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INFLUENCE OF DIFFERENT LIVING HINGES GEOMETRIES TO COMPLIANT STRAIGHT LINE MECHANISM TRAJECTORY

Abstract: *Classical straight-line mechanisms are one of the most interesting, both from a theoretical and practical point of view. In many cases, those mechanisms frequently produce a nearly straight trajectory rather than one perfectly straight. In compliant form, those mechanisms can produce even better results. Compliant mechanism joints' deformability allows engineers to make further modifications. These modifications may improve the mechanism's ability to follow a straight path even further. This paper will provide an analysis of different hinge sizes, thicknesses, shapes, and overall geometrical characteristics. Their influence on the straightness of the mechanism trajectory will be analyzed and quantified.*

Keywords: *straight-line mechanism, compliant mechanism, compliant hinge geometry, 3D modelling, Simulation. (10 pt, italic).*

1. INTRODUCTION

A simple idea to produce straight line movement for rotary movement is, probably, the most useful thing that humanity has achieved. If someone can find a point in history where humanity started to utilize machines for their development, probably that moment in history will be when we learn how to make a wheel and convert from linear motion to rotary and vice versa. From that moment to this day in any machine that humans produce, we can find that some part rotates and governs some other part that has translatory motion and vice versa [1].

To achieve those conversions some type of device or mechanism is necessary. Throughout history for different purposes and applications, various types of mechanisms have been developed, and research for new designs continues, [1][2].

One can say that the simplest machine that converts rotary movement around the fulcrum of one into the planar motion of some object is a lever. The usefulness of this lever completely depends on its geometry (length between its ends and fulcrum position). More complex machines are designed especially when is it necessary to control produced motion in terms of position, speed, and acceleration. For those purposes, different types of gears, pulleys, cam and followers, and other types of mechanisms are designed and produced. All of those require relatively complex to achieve the desired motion compared to the lever [1].

One of the simplest mechanisms that can be produced only using levers is four-bar linkages. From a theoretical standpoint movement of those mechanisms is defined only by its linkages lengths. From a practical standpoint four linkages from stiff material with two precisely positioned holes each, and four pins are one of the simplest parts to manufacture and maintain during operation [1].

Four-bar linkages are utilized in many machines in various configurations, several types also can convert rotary motion to linear, with some limitations. Some types of such mechanisms are watt Figure 1., and lambda mechanism [2].

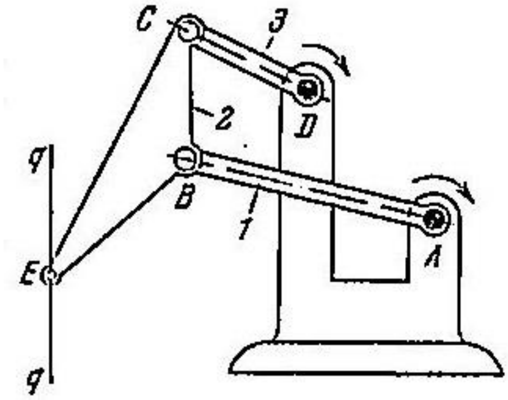

Figure 1 Watt mechanism for straight line[xx].

Lambda and Watt's mechanism does not produce complete straight-line motion but in some finite segments of their trajectory, one of its points almost makes to follow a straight line. This can be enough in some applications [5][4].

Previous mechanisms can be called classical mechanisms which are fully designed under the assumption that linkages are stiff and relative motion between adjacent linkages is pure rotary motion around their joint.

Compliant mechanisms use deformation (compliance) of the body in the mechanism design it can produce a mechanism that does not have separate moving parts but only one part whose segments are deliberately weakened allowing relative movement between stiffer segments [3].

Conversion of the classical mechanism to a compliant mechanism can improve its performance especially when movement is limited around some neutral position [3][4][5].

The weakened structure that conveys relative motion does not transfer only rotary motion to adjacent stiff segments because the pole of planar displacement is moved around. This type of motion consists of the rotary and translational components which means that a segments compliant mechanism has planar motion [3].

[3][5] have shown that compliant hinges (joints) can have a beneficial impact on mechanism motion, and

improve the straightness of a trajectory. This paper will present the continuation of one segment of research started in [3]. The result obtained here will investigate the geometrical approach to compliant hinge orientation and its impact on mechanism trajectory.

2. PROBLEM FORUMATION

Watt's mechanism is shown in Figure 1. Can produce nearly rectilinear if the following relationships between segment lengths are satisfied [2][3]:

$$AD = BE = 0.68AB$$
$$DC = 0.51AB$$
$$CB = 0.49AB$$
$$CE = 1.1AB$$

To obtain a compliant version of this mechanism several assumptions were necessary to be made.

- Stiff segments are significantly thicker than joints. This is necessary to localize deformation around the joint as much as possible.
- Compliant joins are placed in such a way that the middle point overlaps with the axis of rotation of the classical joint.
- All compliant joints are rotated around their middle point to achieve different mechanism configurations.
- Thick segment shape is defined by hinge orientation to achieve a stiff connection between two adjacent joints

Those assumptions are used in [3][4][5] except for the third one. The geometry first mechanism is the same geometry as in [3]. This result is necessary to later compare results with.

The first mechanism is defined as in [3], and is shown in Figure 2., length of AB=100mm, and other segments have dimensions according to the relationship defined for Watt's mechanism. In all mechanism configurations, deformable segments have an 8mm length with 0.5mm thickness and with radius of 1.5mm in corners. The hinges of the first mechanism are parallel with the segments in joints A and B are parallel with linkage AB and joints in C and D follow the direction of CD linkage.

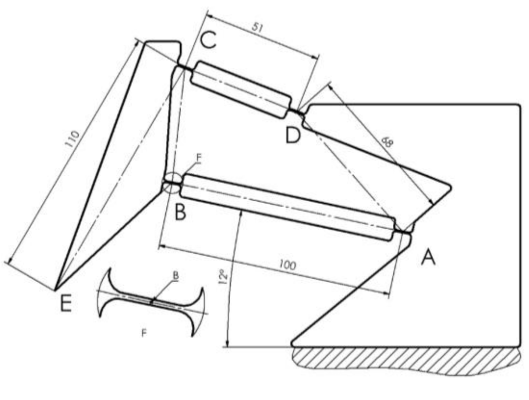

Figure 2 Compliant mechanism with hinges that are parallel to AB and CD segments[3]

The second mechanism is the same mechanism where hinges are rotated in such a way that hinges in joints A and D follows the direction of AD linkage. Also, linkages B and C are parallel to CB linkage, as shown in Figure 3.

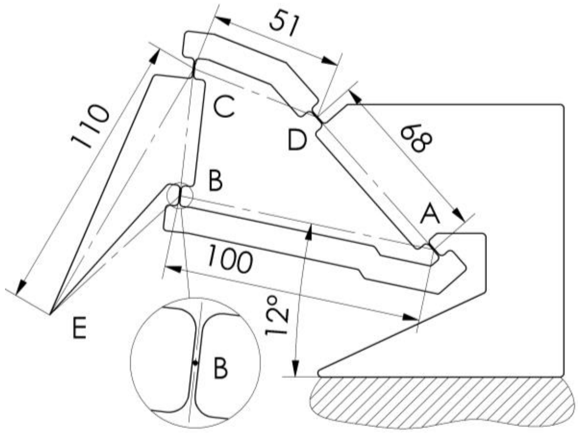

Figure 3 Compliant mechanism with hinges that are parallel to AD and BC segments

Finally, the last mechanism has a hinge direction in between the first and second mechanism configurations. The orientation of hinges in each joint is based on angles between linkages that have a connection in that joint. As shown in Figure 4., the joint B hinge has a direction that is perpendicular to the bisector of an angle between linkages BC and AB. All other orientations of hinges are determined by their angle bisectors.

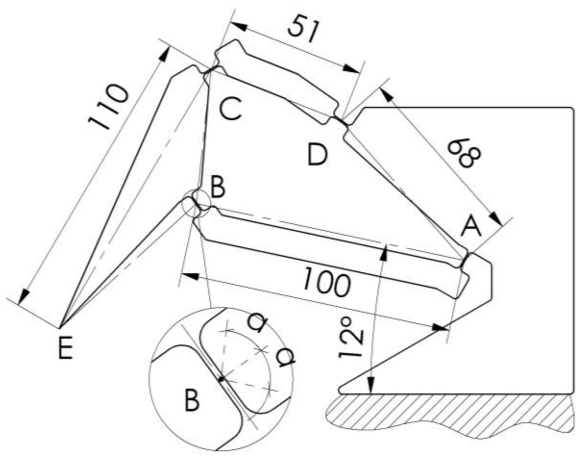

Figure 4 Compliant mechanism with hinges that are perpendicular to angles bisector

Complete geometrical conditions of all three mechanisms are defined in their neutral position (which is shown in Figures 2., 3. and 4.). This neutral position is defined in previous work [3] based on the classical mechanism in such a way that point E is approximately in the middle of the straight segment of the mechanism trajectory. That position is chosen so that the complaint mechanism has a maximal range of linear motion due to the natural springiness of material under deformation.

3. SIMULATION

The software used for simulation is SolidWorks 2022 (SW). Due to the nature of this type of model all of them are subject to large deformations, so a nonlinear type of simulation is necessary to provide adequate results.

Several assumptions have been made to simplify the simulation process [3][4][5]:

- Material used is ABS plastics with 30MPa yield strength, elastic modulus 2000MPa, passion ration of 0.3MPa.
- Due to the complex algorithm necessary to solve nonlinear simulation, and planar movement of a mechanism, plane strain simplification is used. The deformation process is done only in one plane and then later extrapolated to the whole thickness. Plane strain simplification can be used when geometry extends a long distance from the simulation plane compared to the cross-section size on the plane. The mechanism is relatively thin compared to its cross-section but the hinges are much longer compared to their cross-section.
- SW supports two types of nonlinear simulation, static and dynamin. Static simulation is used. Simulation is subdivided into many steps where in each step acting forces are applied in small increments.
- Simulation of each mechanism is divided into two separate parts because it is necessary to simulate movement in both directions from a neutral position, up and down. In "down" case forces acting on linkage AB move point E down and its motion is recorded. In "up" case point E moves along the upper part of the trajectory.
- In both cases the force of 5N acts on linkage AB, the only difference is that one case moves the mechanism up and in the second down.
- Point E is placed in simulation origin where in the initial moment their coordinates are (0,0)
- The number of steps chosen for simulation is 50, this means that 5N is divided into 50 equal incensements. This will produce in total 101 results.
- Complex simulation required relatively complex meshing so SW recommended using "Blended curvature-based mesh" with refinement near thin hinge geometry. Parameters and final mesh refinement are shown in Figure 5. And final mesh can be seen in Figure 6.

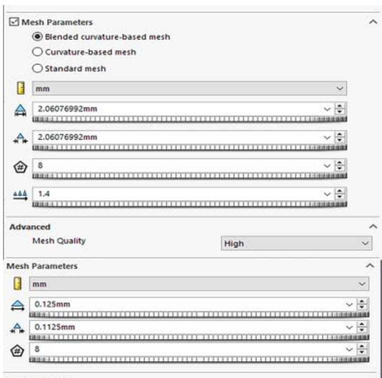

Figure 5 Mesh parameters, basic mesh parameters –upper, and lower mesh refinement parameters.

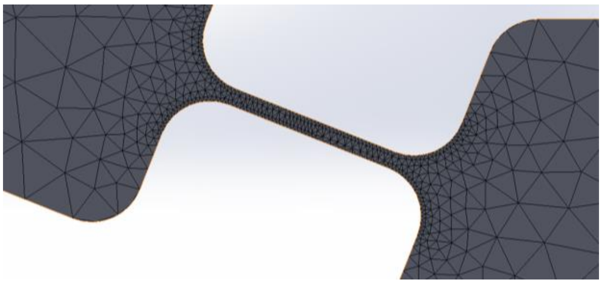

Figure 6 Produced mesh.

4. RESULTS AND DISCUSSION

Simulation results, from up and down cases for all three mechanisms, are combined into unique diagrams and shown in the following figures. The results of the simulation have been divided into two parts. The first part shown in Figure 7, are trajectories of three mechanisms where maximal displacement from a neutral position corresponds to the stress value closest to yield strength. Due to the discretization process necessary to simulate the nonlinear response of the mechanism precise value of point E displacement, at stress of 30MPa, is calculated using linear interpolation. Obtained results from linear interpolation are shown in Table 1. Finally, responses where the trajectory of E is relatively linear are shown in Figure 8. This is not the whole trajectory obtained by simulation but only the linear part, to show differences between hinges orientation. It is necessary to mention those trajectories are obtained when stress is significantly higher than yield strength, which does not have practical significance but from a mechanical point of view this can provide insight into mechanism kinematics.

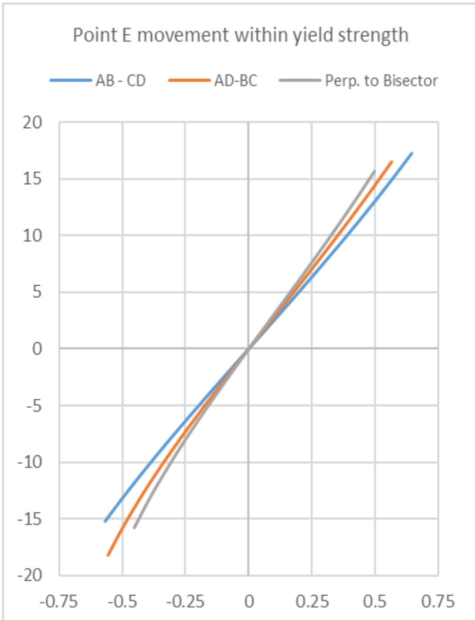

Figure 7 Point E movement within yield strength

Analyzing the results in Figure 7 there are relatively small differences between near neutral point (0,0) but as the mechanism moves up and down trajectories start to separate. The blue line represents the movement of point

E for the mechanism shown in Figure 2 (Mechanism 1). This is the same mechanism as in [3]. The orange and grey lines are mechanisms from Figure 3 (Mechanism 2) and 4 (Mechanism 3) respectively. Interestingly, the trajectory of mechanism 2 is not one with the most deflection from the blue line. All three mechanisms show relatively similar behavior near the neutral point.

Results in Table 1 show that mechanism 2 has the longest trajectory that does when its maximal stress does not exceed 30MPa. One interesting result is that mechanism 3 has the lowest distance travelled. This is an interesting result because when the geometry is analyzed one can expect that the third mechanism will have middle results.

Table 1. Interpolated values for 30MPa.

At 30MPa	AB-CD		AD-BC		Perp. to Bis.	
Down [x,y]	-0.576	-15.47	-0.541	-17.55	-0.444	-15.38
Up [x,y]	0.628	16.76	0.569	16.657	0.525	16.588
Distance	32.258		34.226		31.982	

Finally, from Figure 8, in the near-linear segment of the mechanism's trajectories, there are relatively small deviations between them, but it can be noticed that in the linear segment mechanisms 1 and 2 are very close. Mechanism 3 has a bigger deviation as the distance from the neutral point increases. Quantitatively, form Figure 8 it is obvious that mechanism 2 has a most straight trajectory (orange line).

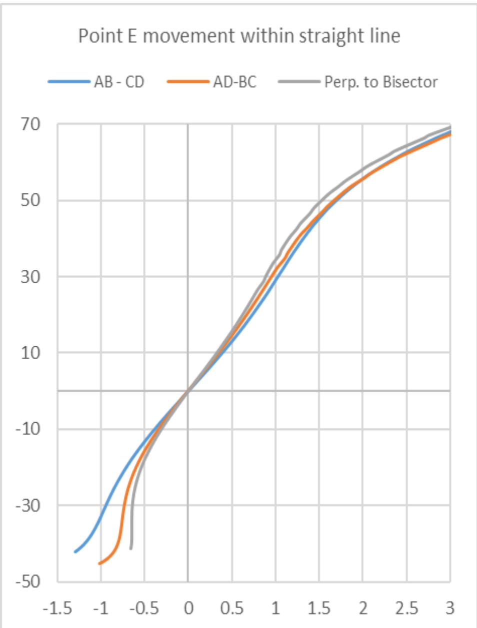

Figure 8 Point E movement within an approximately linear segment of trajectory.

5. CONCLUSIONS

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This paper represent continuation of previous authors work mentioned in references. In that paper author investigated influence of different compliant hinges geometry which was show impact on mechanism movement. Here have shown how orientation or direction of hinges changes mechanisms response. This results opens possibility to use old mechanism configurations which can be improved or tweaked in compliant form to achieve desired response.

Further work will continue to investigate hinges orientation to trajectory shape.

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