A Three-Dimensional Design of the Multi-material Joint System to Realize a Structural Spring-Damper Compliant Mechanism with Versatility in Engineering Fields

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Abstract

Design of a 3D printed cross-spring compliant joint is an emerging topic for its multipurpose applications in various fields due to its realization from a combination of flexible materials with different mechanical properties. It performs the motion by deformation in the elastic region and is suitable for precision engineering applications and instruments. The proposed concept is a modification of a traditional cross-spring pivot, which effectively provides frictionless and wear free in-plane motion. The joint's behavior is analyzed based on a non-linear FEA simulation and the properties were investigated with various loading conditions. Compliant joints are envisaged to bring paradigm shift in the design of high-precision actuators and robotic manipulators.

Keywords cross-spring pivot, compliant mechanisms, FEA simulation, multi-material joint

1. Introduction

Compliant mechanisms are mechanisms that rely on deformation caused by an external loading to perform a motion. In the recent years there is an increased interest in the implementation of compliant mechanisms due to the capabilities of 3D Printing as an appropriate technology for fabricating complex geometry [1]. The advancements in the Additive Manufacturing lead not only to realization of complex geometry but also to the development to variety of new filaments with different behavior and properties. One of the most commonly used materials is Poly Lactic Acid (PLA). This a relatively low cost and environmentally friendly filament used in the FDM (Fused Deposition Modeling) 3D Printing. The mechanical properties of this material are explored at a tensile and flexural test by [2] and [3]. PLA has been compared with other popular 3D Printing filaments such as ABS (Acrylonitrile Butadiene Styrene) in [4]. Other works investigate the relative density of flexible cellular structures fabricated from (thermoplastic polyurethane) [5]. TPU models are flexible and provide larger deformations in the elastic region. Combining the above factors with the unique capability to control the geometry of the model from inside – its orientation and density unlike any traditional technology, make 3D printing suitable for application in the compliant mechanisms allowing for greater range of motion due to the larger deformations. However, there are certain challenges that must be considered while developing compliant mechanisms:

- when large displacements occur, there are nonlinearities in the geometry and the material.
- depending on the orientation of the load, the stiffness of the part can vary in orders of magnitude.
- finding the balance between stiffness and flexibility is a complex design problem.
- to prevent the mechanism from fatigue failure of the material, high stress concentrations should be avoided.
- determining the desired motion parameters is a difficult task.

In rigidly articulated joints the clearances between the components causes backlash in the assemblies. Further, there is friction due to relative motion leading to wear of the parts and increasing the clearances and generating heat in the joint [6]. All of the above disadvantages result in poor accuracy and performance.

On the other hand, to address these issues researchers in the last years have focused on the compliance of the joints rather than restricting such deformations. Compliant joints provide adaptive and monolithic motion, avoiding entirely the assembly process.

Flexural hinges have been widely studied in the literature and several applications in machine design which harness the advantages of flexure-based design elements have been realized. Being monolithic in structure and with the advent in Additive manufacturing techniques, it is even simpler nowadays to design, prototype, test and verify the performance of these hinges in various applications, especially in the field of Precision Engineering. The most popular type of flexural hinge is the Cross-spring pivot, commercially known as Free-flex joints.

Primitive flexural joints primarily consist of leaf-type or notch-type configurations, but they have their own inherent limitations. Notch-type hinges have high stiffness in transverse directions and the rotation capability is limited by stress concentrations. However, the leaf-type flexures provide large rotations but at expense of drifting rotation centers. In-order to mitigate these issues several complex flexural hinges have been proposed like the cartwheel hinges [7], butterfly hinges [8]. While these hinges provide greater benefits over conventional leaf or notch type, Cross-spring pivots are relatively simpler and versatile in applications. The diversity of these flexures stems from the fact that they were extensively explored in the literature for decades. They were first studied analytically in [9] and more recently in [10]. Goncalves provides a thorough theoretical formulation and laser based optical experiments to characterize the performance of Cross-spring pivots.

Such accuracy provided by compliant pivots is useful for small displacement in precise mechanisms and instruments [11]. Relaying on material deformation, flexure joints have become major component in development of precise instruments with high resolution of positioning.

Th other sections of this paper are structured as follows: Section 2 explains methodology of the design and the mathematical modelling of the multi-material joint; Section 3 focuses on the results; Section 4 gives the discussion and Section 5 concludes this paper.

2. Methodology

2.1. *Design of the Compliant Joint*

As discussed in the previous section, compliant mechanisms and joints are becoming a replacement of the traditional equivalents in certain applications regarding their benefits. In the current study, a new compliant type of universal joint realized from two materials is proposed. Rigidly articulated universal joints have two perpendicular axes of rotation where two pin joints are connected. The motion occurs as two rotations in orthogonal planes.

The design of the compliant multi-material joint consists of two cross-spring pivots rotated at a right angle according to the Z-axis of the origin coordinate system as shown on Figure 1.

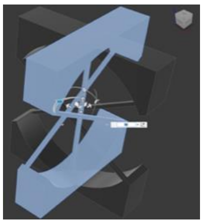

Fig. 1. Orientation of the Cross-Spring Pivots Compounding the Universal Compliant Joint

That type of orientation allows the joint to deform according to X- and Y-axis and provides stability for out of plane movements and moments around the Z-axis. Another advantage of the configuration is minimal axial drift of the center of the joint.

2.2. *Modelling and Physical Prototype*

As illustrated on Figure 2 below, in XY plane the model of the joint consists of three beams oriented at 60º angle (α) from each other (beams A, C and E shown in Figure 5). Another identical unit is attached to it at a perpendicular orientation around Z-axis. All bars of the joint have same dimensions: length (L), and square cross-section (a). The offset between beams from a single cross-spring joint is also equal to (a) and the beams do not intersect. A general view representation of the joint is shown on Figure 2. The joint has two platforms – top and bottom (1) and five beams (2).

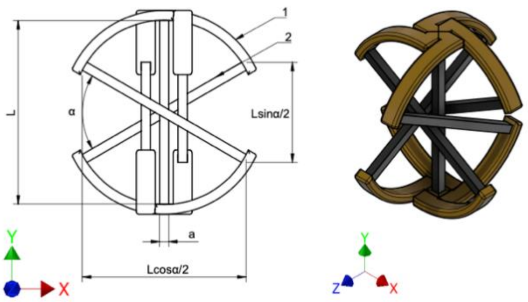

Fig. 2. General View of the Compliant Joint

On Figure 3 are shown a) a 3D rendered model and b) a physical 3D printed prototype of the compliant multi-material joint. The platforms are printed from a solid material PLA (polylactic acid) and the beams from a flexible filament – TPU (Thermoplastic Polyurethan). This multi-material combination provides unique capabilities. The platforms that attach to other components are rigid but the beams that execute the motion throughout deformation are flexible.

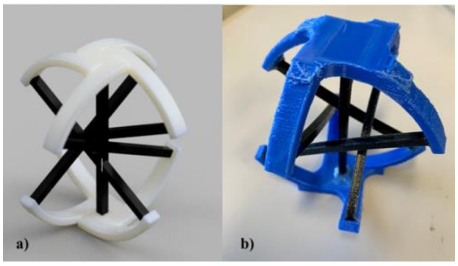

Fig. 3. A Model and 3D Printed Prototype of the Compliant Multi-material Joint

This two-material approach provides diversity for combining and experimenting with different materials pairs. However, this joint is not a single unit, the platforms and the beams have been 3D Printed separately and later assembled.

Technology, chosen for rapid prototyping of this specimen is Fused Deposition Modeling (FDM). The filament used for printing the model is PLA (polylactide) and TPU (Thermoplastic Polyurethan with diameter of 1.75 mm. The 3D printer used for fabricating the sample is Anycubic i3 Mega S, a desktop type machine. 3D printing process is described in Table 1. As discussed in [8], 3D printing parameters could impact the anisotropic behavior of the fabricated parts. Therefore, the configuration set up of the working process is essential for the properties of the physical prototypes. For configuring the printing process is used slicing software Ultimaker Cura. The 3D model was designed in Autodesk Fusion 360 CAD software. The flexible TPU filament is called Ninjaflex from the company Ninjatek and according to their recommendations the appropriate 3D Printing temperature of the nuzzle (extruder)is 230 ºC [12]. The infill pattern used for the beams is called Cross 3D described in the slicing software as suitable for 3D deformations and flexible material prints [13].

Table 1: 3D Printing Configurations

Parameter	***Value of the Printing Parameter***	
	Platforms	***Beams***
Filament	PLA	TPU
3D Printer	Anycubic i3 Mega s	
Slicin Software	Ultimaker Cura	
Layer Height	0.1 mm	0.1 mm
Infill Density, %	100	100
Infill Pattern	Grid	Cross 3D
Printing Temperature, ºC	210	230
Building Plate Temperature, ºC	60	60

Parameter	*Value of the Printing Parameter*	
	Platforms	***Beams***
Filament	PLA	TPU
3D Printer	Anycubic i3 Mega s	
Slicin Software	Ultimaker Cura	
Print Speed, mm/s	45	30
Support	yes	no

2.3. *Analysis of the Loading Conditions*

The performance of joint has been analyzed under various loading conditions illustrated alongside with the deformations on Figure 4 such as a) compression, b) tension, c) bending of the model. On the right side of the figure, the platforms are removed, and the direction of the forces is annotated for the different loading cases.

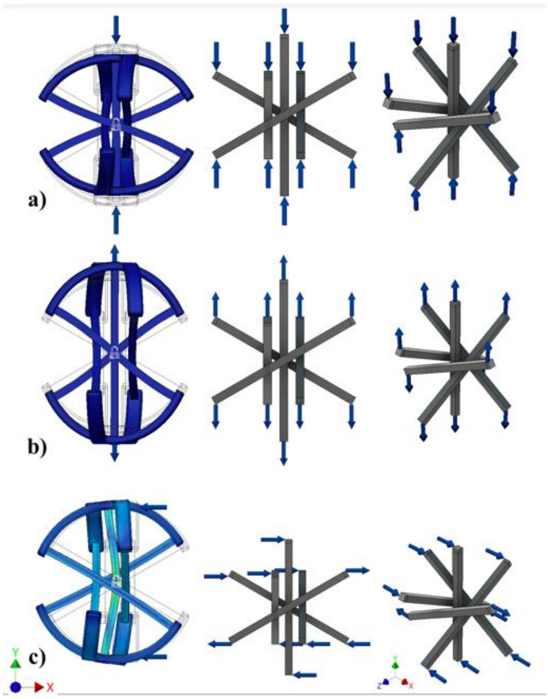

Fig. 4. Loading Conditions of the Joint

To better visualize the position and orientation of the joint components in the space, on Figure 5 the top and bottom platforms are removed, and the beams are color coded and annotated with letters. The coordinate systems in the different orientations are given as well.

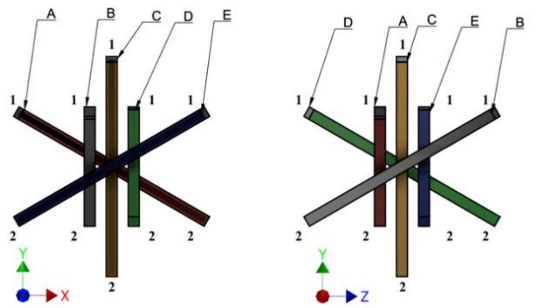

Fig. 5. Position and Orientation of the Beams

On Figure 6 are illustrated all unique loading condition of the beams taken from Figure 6 tension, compression and bending. There are three beams that have different force distribution and using the annotation of Figure 5 they are A, B and C. Beams D is symmetrical to B and E is sumetrical to A and therefore, forces with same magnitude and direction are acting on them.

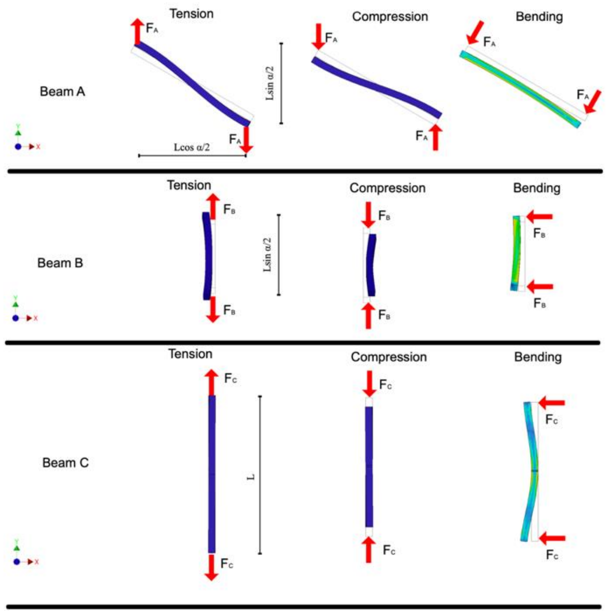

Fig. 6. Loads Acting on the Individual Beams

2.4. *Mathematical Modelling of the Cross-spring Pivots*

The proposed design can be modelled as an assembly of two Cross-Spring Pivots (CSPs) with free center of rotations. Behavior of CSP is widely studied in literature analytically [9,10] and experimentally [10, 11]. In figure 5 beams A and E corresponds to the leaf springs of the pivot 1 and beams B and D, rotated at 90 degrees along the Y-axis consists of pivot 2. The beam C at the center of the joint acts as a stiffener and provides additional rotational stability to the joint.

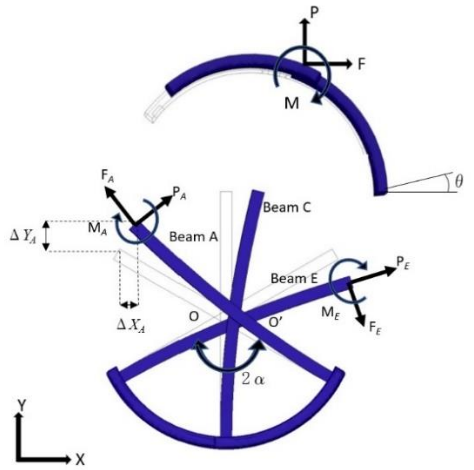

Fig. 7. Generalized Forces and Moments acting on the CSP

Figure 7 illustrates the generalized forces and moments acting on the CSPs and the behavior is described by 11 variables [14]. The load rotational relationship of a cross-spring pivot under a generalized loading condition M-couple, F-horizontal loads, P- vertical loads is characterized by 11 variables (θ , P_A , P_E , F_A , F_E , M_A , M_E , ΔY_A , ΔY_E , ΔX_A and ΔX_E). Similarly, the pivot 2 is characterized by the same set of variables corresponding to beams B and D. For each pivot a system of 11 equations is required to solve the problem. Five are obtained from the equilibrium conditions of forces in X and Y directions, the moment balance, and the compatibility at the edges of beams A and E. The remaining six are obtained from curvature equations for each beam as given in equation 1.

$$EI\frac{d^2y/dx^2}{\left[1+\left(dy/dx\right)^2\right]^{\frac{3}{2}}} = P_{A(E)}y + M_{BA(E)} - F_{A(E)}x \qquad (1)$$

Where, subscripts A and E refers to the beams as shown in figure 7.

3. Results

Simulation studies were carried out in Comsol Multiphysics. The material properties used for the analysis are illustrated in Table 2.

Table 2: Materials Properties used in the FEA

Material	Young's Modulus	Poisson Ratio	Density
Polylactic Acid (PLA)	3.5 GPa	0.3	1.24 g/cm3
Thermoplastic Polyurethane (TPU)	15.6 MPa	0.346	1.23 g/cm3

On Figure 8 are shown the result from the studies for tension a) and b) and bending c) and d). As it can be observed, in b), there is a rotation of the top platform due to the tensile forces. The results for compression are similar to the tension with the reversed direction of the rotation.

The displacements corresponding to axial load ranging between 2 N and 20 N with the increment of 2 N are shown on the plots of Figure 9 a). On Figure 9 b) the displacements related to the transverse load are given, the range of which is 0.05 N to 0.2 N with the step size of 0.05 N.

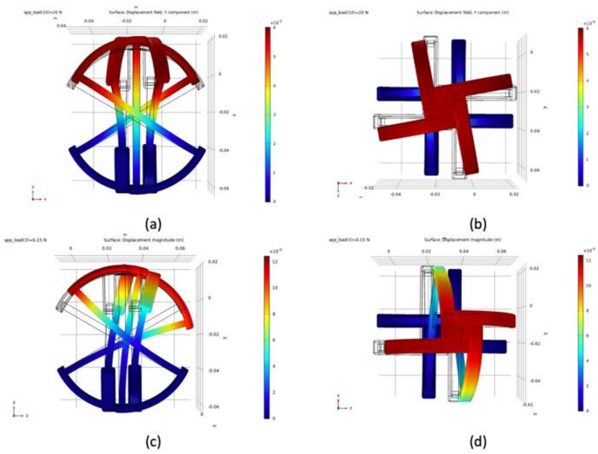

Fig. 8 – Illustrates of the Strains Induced due to Axial Loading (a, b) and Transverse Loading (c, d).

As illustrated a nonlinear behavior of the model can be observed when large deformations occur due to the nonlinear properties of the joint.

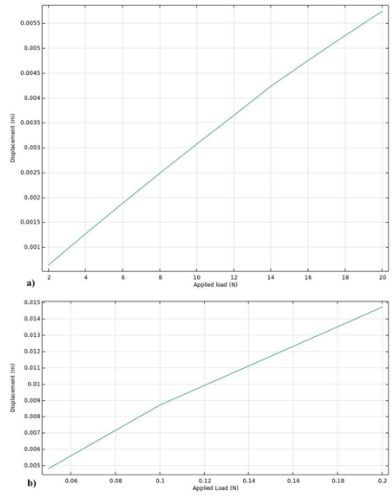

Fig. 9 – Displacement vs Load Plot a) Axial Loading (tension/compression); b) Transverse Loading (bending)

4. Discussion

The FEA simulation studies yields conforming results to the physical behavior of the design. The proposed configuration of the cross-spring pivot provides greater rotational stability due to the additional center leaf placed along the axis of the joint. However, in transverse plane when axial forces applied additional rotation can be observed about Z-axis. Designing such compliant joint for specific applications can be improved by parameterization of center-shift phenomenon and characterizing the mechanical properties of the flexible 3D printing materials.

The proposed design of a cross-spring joint has geometry similar to the ligaments of the human knee joint. The ligaments are tissue made from small fibers of collagen, twisted like a rope that attaches bones to other bones in the human body and provides stability of the joint. The application of the proposed compliant multi-material joint has been inspired by the knee ligament application since their geometrical similarities such as precision adjustments unbalanced forces in small displacement sensitive instruments. The proposed improved design of a cross-spring pivot is an ideal candidate owing to the degree of compliance it provides.

In addition, the joint can be 3D printed as one monolithic unit avoiding the assembly process as shown on Figure 10 (extracted from [14]). This prototype, made from PLA has the purpose to illustrate the model can be fabricated at once without assembling the parts. This can be especially applicable for 3D Printer using metal powder such as SLS (selective laser sintering) machines.

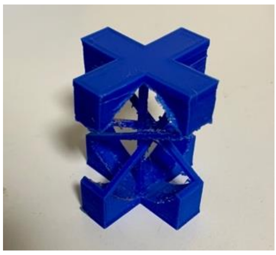

Fig. 10. Single 3D Print Prototype

The plans for future development of the current design extends to conduct experimental studies of a 3D printed prototype by 3D Laser Doppler Vibrometer (LDV) to validate its performance characteristics such as stress, displacements, rotational stiffness, natural frequency, etc. Both single and multi-material samples will be studied in this context as well. The frequency analysis will determine the vibration damping responses of the joint, to be used for stabilizing purposes. To optimize the stabilizing properties of the joint, 3D printing parameters - infill density, infill geometry, layer thickness, etc. - can be tuned (as mentioned in [15] and [16] the infill orientation, geometry and density could impact the stress performance of the printed samples).

5. Conclusion

In this paper a novel type of compliant multi-material joint is presented. The joint consists of two cross-spring compliant joints perpendicular to each other. The pivot has two rotations around its center according to X-axis and Y-axis. It has relatively small axial drift and stability in other planes of motion.

The design and methodology of creating the joint are described and 3D printing parameters are illustrated. The forces have been dissolved for all beams individually and depending on the various loading conditions as compression, tension and bending. A static FEM analysis has been conducted to demonstrate the behavior of the model.

Among the highlights of this model are its compactness – the rotational axis has matching center points. Its compliance leads to frictionless and wear free motion which preserves the reliability and durability in time. The multi-material pairing can be varied, and different material couple can be used depending on the requirements. Another advantage of its compliance is the adaptivity it has due to the flexibility of the elastic deformations.

There are several challenges that need to be considered in the design stage. Experiments need to be performed to determine the flexure from plastic buckling due to greater forces. Another important point is the material's fatigue. Further investigation needs to be conducted on fatigue testing of the joint. Lastly, it has relatively complex geometry which makes its fabrication by using traditional technologies with removing material nearly impossible task.

On the other hand, the rapid development of 3D Printing and Additive Manufacturing in general allows more creativity in the design stage and provides further future opportunities before the manufacturing in the context of the Fourth Industrial Revolution.

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