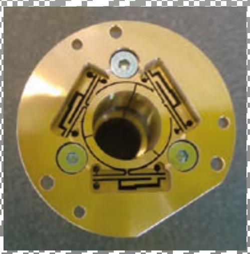
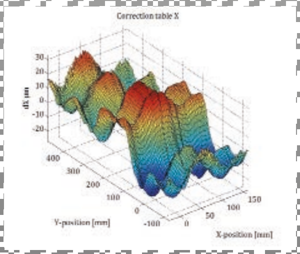
DSPE MIKRONIEK

2017 (VOL. 57) ISSUE 3

PROFESSIONAL JOURNAL ON PRECISION ENGINEERING

- THEME: **FLEXURES AND MECHANISMS**
- **EUSPEN CONFERENCE 2017** REPORT
- **PLACEMENT ACCURACY** IMPROVEMENT
- PRECISION **SURFACE FINISHING**





MIKRONIEK IS A PUBLICATION OF THE DUTCH SOCIETY FOR PRECISION ENGINEERING WWW.DSPE.NL

PUBLICATION INFORMATION

Objective
Professional journal on precision engineering and the official organ of DSPE, the Dutch Society for Precision Engineering. Mikroniek provides current information about scientific, technical and business developments in the fields of precision engineering, mechatronics and optics.
The journal is read by researchers and professionals in charge of the development and realisation of advanced precision machinery.

Publisher
DSPE
Annemarie Schrauwen
High Tech Campus 1, 5656 AE Eindhoven
PO Box 80036, 5600 JW Eindhoven
info@dspe.nl, www.dspe.nl

Editor
Hans van Eerden, hans.vaneerden@dspe.nl

Advertising canvasser
Gerrit Kulsdom, Sales & Services
+31 (0)229 – 211 211, gerrit@salesandservices.nl

Design and realisation
Drukkerij Snep, Eindhoven
+31 (0)40 – 251 99 29, info@snep.nl

Subscription
Mikroniek is for DSPE members only.
DSPE membership is open to institutes, companies, self-employed professionals and private persons, and starts at € 80.00 (excl. VAT) per year.

Mikroniek appears six times a year.

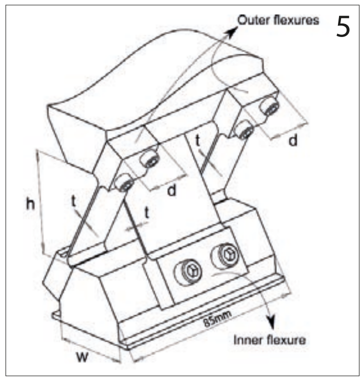
ISSN 0026-3699

The main cover photo (featuring a deployable solar array) is courtesy of Prof. L.L. Howell, Brigham Young University Compliant Mechanisms Research group. Read the article on page 13 ff.

IN THIS ISSUE

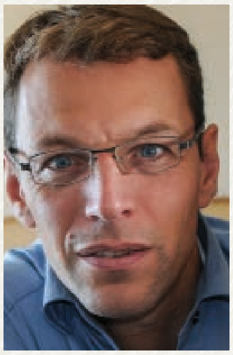
ISSUE 3 2017

Theme: Flexures and mechanisms



FEATURES

FLEXURE FUTURE



In precision mechatronics, flexure mechanisms have become commonplace but developments haven't stopped. Therefore, this issue of Mikroniek is devoted to recent trends in flexures, or rather compliant mechanisms, as their family name has come to be, usually defined as those mechanisms that move due to deformation. They lend themselves very naturally for high precision as they lack friction and backlash, and no lubrication is needed, which is beneficial in hostile environments such as vacuum, underwater or in the human body. On the other hand, their design has some inherent complications: there is always mechanical stress involved in any motion, and the behaviour is dependent of the load case. This implies that kinematics (motion) and kinetics (load case) must be treated simultaneously and that the concept of degrees of freedom fades in compliant mechanisms, because they behave differently for any load case. Many efforts have been undertaken to arrive at workable definitions of mobility, for instance by defining compliance ellipsoids of the point of interest.

Over time, various configurations of wire and leaf flexures, also known as compliant architectures, have been identified that are less affected by the above complications. While their design principles remain of vital importance, there are several drivers for renewed interest in this field. Increased computer power resulted in desktop tools for the analysis of compliant structures right from the drawing board. Although non-linear phenomena like buckling and large deflection remain very tricky, a first impression of linearised behaviour is now at our fingertips. More important is the development of new modelling theory which supports the synthesis of compliant mechanisms directly.

A simple example is so-called pseudo-rigid-body modelling (PRB), where virtual joints emulate the effect of distributed deflection. This results in models with very few parameters, and provides a portal to the large domain of known linkages. Another new modelling approach is the freedom and constraint topology method (FACT), which is based on spatial kinematics and its duality with statics. This method allows one to find the solution space for a given motion or load task, rather than a single solution, giving more freedom to the designer. Also topology optimisation (TO) is maturing and becoming accessible, while the irregular shapes that tend to come out can now be produced by additive metal manufacturing, a promising combination. Interestingly, TO results oftentimes appear organic, providing a link to biomimicry and bio-inspiration, which is very topical.

The drive for miniaturisation has revived interest in methods for manufacturing compliant mechanisms from flat layers of material, i.e. compatible with MEMS technology. Effort into so-called lamina-emergent mechanisms (LEM) has led to a hype in engineering origami and pop-up where spatial compliant structures are created that are hard to produce otherwise. Generalising the idea of origami has also given rise to the development of shell mechanisms, i.e. spatially curved compliant structures, and methods for their synthesis helping the designer create and understand these complex shapes.

Actuation of compliant mechanisms is always a challenge, typically solved by ensuring that part of the mechanism motion is compatible with a given actuator. Avoiding this challenge, and exploiting the large deforming surface, distributed actuation and sensing technology is under investigation where besides piezo layers also polymer-based types are used for driving the mechanism or reducing the adverse effects of undesired degrees of freedom.

Clearly, a lot is going on in compliant mechanisms, with many promising directions for more than incremental progress being explored and included in modern educational curricula.

Just Herder
Professor of Interactive Mechanisms and Mechatronics, Delft University of Technology
j.l.herder@tudelft.nl

LARGE-STROKE FLEXURE HINGES

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

MARK NAVES, RONALD AARTS AND DANNIS BROUWER

Introduction

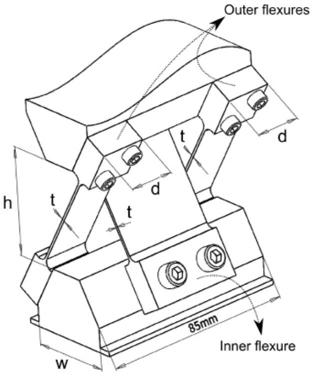
In high-precision manipulators, flexure-based mechanisms are often used for their deterministic behaviour, which is due to the absence of friction, hysteresis and backlash. However, when designing flexure hinges, designers face a trade-off between flexibility for motion in certain desired directions, and stiffness to constrain motion for guiding in the remaining directions. Typical flexure hinges have a range of about 10°, beyond which the guiding stiffness and load-bearing capacity decrease dramatically. Consequently, it is not a minor thing to design flexure hinges suited to large-stroke applications. By using a topology optimisation suitable for large deflections, guiding stiffness can be greatly increased for flexure hinges vastly exceeding a 10° range of motion.

Typical structural topology optimisations are often based on density distribution functions, which 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. This method shows good results for small deformations. However, when more complex three-dimensional topologies are considered, the design domain becomes very large and topological optimisations can become computationally intensive. Furthermore, geometrical nonlinearities are mostly disregarded, as they significantly increase computational load, and often iterative solvers are required, which have the potential to fail to converge. This makes finite-element modelling currently impractical for optimising three-dimensional large-stroke flexure mechanisms including the required nonlinear effects.

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

Topology synthesis method

The topology synthesis begins with a shape optimisation 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.
The goal of this shape optimisation is to obtain the optimal geometrical shape (flexure thickness, width, length, etc.) that will provide maximum support stiffness for the application considered. To obtain the optimal shape, a parameterised description of the flexure hinge is used, where an optimisation algorithm searches for the optimal set of design parameters, taking all constraints into account (in the example given, maximum stress and required stroke).

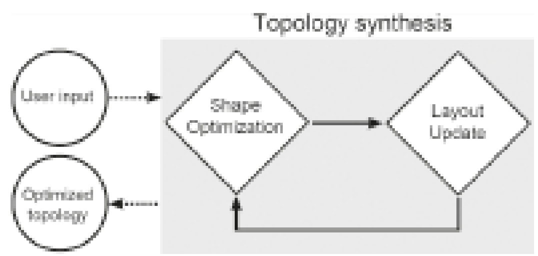


1 *Parameterised model of a three-flexure cross hinge (TFCH).*

AUTHORS' NOTE

Mark Naves, Ph.D. student, and Dannis Brouwer, Professor, are members of the chair of Precision Engineering, and Ronald Aarts, Associate Professor, is a member of the chair of Structural Dynamics, Acoustics & Control, all in the Department of Mechanics of Solids, Surfaces & Systems at the University of Twente, the Netherlands.
Some of this work was presented at the 17th euspen Conference & Exhibition on 30 May - 2 June 2017 in Hannover, Germany.

m.naves@utwente.nl
www.utwente.nl/en/et/ms3



2

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 nonlinear finite-beam elements. The 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, the layout is updated to improve support stiffness, and the newly obtained layout is re-optimised. In an attempt to find the optimal solution, this process of consecutive shape optimisation and layout update is repeated. This strategy is schematically illustrated in Figure 2.

Building-block approach

In order to obtain the optimal flexure layout, a number of compliant 'building blocks' are defined to synthesise the layout effectively [2]. With each layout update, a building block is replaced or added in order to try to improve support stiffness, based on the typical stiffness properties of each building block and the critical support stiffness from the antecedent shape optimisation. Three building blocks are combined to construct a single flexure hinge: one building block at the inner position of the flexure hinge (in the example, the middle leaf spring of a TFCH); and two identical building blocks at the outer position of the flexure hinge (Figure 1).

The building blocks used to update the layout are a leaf spring (LS), a torsionally reinforced leaf spring (TRLS) and a three-flexure cross hinge (TFCH). Each building block is schematically shown in Figure 3. An overview of the typical stiffness properties at a 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 – given a building block width of 20 mm, height of 50 mm, flexure thickness of 0.5 mm, E-modulus of 210 GPa and deflection angle of 0.6 rad – are presented between parentheses. Note that these values are affected by selected geometry and material properties. However, they do provide a proper indication of the typical stiffness characteristics of each building block.

Table 1. Stiffness properties of building blocks in a deflected state.

	LS	TRLS	TFCH
Support stiffness			
x-translation [N/mm]	– (4.1)	– (8.6)	+ (120)
y-translation [N/mm]	– (41)	– (8.2)	+ (290)
z-translation [N/mm]	+ (6,600)	+ (6,700)	– (650)
x-rotation [Nm/rad]	– (48)	+ (1,400)	– (31)
y-rotation [Nm/rad]	– (5.6)	+ (1,300)	– (16)
Motion compliance			
z-rotation [rad/Nm]	+ (13)	– (0.49)	+ (13)

Leaf spring (LS)

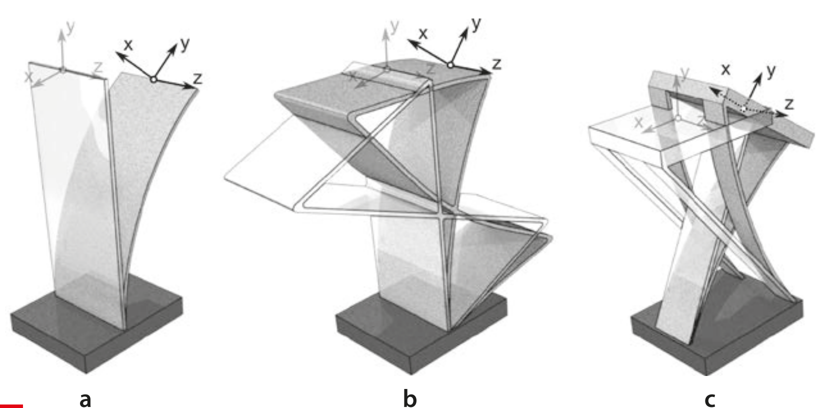
The first building block considered is the customary leaf spring (Figure 3a). This element typically has only limited support when considering the stiffness properties in its deformed state, except for translational stiffness in z-direction. Furthermore, it provides high compliance in the desired degree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

Torsionally reinforced leaf spring (TRLS)

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

Three-flexure cross hinge (TFCH)

The third building block, which aims to increase translational stiffness in x- and y-direction over the range of motion, is a three-flexure cross hinge (Figure 3c). Two TFCHs can be stacked in series to form the so-called double TFCH (DTFCH), which provides increased translational support stiffness.



3

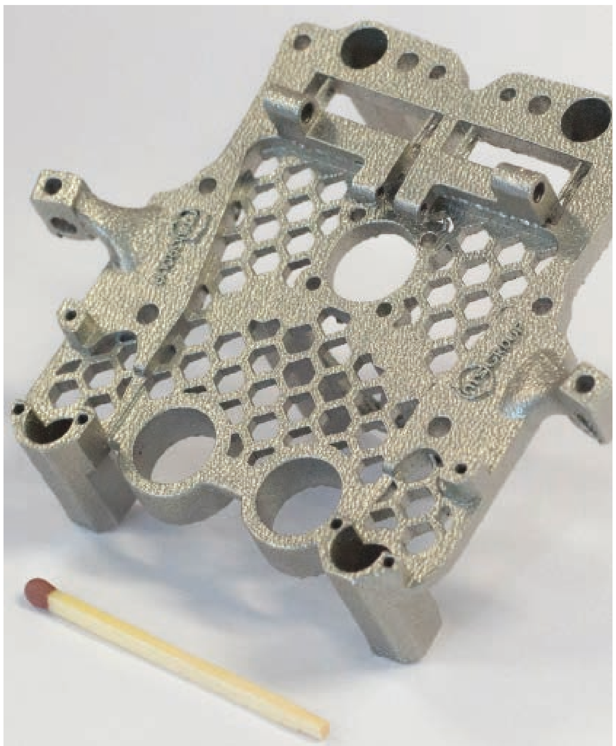
2 *Schematic representation of the topology synthesis method.*

3 *Deflected flexural building blocks used to 'synthesise' flexure layout.*
(a) LS.
(b) TRLS.
(c) TFCH

MONOLITHIC MECHANISMS BEYOND EDM

About four years ago, high-tech system supplier NTS started to invest in 3D printing, or additive manufacturing, by participating in AddLab, a facility which was built on the ambition to develop a broad range of high-end applications for 3D metal printing. Recently, the transition was made from the lab to the fab, AddFab, and NTS strengthened its focus on industrial metal printing. This article briefly describes the challenges involved in printing metal parts with integrated flexures, supported by cases developed by NTS over the last three years.

JEROEN JONKERS



Design principles are widely used in the high-tech industry. Construction elements such as hinges, struts, etc., are nowadays designed to be manufactured using technologies like milling, wire-erosion, sheet metalwork, etc. Additive manufacturing (AM), or 3D printing, however, is not yet commonly used for this purpose, but it turns out to be a very suitable manufacturing technology for this field of application as an alternative to Electric Discharge Machining (EDM). It opens up new design opportunities for multi-DoF mechanisms (DoF = degree of freedom) and optimisation of product mass.

AUTHOR'S NOTE

Jeroen Jonkers is design engineer at NTS-Group, based in Eindhoven, the Netherlands.

jeroen.jonkers@nts-group.nl

Additive manufacturing challenges

NTS is a high-tech system supplier specialised in the development, production and assembly of opto-mechatronic systems, mechanical modules and its critical components. At AddFab [1], NTS uses the AM process called powder bed fusion, which is capable of producing metal parts with mechanical properties close to what is known from bulk material. Powder bed fusion, which uses a focused laser beam to melt thin layers of metal powder, is an excellent process for fabricating metal parts.

Although the process is able to create dense material with predictable properties, thermal variations do induce thermal stresses and shrinkage. The latter makes 3D printing of flexures a challenge. Thermal stresses and shrinkage can result in part deformation which conflicts with the need for defined position and shape accuracy.

When designers select AM as the manufacturing technology for their design, they have considerable influence on both geometrical accuracy and other properties. 3D printing of flexures requires in-depth process knowledge to produce successful designs. In order to have full control over the manufacturing process, designers need to specify supporting structures and laser strategies specifically for the used material, layer thickness and geometry. This extends far beyond the specification of only the end product, so in fact the AM designer has to define the production strategy for the product as well.

Mechanical properties

Over the years the mechanical properties and density of printed products have been tested/monitored and at AddFab this practice is continued. Despite the testing and material knowledge, micro-cracks and notch effects are a matter of concern regarding fatigue strength. The good news is that areas of risk are predictable to a great extent and if required, post-processing can be used to remove defects. It is the nature of the material/AM process combination, but experience has learned that 3D-printed flexures are very usable in applications that undergo a small number of load cycles during the product lifetime. Although fatigue strength is a point of attention, the increased degree of design freedom allows the manufacturing of organic shapes that can avoid stress and strain concentrations which reduces the risk of fatigue, see Cases 2 and 3 below.

Subtractive manufacturing challenges

AM is all about the creation of new starting material. It is great that the technology enables creating parts out of pure functional material but as stated before, thermal stresses can cause deformation. If accurate features and/or surface finishing are required, post-machining will probably be needed. It is nothing new for designers to be aware of all manufacturing technologies involved with the product design. With AM it is easy to manufacture complex-shaped parts and the requirements for post-machining might be overlooked. AM designers need to think ahead and ensure that post-machining is possible after printing and therefore take account of clamping/machining forces, vibrations, tools paths, thread tapping, cleaning, etc.

In conclusion

Although 3D printing of high-tech components with flexures is challenging, it definitely shows promise for the industry. Through the design cases, NTS has gained insight into manufacturability and costs. By having AM in its design and manufacturing portfolio, NTS is well prepared and ready for the next challenges in high-tech systems development.

REFERENCES

[1] "From AddLab to AddFab – KMWE, NTS-Group and Machinefabriek de Valk continue 3D printing collaboration", *Mikroniek* 56 (5), pp. 32-34, 2016.

INFORMATION
WWW.NTS-GROUP.NL
WWW.ADDFAB.NL

Case 1: Model conversion (2014)

The function of the original part is to align a laser beam by means of two adjustable mirrors on flexure tilt mechanisms. The goal was to make a printable version and therefore avoid the need to make the hinges by means of wire erosion (which is time-consuming, hence expensive, and for complex products presents a real risk of rejection due to wire break). For the AM part (b), the goals were set to have a comparable surface roughness at the mirror interfaces and mechanical properties of the hinges. By adding only the functional material the AM part is printed from 90% (!) less material compared to the starting situation for the conventional (subtractive) process.

a *Original part with illustrated beam path.*

b *AM conversion.*

c/c* *Detail of leaf spring.*

d *Leaf spring, thickness 1 mm.*