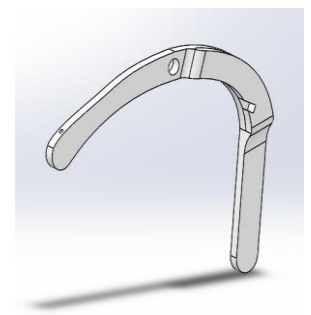

Fig-4.3   **Fig-4.4**

Fig-4.5

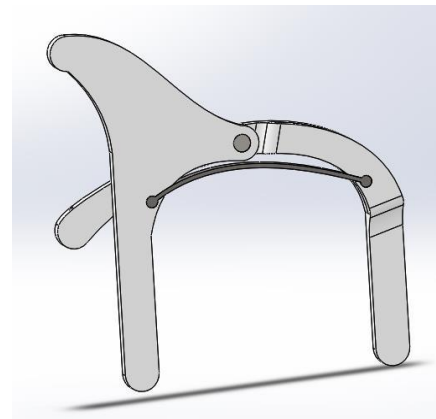## 4.4 ANALYSIS

The analysis of compliant prototype was done using Solidworks simulation. The force was provided of 100N on each link and the free rotation was provided at the pin point. The maximum stress was found out to be induced at middle of compliant link. The maximum stress is 240Mpa
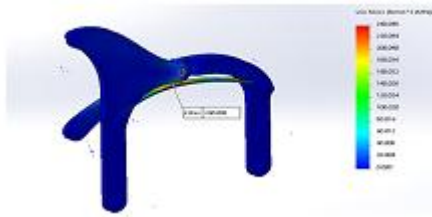
Fig-4.6: Von Misses Stress Analysis

The displacement of the clamping part was found out to be around 1.1mm which was the required displacement.
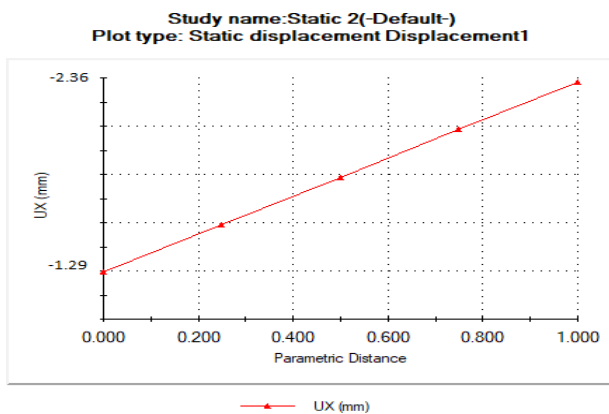

Fig-4.5

4.5 PROTOTYPE

Fig-4.6: Actual Prototype

5. DEVELOPMENT IN DESIGN OF JOINTS

Our main purpose is to replace the joints of conventional four bar mechanism so to do this we design various kind of joints and analyze it to get required stress and deflection.
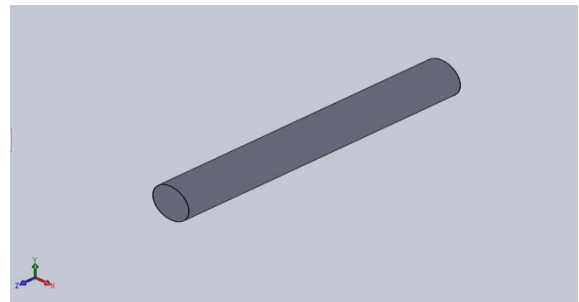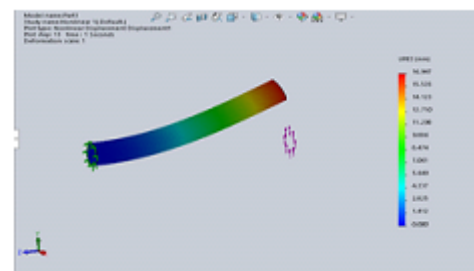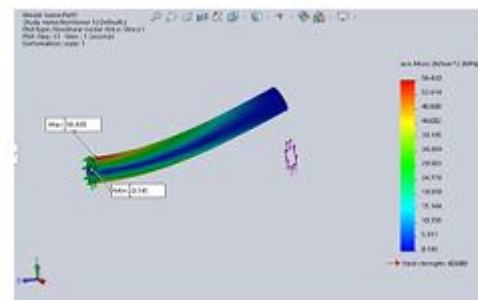
5.1 FIRST ITERATION

Fig-5.1

Fig-5.2

Fig-5.3

5.2 SECOND ITERATION

Fig-5.4

Fig-5.5

Fig-5.6
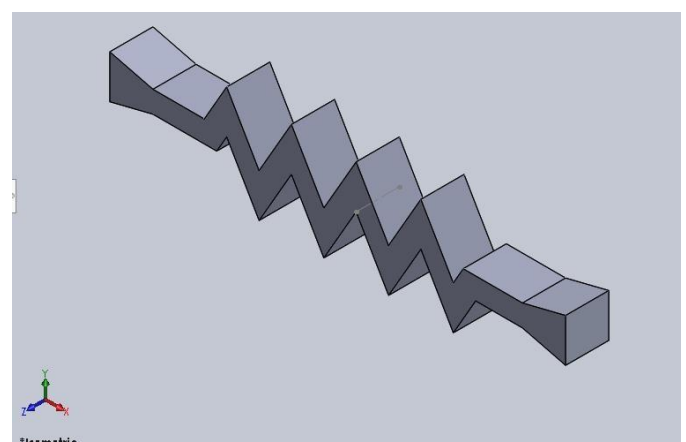
5.3 THIRD ITERATION
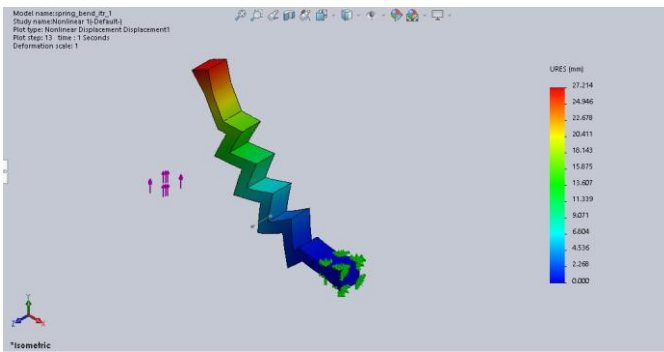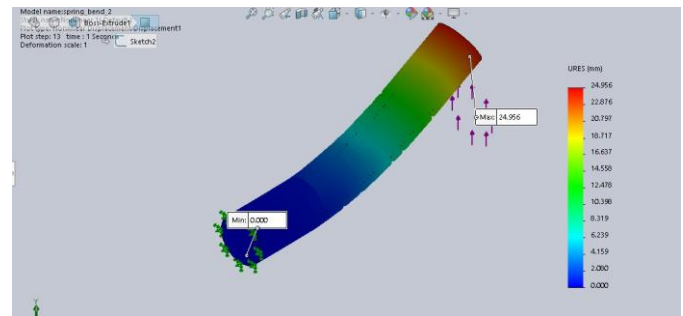
Fig-5.7

Fig-5.8

Fig-5.9

5.4 FOURTH ITERATION

Fig-5.10

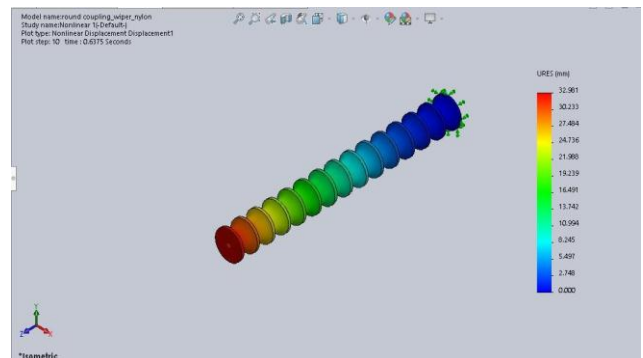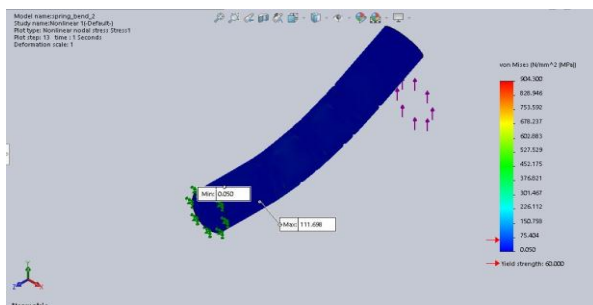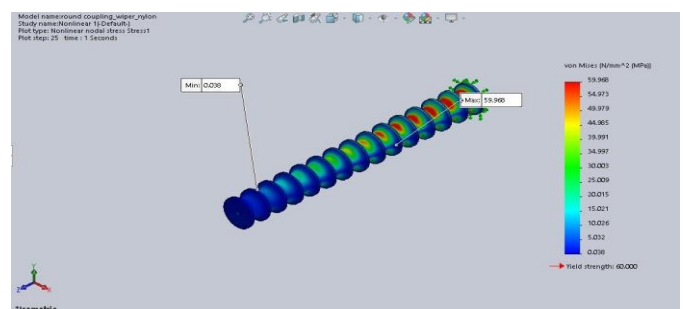**Fig-5.11**

Fig-5.12

6. COMPARISION

In above four iterations we see that in first and second iteration stress is up to the considerable limit but deflection is very low and in third iteration stress is very high but in fourth iteration stress and deflection is of required limit, so we select fourth iteration to proceeding further.

Table -2: Comparison between Stress and Deflection

Iteration	1	2	3	4
stress	50.420	72.559	90.43	59.96
deflection	16.947	27.214	24.95	32.96

7. CONCLUSION

Study of compliant mechanism provides the insights on the designing the mechanism using the flexible nature of materials. Key thing to remember here is that stiffness and strength are not same thing and any component can be flexible while maintaining its strength. In our study we focused on three applications i.e. steering wiper mechanism, steering mechanism, bicycle brake mechanism. Pseudo Rigid Body Mechanism provides the methodology for converting any complaint member into rigid member with torsion spring at the end. PRBM provides analytical solution for any compliant mechanism problem. For verification of analytical solution non-linear FEA analysis was carried out using FEA packages. And FEA solutions are in agreement with analytical one.

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