euspen's 25th International Conference & Exhibition, Zaragoza, ES, June 2025
www.euspen.eu

Design of modified sheet flexure based rotary to linear actuating mechanism

Subrat[1], Jitendra P. Khatait[1]

[1]*Indian Institute of Technology Delhi, Department of Mechanical Engineering, New Delhi 110016, India*

jpkhatait@mech.iitd.ac.in

Abstract

The length of a sheet flexure reduces as one of the ends is twisted along its longitudinal axis. However, this reduction in length is limited as the outer edges deform in a helix and therefore get stretched. The material along the centre line is compressed as the ends are twisted. This leads to an increase in stiffness and stress. In this paper, the geometry of the sheet flexure is modified to increase the compliance along the length as the ends are twisted. As a result, relatively larger linear displacement is achieved by twisting the ends. A mathematical model is developed to characterize the modified sheet flexure based rotary to linear actuating mechanism. Stiffness and stress calculations are verified using FEM models. An exemplar of proposed linear actuating mechanism is designed, developed and fabricated. The relationship between the input rotary to output linear motion is validated. The stiffness and repeatability of the motions are measured and validated. Different configurations are designed and verified for larger range of motion of the order of 10 mm. The designed actuating mechanism can replace conventional ball screw based actuators for limited range of motion.

flexure, actuator, precision, linear actuator

1. Introduction

Rotary to linear transmission, such as ball screw or lead screw are widely used in robotics and manufacturing applications, which use rolling or sliding elements for required force transmission and mobility. Friction between mating components of these transmissions causes wear and backlash which reduces accuracy and repeatability of the machine. In flexure-based mechanism, mobility is due to the elastic deformation of relatively low stiffness components. The absence of friction and play in such mechanism ensures deterministic behaviour, making it a preferred choice for precision machines [1].

2. Modified sheet

The edges of thin rectangular sheet transform into helix under torsion and the length gets reduced. The material along the centre line experiences compressive stress and resists further shortening [2,3]. However, this reduction in length may be used for linear actuation. Removing the material along the centre line increases the compliance and results in larger linear displacement as the ends are twisted. A schematic diagram of the rectangular modified sheet is shown in Figure 1. Here, l_o and d represent the total length and width of the sheet respectively.

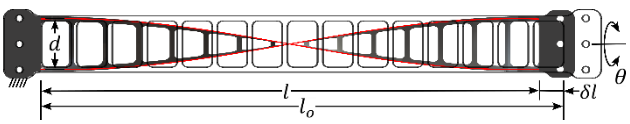

Figure 1. Schematic diagram of the sheet

When load and torque are applied to the modified sheet, its segments perpendicular to the torque axis act as fixed-end columns under torsion and the segments parallel to the torque axis, between two vertical segments, behave as fixed-end beams subjected to a combination of tension, bending, and torsion simultaneously.

2.1 Cylindrical helix

The longitudinal edges of the twisted modified sheet are approximated as a cylindrical helix with the length of the rectangular sheet (l_o) as the arc length and width (d) as diameter. With constant arc length and diameter, the axial length of the helix depends on the number of turns (n). Twisting the sheets from 0 to n rotation, the change in length of the modified sheet (δl) is the change in axial length of the cylindrical helix and is represented as [4]

$$\delta l = l_o - l = l_o - \sqrt{{l_o}^2 - (n\pi d)^2}$$

2.2 Experimental analysis

Modified sheet as shown in Figure 1, with $l_o = 280\ mm$ and $d = 22\ mm$, is manufactured using waterjet cutting from $0.2\ mm$ spring steel sheet. For comparison, a plain sheet is manufactured with the same effective length and width. Images at different rotation angles of plain and modified sheet are shown in Figure 2.

An experimental setup is developed for kinematic analysis of sheets. One end of sheet has only one rotation DOF and another end has only one translation DOF as shown in Figure 3. An optical rotary encoder with 10,000 steps per revolution is attached to measure the angular displacement input. On the other end of the sheet, a linear displacement sensor with 10 μm accuracy is attached to measure the linear displacement output. At the same end, a fix load of 12 N is applied to ensure constant tension in the sheet to prevent unwanted warping.

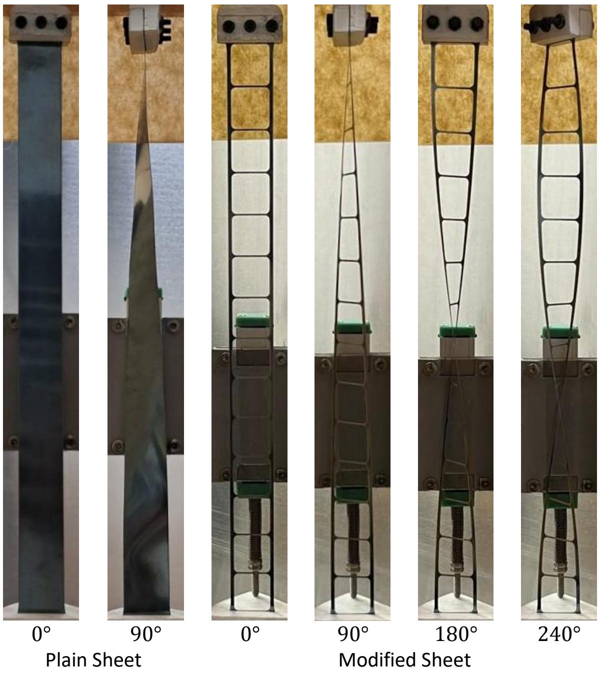

Figure 2. Plain sheet and modified sheet at different rotation angle.

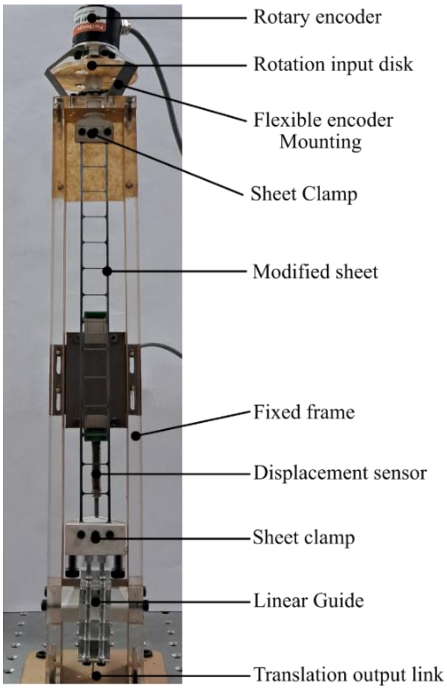

Figure 3. Experimental setup

3. Results and discussions

The plot between rotation $(n) = \theta/360$ of sheet and percentage change in length is shown in Figure 4. The slope of this plot represents the pitch of transmission, $(P_t) = d(\Delta l)/dn$.

Change in length of the modified sheet and cylindrical helix follows a similar curve. Since both ends of the modified sheet are fixed, longitudinal edge does not follow the helix at the fixed ends and hence both have different change in length for the same rotation.

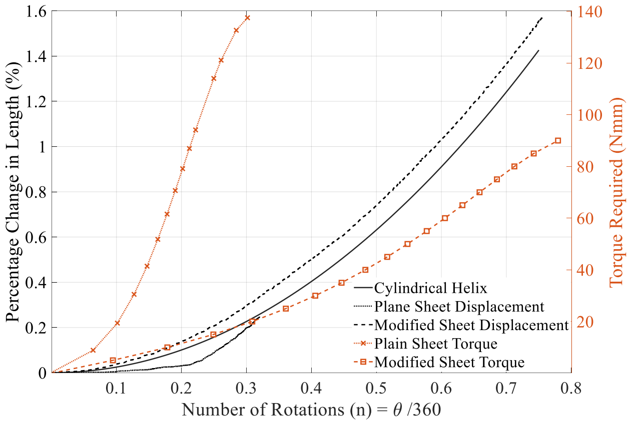

Figure 4. Relation between percentage change in length of plain sheet, modified sheet, torque required for plain sheet, modified sheet with rotation.

Experiments show that change in length of the plain sheet is significantly less than the modified sheet for same rotation. Plain sheet starts warping at $\approx 27°$. Increasing the applied load from $12.5N$ to $25N$, warping delayed to $42°$. After the initiation of warping in the plain sheet, the shortening increases abruptly and at $\approx 110°$, the sheet reaches into the plastic zone. Whereas in the modified sheet, warping starts at $\approx 260°$ and the plastic zone starts at $\approx 240°$, which shows a large range of motion compared to the plain sheet.

Spring steel material with $E = 2 \times 10^{11}\ MPa$ and $\mu = 0.3$ is used for finite element analysis in ANSYS mechanical, which shows nonlinear increase in torque with rotation, and its ratio for plain sheet to modified sheet increases from 0 to ≈ 7 at 90° as shown in Figure 4.

Initially at $n = 0, P_t = 0$, in this range, a large rotation causes small reduction in the length of the sheet which shows its application in accurate linear actuation. With increase in rotation P_t increases, hence a large reduction is achieved, which shows its use in large displacement application.

Applied load affects the kinematics of the system. A closed loop control is required for precise displacement if the external load changes. If the load is constant, since the system is deterministic, precise displacement can be achieved with open-loop control using mathematical relation between n and δl.

4. Conclusion

A new rotary to linear transmission system is developed in this study. An experimental setup is designed to compare the transmission characteristics between sheets and cylindrical helix. The developed flexure-based transmission system has a displacement range of $4.5\ mm$ and can be extended by increasing the length of the modified sheet. Finite element analysis shows that the modified sheet has less torsional stiffness than the plain sheet. The developed rotary to linear transmission system can be implemented to design a precise linear actuator.

References

[1] Soemers H. M. J. R., 2010, *Design Principles for Precision Mechanisms*, T-Point Print, Enschede, Netherlands.

[2] Chopin J., Filho R. T.D. 2019. Extreme contractility and torsional compliance of soft ribbons under high twist. *Physical Review E*, **99(4)**, 043002.

[3] Faghfouri S., Rammerstorfer F. G., 2020, Mode transitions in buckling and post-buckling of stretched-twisted strips. *International Journal of Non-Linear Mechanics*, 127, 103609.

[4] O'neill B., 2006, *Elementary differential geometry*, (Elsevier), ISBN 13: 978-0-12-088735-4