Multibody-based topology synthesis method for large stroke flexure hinges

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Abstract

Large stroke flexure hinges inherently lose support stiffness when deflected due to load components in compliant bending and torsion directions. To maximize performance over the entire range of motion, a topology optimization suited for large stroke flexure hinges is developed to obtain an optimized design tuned for a specific application. This method is applied on two test cases which have resulted in two hinge designs with unmatched performance with respect to the customary three flexure cross hinge.

Introduction

In high precision manipulators flexure-based mechanisms are often used for their deterministic behavior due to the absence of friction, hysteresis and backlash. However, when designing flexure hinges, designers face a trade-off between flexibility for motion in certain desired directions and stiffness to constrain motion for guiding in the remaining directions. Typical flexure hinges have a range of about 10 degrees beyond which the guiding stiffness and load bearing capacity decrease dramatically. Consequently, it is far from trivial to design flexure hinges suited for large stroke applications. By using a topology optimization suited for large deflections, guiding stiffness can be greatly increased for flexure hinges vastly exceeding 10 degrees range of motion.

Typical structural topology optimizations are based on density distribution or level set-functions. These methods divide the design domain into a large number of finite elements and employ piecewise constant "element densities" in each of the finite elements as the design variables. These methods show good results for small deformations. However, when more complex three-dimensional topologies are considered, the design domain becomes very large and topological optimizations can become computationally intensive. Furthermore geometrical nonlinearities are mostly disregarded as it significantly increases computation load and often iterative solvers are required which have the potential to fail to converge. This makes finite element modeling currently impractical for optimizing three-dimensional large stroke flexure mechanisms including the required non-linear effects.

To overcome limitations of existing optimization strategies, a new multibody-based topology synthesis method is developed for optimizing large stroke flexure hinges. This topology synthesis consists of a layout variation strategy based on a building block approach combined with a shape optimization to obtain the optimal design tuned for a specific application.

Topology synthesis method

The topology synthesis starts off with a shape optimization of an initial reference layout which is capable of obtaining an acceptable level of performance. For this initial layout the customary three flexure cross hinge (TFCH) is used, schematically illustrated in figure 1. Goal of this shape optimization is to obtain the optimal geometrical shape (flexure thickness, width, length, etc.) which provides maximum support stiffness for the considered application. To obtain the optimal shape, a parameterized description of the flexure hinge is used where an optimization algorithm searches for the optimal set of design parameters taken all constraints into account (in example maximum stress and required stroke). The performance of a specific set of design parameters is numerically evaluated with the flexible multibody program SPACAR [1] which uses a series of interconnected non-linear finite beam elements. Flexibility of these elements is naturally included in the formulation owing to a specific choice of discrete deformation modes. Therefore, only a limited number of elements is required to produce fast and accurate results. After the optimal shape of the initial reference is obtained, layout is updated to improve support stiffness and the newly obtained layout is re-optimized. By repeating this process of consecutive shape optimizations and layout updates, the optimal solution is attempted to be found. This strategy is schematically illustrated in figure 2.

Figure 1
Parameterized model of a TFCH

Figure 2
Schematic representation of topology synthesis method

Building block approach

In order to obtain the optimal flexure layout, a number of compliant "building blocks" are defined to synthesize the layout effectively [2]. With each layout update, a "building block" is replaced or added in order to try to improve support stiffness following from the typical stiffness properties of each building block and the critical support stiffness from the antecedent shape optimization. Three building blocks are combined to construct a single flexure hinge, one "building block" at the inner position of the flexure hinge (in example the middle leafspring of a TFCH), and two identical "building blocks" at the outer position of the flexure hinge (figure 1).

The building blocks which are used to update the layout are a leafspring (LS), a torsionally reinforced leafspring (TRLS) and a three flexure cross hinge (TFCH) as a sub-component of the flexure hinge. Each building block is schematically shown in figure 3. An overview of the typical stiffness properties at deflected state of each "building block" is given in table 1. Numerical values of the directional support stiffness (defined as the resistance to deformation in a specific direction while motion in all other directions is constrained) for each building block considering a "building block" width of 20mm, height of 50mm, flexure thickness of 0.5mm, E-modulus of 210GPa and an deflection angle of 0.6 rad is given between parentheses. Note that these values are affected by chosen geometry and material properties. However, they do provide a proper indication of the typical stiffness characteristics of each building block.

Leafspring: The first building block considered is the customary leafspring (LS, figure 3a). This element typically has only limited support when considering the stiffness properties in deformed state, except for translational stiffness in z-direction. Furthermore it provides high compliance in the desired degree of freedom (z-rotation).

Torsionally reinforced leafspring: In order to improve torsional stiffness around the y-axis and in-plane bending stiffness around the x-axis, the so-called torsionally reinforced leafspring (TRLS, figure 3b) is presented, which is inspired on the infinity hinge [3]. This building block consists of a single central leafspring reinforced with one or more folded leafsprings to improve torsional and in-plane bending stiffness. Motion compliance in the degree of freedom is reduced due to the added folded leafsprings.

Three flexure cross hinge: The third "building block", which aims at increasing translational stiffness in x and y-direction over the range of motion, is a three flexure cross hinge (TFCH, figure 3c). Two three flexure cross hinges can be stacked in series to form the so-called Double Three Flexure Cross Hinge (DTFCH) which provides increased translational support stiffness.

Figure 3

Deflected flexural building blocks used to "synthesize" flexure layout

Support stiffness	LS	TRLS	DTFCH
X-translation [Nm]	− (4.1E+03)	− (8.6E+03)	+ (1.2E+05)
Y-translation [Nm]	− (4.1E+04)	− (8.2E+03)	+ (2.9E+05)
Z-translation [Nm]	+ (6.6E+06)	+ (6.7E+06)	− (6.5E+05)
X-rotation [Nm/rad]	− (4.8E+01)	+ (1.4E+03)	− (3.1E+01)
Y-rotation [Nm/rad]	− (5.6E+00)	+ (1.3E+03)	− (1.6E+01)
Motion compliance			
Z-rotation [rad/Nm]	+ (1.30E+01)	− (4.9E-01)	+ (1.30E+01)

Table 1:

Stiffness properties of building blocks in deflected state

Optimization examples

In order to illustrate the applicability of the suggested method, two optimization cases will be discussed. The first case aims at a maximization of a directional support stiffness, and the second case gives an optimization aimed at maximizing the first parasitic frequency for a specific mechanism. For both case an allowable stroke of -45 to 45 degrees deflection is considered and the maximum width is bounded to 85 mm. Furthermore, selected material is steel where we limit the allowable stress due to deformation to 600 MPa, about 1/3 of the yield stress.

Case 1: The first case aims at optimizing the support stiffness orthogonal to the axis of rotation (for this case the vertical support stiffness). The support stiffness for the shape optimized initial reference layout (the TFCH consisting of leafsprings for the inner and outer building block) decreases to 250 N/mm at a maximum deflection angle, which is less than 1% of the stiffness without deflection. The final optimized layout after 2 layout updates, consisting of a double TFCH for either the inner and outer building block, shows a minimum support stiffness of 2100 N/mm over the range of motion, which is an increase in performance of about a factor eight. A CAD rendering and a photograph of a prototype resulting from the optimized topology (made of duraform PA) is shown in figure 4. An overview of the support stiffness of intermediate shape optimization is given in table 2.

Figure 4a

CAD rendering of optimized flexure hinge

Figure 4b

Photograph of optimized flexure hinge

Iteration	Outer building block	Inner building block	Minimum support stiffness (45° deflection)	Maximum support stiffness (0° deflection)
1	Leafspring	Leafspring	250 N/mm	88.000 N/mm
2	Leafspring	Double TFCH	800 N/mm	41.000 N/mm
3	Double TFCH	Double TFCH	2100 N/mm	63.000 N/mm

Table 2

Support stiffness for intermediate shape optimizations

Case 2: For the second case, an optimization is performed aimed at maximizing the first parasitic frequency of the mechanism presented by Folkersma et al. [4]. In short, the flexure hinge considered for this application is subjected to a mixed load of inertia ($I_{xx} = 3.8e^{-3}$, $I_{yy} = 3.5e^{-2}$, $I_{zz} = 3.8e^{-2}$) and mass ($m = 0.57 \text{ kg}$) concentrated in the pivot of the joint, where most emphasis is put in the inertial load. In table 3 an overview is given of the minimum parasitic frequency over the range of motion of each optimized layout at each layout update step. The first parasitic eigenfrequency for the shape optimized initial reference (again the TFCH consisting of leafsprings for the inner and outer building block) decreases up to 10 Hz, which is about 7% of the frequency without deflection. The final optimized layout, consisting of six reinforced leafsprings stacked in series supported by two double TFCH's at either side of joint, shows a minimal parasitic frequency of 100 Hertz, which is an increase of about a factor ten in parasitic frequency. A CAD rendering and a photograph of a prototype resulting from the optimized topology is shown in figure 5.

Figure 5a
Cad rendering of optimized flexure hinge

Figure 5b
Photograph of optimized flexure hinge

Iteration	Outer building block	Inner building block	Minimum parasitic frequency (45° deflection)	Maximum parasitic frequency (0° deflection)
1	Leafspring	Leafspring	10 Hz	150 Hz
2	Leafspring	TRLS (1x)	14 Hz	56 Hz
3	Leafspring	TRLS (2x)	39 Hz	154 Hz
4	Double TFCH	TRLS (2x)	43 Hz	203 Hz
⋮	⋮	⋮	⋮	⋮
8	Double TFCH	TRLS (6x)	100 Hz	132 Hz

Table 3
Frequency of first parasitic mode for intermediate shape optimizations

For a step-by-step animation of this optimization case, go to <https://www.youtube.com/watch?v=5scbEwPiq6Q> (Appendix A)

Experimental validation

To validate the models which are used for evaluating the performance of the flexure hinges, an experimental validation is conducted. For this validation, the optimized flexure hinge of figure 5 is used. For practical reasons, this flexure hinge is made of duraform PA (Nylon) and is manufactured with selective laser sintering. Furthermore, due to the different material properties of Nylon with respect to steel and due to geometrical limitations with respect to the sintering process, the flexure thickness is increased to at least 0.7mm to comply with the SLS Nylon additive manufacturing technology.

To verify the results, a series of measurements were performed to confirm the frequencies of the first four disturbing vibrating modes of interests. In figure 6 the measurement setup is shown for measuring rotational modes around the x-axis. To measure the eigenfrequencies over its entire range of motion, the hinge was held in deformed state by a wire flexure to prevent any interaction with the considered eigenmodes. Those measurements were repeated over the entire range of motion in steps of 5 degrees, where a protractor was used to obtain the deflection angle.

An overview of the experimental results over the entire range of motion is given in figure 7. The frequency of the first disturbing mode, consisting of a rotation around the x-axis, shows a good agreement with the model results. The second and third disturbing mode, consisting of translations in the x and y-direction, and the fourth disturbing mode consisting of a rotation around the y-axis, shows a slight deviation in frequency. However, these deviations are in an acceptable range and only provide a positive increase in frequency. The deviations with respect to the experimental results can be explained by interaction between modes with frequencies close to each other and mixing of eigenmodes. Furthermore, possible inconsistencies in material properties and flexure thickness due to the sintering process can be of influence. The overall trend of the disturbing eigenfrequencies shows good agreement and confirm the used models, although the exact modeshape could only be confirmed for the first vibrational mode.

Figure 6
Measurement setup for testing vibration modes at -20 degrees deflection

Figure 7
Experimental validation of the first four parasitic eigenfrequencies

Conclusion

To effectively optimize topology for large stroke flexure hinges, a new multibody-based topology synthesis method has been developed which combines a building block based layout variation strategy with a shape optimization method to obtain the optimal topology. This method shows good results for optimizing flexure hinges vastly exceeding the 10 degrees range of motion and is capable of obtaining optimized solutions in a matter of hours.

The proposed method is used to design two flexure hinges for two selected applications which both resulted in a flexure design with unmatched performance. An optimization case aimed at maximizing support stiffness showed an increase in support stiffness of a factor eight with respect to the customary three flexure crosshinge. For a second case, a flexure hinge is optimized to maximize parasitic frequency, which resulted in a increase in performance of a factor ten.

REFERENCES

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- [4] Folkersma KGP, Boer SE, Brouwer DM, Herder JL, Soemers HMJR. A 2-dof Large Stroke Flexure based Position Mechanism. IDETC ASME, Chicago, IL, USA, Aug, 12-15, 2012

Appendix A: Snapshots "Multibody-based topology synthesis optimization of a large stroke flexure hinge"

Link: <https://www.youtube.com/watch?v=5scbEwPiq6Q>

Iteration 1: LS & LS

Iteration 2: TRLS (1x) & LS

Iteration 3: TRLS (2x) & LS

Iteration 4: TRLS (2x) & DTFCH

Iteration 5: TRLS (3x) & DTFCH

Iteration 6: TRLS (4x) & DTFCH

Iteration 7: TRLS (5x) & DTFCH

Iteration 8: TRLS (6x) & DTFCH