HYBRID BI-DIRECTIONAL FLEXURE JOINTS

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INTRODUCTION

Flexures can be found in many precision machines and mechanisms, including. Micro-positioning stages, load cells, micro electromechanical systems (MEMS), and precision measuring instruments. The most typical flexure setups include notch flexures, and leaf flexures (Figure 1).

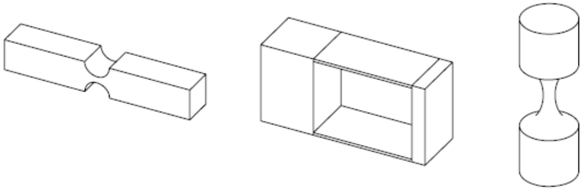

FIGURE 1: From left to right: a) Notch flexure, b) leaf flexure, c) 2 degree of freedom spherical notch flexure.

Flexural elements provide a means to allow displacement without the need for sliding mechanical interfaces such as sliding contacts or pinned connections. This is accomplished by connecting two rigid members using a thin elastic member that flexes at predefined locations or in a predictable shape, thus creating an elastic hinge [1]. The dimensions of the flexure joint determine the kinematic characteristics of the flexure, including: range of motion, in plane stiffness, out of plane stiffness, axial stiffness, pivot point location, and degrees of freedom. A typical goal of a flexure joint is to have the stiffness very high in all degrees-of-freedom except those that are intended to provide motion.

Notch and leaf-type flexures are typically intended to replace pin-type joints, providing 1 degree-of-freedom of relative motion between the rigid members. However, there are numerous applications where 2-DOF flexure joints are desirable, including micro electromechanical systems (MEMS), mirror positioning, optical mounts, multi-dof motion stages, metrology instruments, and microscopy [2, 3]. It is possible to connect 2 1-DOF flexures in series to create a 2-DOF joint (Figure 2). However, this joint does not provide intersecting axes of rotation for the 2 motions and is substantially more complex to manufacture and package since care must be taken to insure that the two notches can indeed be cut when fixtured in the cutting machine. Spherical notch flexures (FIGURE 1c) resemble thin wires connecting the rigid bodies and provide co-located 2-DOF motion. However, the very thin waisted joint has poor axial strength [3] and relatively low torsional stiffness

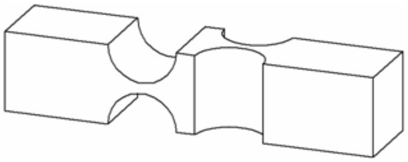

FIGURE 2: 2 DOF cross notch flexure example, axes of rotation are arranged orthogonal to each other

Two recent novel designs for multiple DOF flexural joints that attempt to address some of these issues are braided steel rope flexures, and the toroidal flexure [3, 4]. In these designs separate flexural elements are assembled between the two rigid members with the goal of providing a 2-DOF joint that is axially strong & stiff, has high out of plane stiffness, and is capable of a large range of motion. A drawback with these assembled designs is that they are not monolithic and it may be difficult to insure proper joint locations during assembly, which may affect the mechanism kinematics.

HYBRID BI-DIRECTIONAL FLEXURE JOINT

This report describes a novel 2-DOF flexure joint design that we have dubbed the Hybrid Bi-directional Flexure Joint (HBFJ) (FIGURE 3).. The HBFJ consists of two curved thin section members that form an annulus. As shown in Figure 4, the curved members that form the annulus can deform to permit rotation about both the Y and Z axes. However, this open structure is also very compliant in the X-direction which is not generally desirable. To overcome this, the annular cavity is filled with an elastomeric material. This is easily accomplished using 2-part liquid urethane compounds that fill the cavity and cure in place. The elastomer does not significantly increase the bending stiffness of the joint about the Y and Z axes due to the low flexural modulus of the material; but does drastically increase the axial stiffness of the system due to the much higher bulk modulus of the material. Due to the planar nature of the HBJF, it can be easily manufactured monolithically using traditional manufacturing techniques such as wire electro discharge machining (WEDM), high speed milling, and rapid prototyping.

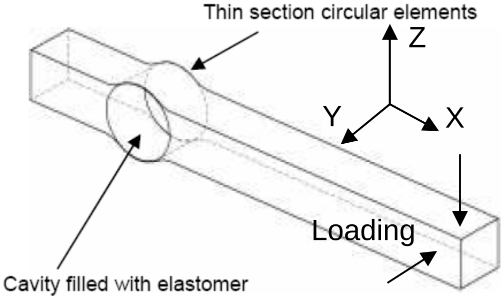

FIGURE 3: Hybrid bi-direction flexure joint

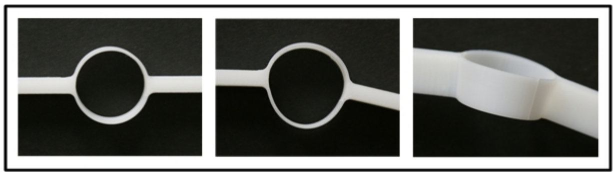

FIGURE 4: Prototype HBFJ constructed of ABS via rapid prototyping (cavity unfilled).

The geometry of the HBFJ is defined by 6 parameters, as illustrated in the following figure (FIGURE 5).

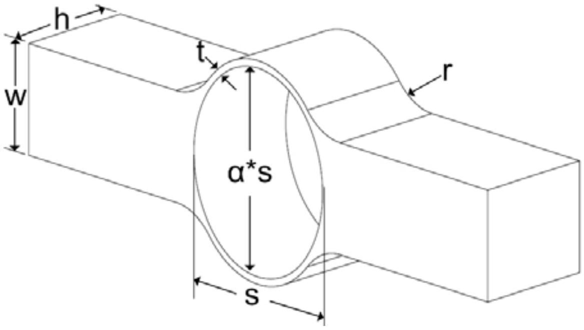

FIGURE 5: Parameters defining HBFJ

FEA MODELING OF THE *HBFJ*

In designing the HBFJ, finite element analysis (FEA) was used to determine stiffness, range of motion and stress distributions within the joint, and how utilizing different geometry and materials affect these properties. Here, the annulus is assumed to be elliptical in shape with major and minor axes *S* and *αS*. The rigid elements have height and width, *h* and *w*. The wall thickness of the annulus is *t*, and the fillet radius is *r*. A set of computational experiments was performed to show the effect of the geometric parameters on the stiffness, deflection, and load carrying properties of the HBFJ. For the FEA analyses, the structure was fixed at one end and force was applied at a distance 2.5S from the center of the joint. Figure 6 shows the free body diagram of the structural model, and a typical FEA result.

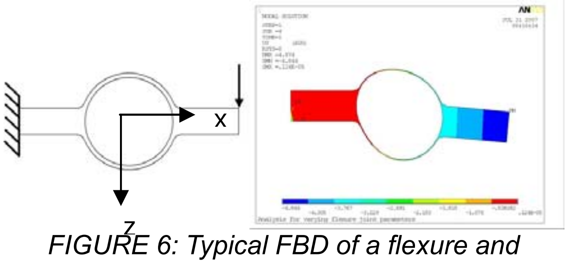

FIGURE 6: Typical FBD of a flexure and corresponding FEA results

STIFFNESS PROPERTIES OF THE *HBFJ*

The effect of joint geometry on stiffness was studied computationally by holding the material properties fixed and varying the geometric parameters shown above. A unit force was applied in the X, Y, and Z directions at a point 2.5S from the center of the annulus, and the resulting displacements were recorded. Figure 7 shows how the stiffness in the horizontal (Y), vertical (Z), and axial (X) directions are affected by variations in the parameters (Note differing scales Kx vs. Ky and Kz) . It can be seen that it is possible to obtain equal stiffness in both Y and Z directions by adjusting parameter *h* , and also to obtain axial stiffness 1 to 2 orders of magnitude higher than the transverse stiffnesses.

DEFLECTION PROPERTIES OF THE *HBFJ*

One desirable property of the HBFJ is that it can be designed to allow larger ranges of motion than notch-type flexures of the same size without sacrificing axial stiffness or load capacity. This is due to the extended length of the curved thin members which define the annulus, and function much like the leaves in a leaf-type flexure. However, when the joint is loaded axially it is not subject to the same buckling failure mode seen in the leaf flexure because the members are already curved and the embedded elastomer absorbs the load.

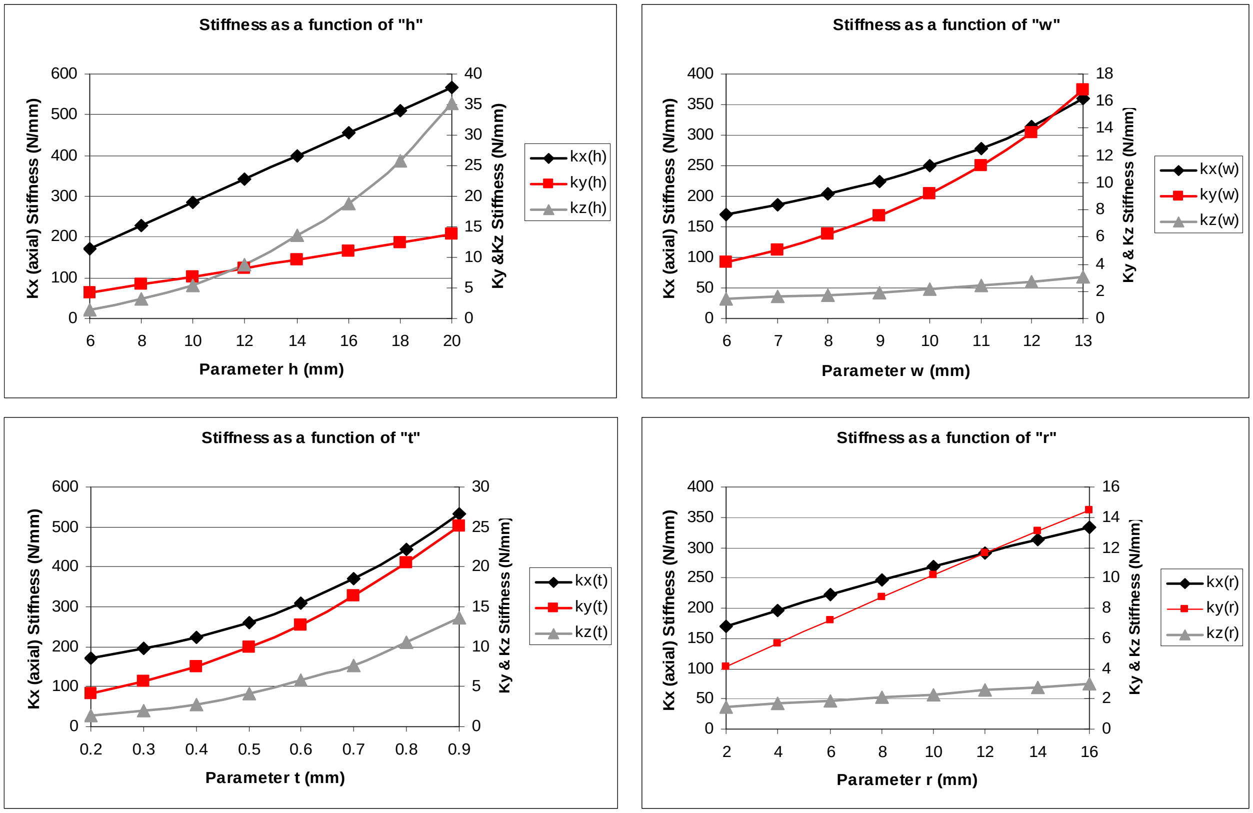

FIGURE 7: Stiffness change as a function of four different geometric parameters. Flexure material Aluminum E=70GPa, v=0.33; filler material Urethane E=30MPa, v=0.45

COMPARISON OF FLEXURE DESIGNS

The HBFJ is compared to more traditional notch-type and spherical notch-type flexures by creating designs which utilize the same material, the same minimum material thickness, and the same amount of axial space (see Figure 8). The stiffness, deflection, and load capacity properties are compared in Table 1. The range of motion for each design was computed using FEA by loading the flexures until the maximum von-Mises stress reached a target value of 200 MPa. It can be seen that it is possible to design a HBFJ of the same overall size as more traditional notch-type flexures, and with equivalent stiffness properties; but which allows significantly larger range of motion, and has higher axial load capacity.

Table 1. Comparison of flexure designs.

	Range (mm)		Stiffness (N/mm)			Max Axial Load(N)
	Y	**Z**	**Kx**	**Ky**	**Kz**	**Fx**
HBFJ	0.83	0.48	117	0.9	2.6	22
Circular Notch	0.48	N/A	4.5e3	2.4	N/A	800
Spherical Notch	0.77	0.77	443	0.01	0.01	3.5

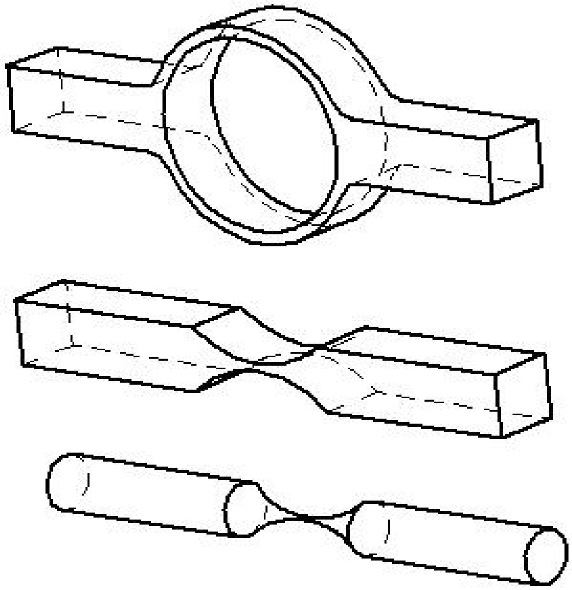

FIGURE 8. Flexure designs with comparable physical dimensions.

PHYSICAL TESTING OF THE HBFJ

Based on the FEA results, several HBFJ designs were fabricated and the stiffnesses were measured. The flexures were fabricated in ABS plastic via rapid prototyping, and the cavities were filled with a 2-part urethane. Three different grades of urethane (Shore Durometer 40, 60, and 80) were used to test their effectiveness in supporting axial loads and their effect on the bending stiffness of the joint. Also, 10 identical flexures with different heights "*h*" were tested to observe the effect of this variable on stiffness in the Y and Z directions.

Stiffness measurements were performed by clamping one end of the joint in a vise and hanging a known weight on the other, and measuring the resulting deflection with a height guage.. Figure 9 shows a comparison of the stiffness predicted by the FEA analysis, and the measured stiffness.

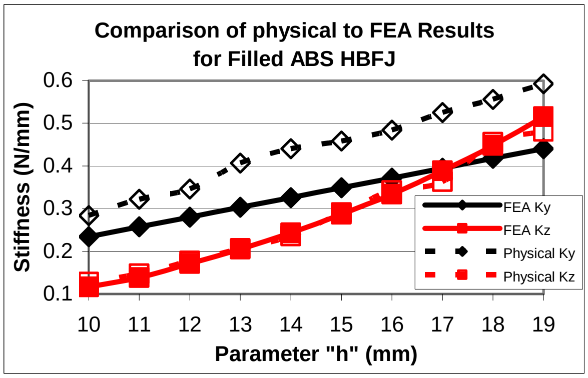

FIGURE 9. Comparison of experimental and FEA stiffness results.

APPLICATIONS OF THE HBFJ: 3-DOF FLEXURE STAGE

It is common to create planar motion stages comprised entirely of flexure joints. These typically take the form of flexural parallelogram mechanisms in a series configuration. Figure 10 shows a prototype stage with all HBFJ flexures. Because the HBFJ permits 2-DOF motion, this stage is capable of translating in 3-DOF while still capable of being fabricated as a planar structure.

CONCLUSIONS

This report describes a novel flexural joint design which can accommodate 2 degrees of freedom of motion. The joint consists of pairs of curved leaf-type elements that enclose an annulus. To increase axial stiffness of the joint, the annulus is filled with an elastomeric material that allows relatively low stiffness bending motions due to the low flexural stiffness of the material; while providing relatively higher axial stiffness due to the large compression area and rigid constraint from the leaf elements. FEA parameter studies show that it is possible to design HBFJ with low bending stiffness in the transverse DOF, combined with high axial stiffness. The HBFJ can provide larger range of motion than spherical notch flexures, combined with much larger axial load capacity.

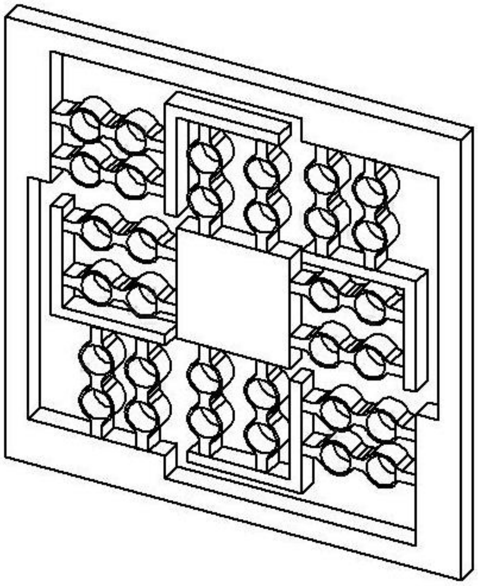

FIGURE 10. Proposed 3-DOF flexure stage.

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ACKNOWLEDGEMENTS

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