DSPE MIKRONIEK
2021 (VOL. 61) ISSUE 2
PROFESSIONAL JOURNAL ON PRECISION ENGINEERING

- THEME: MICROSYSTEMS
- WATCH INNOVATION BASED ON COMPLIANT MECHANISMS
- DUAL-LOOP CONTROL STRATEGY TO COUNTERACT GEAR BACKLASH
- TUNING THE STIFFNESS OF COMPLIANT ORTHO-PLANAR MECHANISMS

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.

DSPE
YOUR PRECISION PORTAL

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

Editorial board
Prof.dr.ir. Just Herder (chairman, Delft University of Technology),
Servaas Bank (VDL ETG), B.Sc.,
ir.ing. Bert Brals (Sioux Mechatronics),
Maarten Dekker, M.Sc. (Philips),
Otte Haitsma, M.Sc. (Demcon),
dr.ir. Jan de Jong (University of Twente),
ing. Ronald Lamers, M.Sc. (Thermo Fisher Scientific),
Erik Manders, M.Sc. (Philips Innovation Services),
dr.ir. Pieter Nuij (MaDyCon),
dr.ir. Gerrit Oosterhuis (VDL ETG),
Maurice Teuwen, M.Sc. (Janssen Precision Engineering)

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.

© Nothing from this publication may be reproduced or copied without the express permission of the publisher.

ISSN 0026-3699

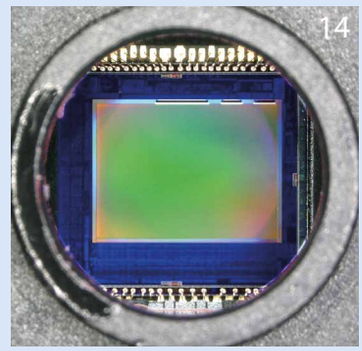
The cover image (featuring an exploded view of the Slimline Monolithic Manufacture) is courtesy of Frederique Constant. Read the article on page 5 ff.

IN THIS ISSUE

THEME: MICROSYSTEMS

05
Watch innovation based on compliant mechanisms
Swiss watchmaker Frederique Constant has launched a technological breakthrough in the field of precision timekeeping. Its Slimline Monolithic Manufacture features a high-frequency, monolithic oscillator, designed as a compliant mechanism by Dutch company Flexous Mechanisms.

08
Positive, negative or close to zero
Compliant ortho-planar mechanisms can be fabricated from a single sheet of material and they can move out of the plane in which they are fabricated. A design is presented that allows tuning of the stiffness.



12
Precision drive technology – Dual-loop control
Maxon presents dual-loop control for positioning loads dynamically, with high precision and no oscillation, despite the presence of mechanical backlash and elastic components.

14
Manufacturing technology – CO_2 snow-jet cleaning
Acp systems has developed CO_2 snow-jet technology for the efficient and reliable cleaning of delicate image sensors and system housings.

16
Manufacturing technology – Milling, hard-turning and grinding in one machining centre
Spinner Machine Tools is the first to integrate hard-turning, external grinding and internal grinding in one machine. An impressive achievement, because the Microturn Grind can mill accurately as well.

FEATURES

04 EDITORIAL
Paul Desmedt, programme manager at Eindhoven Engine, on the introduction of agility in the transition from research to development, to accelerate the innovation process.

11 UPCOMING EVENTS
Including: DSPE Conference on Precision Mechatronics 2021.

20 ECP2 COURSE CALENDAR
Overview of European Certified Precision Engineering courses.

21 NEWS
Including: Mikrocentrum director Geert Hellings resigns.

TO BE AGILE OR NOT TO BE?

(Photo: Bart van Overbeeke)

In an ever faster-paced world, the answer is obvious: we should definitely be 'agile', to learn to adapt swiftly to different circumstances. Yet should we embrace the agile methodologies so popular in software development (Scrum, Scaled Agile Framework, etc.) in other disciplines such as precision engineering?

Software development walls often show flourishing post-it collections used by dynamic self-steering teams that deliver very frequent product updates for customers. Software development is now basically agile development around the globe. In extreme cases, it results in multiple releases every hour. Hardware development has been slower in adopting these agile technologies. The key advantage of software development is that innovation is faster and yields more results, with cross-silo development and more customisation, so it is not surprising that 'hardware companies' such as ASML (Scaled Agile Framework) and Bosch (Scrum at scale) are working currently on an agile transition.

However, this transition is not a straightforward one for hardware development, in the same vein as it was not easy for software development. To make software development agile, many steps require revision: requirements and test creations become intertwined; planning is critical; software testing needs automation; etc. Every aspect of the development process has to facilitate the creation of releases.

For precision engineering and hardware development in general, inherent limitations will not allow such extremely fast releases; for instance, material handling and transportation will always introduce delays. However, production with high flexibility is already possible: automotive production lines are succeeding in producing individual cars seconds apart. Hardware development is still far away from keeping up with this flexibility of the production process. Fortunately, for hardware engineering, many fields are progressing to enable agility: systems engineering is crossing the boundaries of disciplines (every boundary is a delay); digital engineering and digital twins are creating digital connectivity; 3D printing for prototyping/testing; platform development; etc.

Though all these fields and process supports are extremely important, we, humans, are the critical factor in achieving these fast innovations. Not surprisingly, agile methods encourage human interaction: the Manifesto for Agile Software Development (*www.agilemanifesto.org*) starts with "Individuals and interactions over processes and tools". Agile methods hence put heavy emphasis on self-steering teams, intense interaction between teams (program increment planning events), cross-disciplinary value chains (development trains), and customer involvement. This is equally so at Eindhoven Engine.

At Eindhoven Engine, we want to accelerate innovation to match the 'exponentiality' of the world. We are introducing agility in the transition from research to development, to accelerate a process that up until now is essentially linear (and time consuming). With currently 15 projects in key areas of the Brainport region (healthcare, mobility, precision engineering, etc.), the Eindhoven Engine ecosystem is building. Agile methodologies (self-steering teams, cross-disciplinarity, customer involvement) shorten the path to innovation. The realisation of innovation is powered by the integral support of bright minds at all levels from Eindhoven University of Technology, TNO and Fontys University of Applied Sciences (the founding fathers of Eindhoven Engine), hospitals and companies. If you are keen to be involved in our community or to actively participate in this ecosystem, do not hesitate to contact us.

Paul Desmedt
Programme manager at Eindhoven Engine
p.a.c.desmedt@tue.nl, www.eindhovenengine.nl

SLIMLINE MONOLITHIC MANUFACTURE

Last month, Swiss watchmaker Frederique Constant launched a technological breakthrough in the field of precision timekeeping. Redefining the principles of mechanical watch regulation, its Slimline Monolithic Manufacture delivers industry-leading precision by ticking ten times faster than most mechanical movements. Etched from silicon, its monolithic oscillator, designed as a compliant mechanism by Dutch company Flexous Mechanisms, replaces an assembly of several parts and eliminates many of the major weaknesses of mechanical watches. The high-frequency oscillator fits inside a traditional movement configuration, housed inside a 40-mm case.

The way mechanical watches are regulated has not changed during the last three centuries. The invention of the sprung balance in the 17th century has exerted a lasting influence on mechanical watchmaking. Since then, mechanical watches have relied almost exclusively on the sprung balance. Consisting of a thin, coiled spring attached to the balance wheel, it allows the balance to oscillate back and forth at a constant frequency. In doing so, it controls the speed at which the gears of the watch rotate and influences the rate. Although it has been improved over time, the principle of the sprung balance has remained unchanged and virtually unchallenged for over three centuries.

1

Presented in a 40-mm round case, the Frederique Constant Slimline Monolithic Manufacture features an elegant dial with a guilloché/stamped hobnail pattern, printed Roman numerals paired with Breguet-style hands. The pulsating high-tech oscillator is visible in an aperture at 6 o'clock, while the pointer date at 12 o'clock was designed to create a classic counterpoint [V1].

Watch principles

The basic principle behind a mechanical watch is as follows:

Energy ⟶ Transmission ⟶ Escapement ⟶ Oscillator

The energy (stored by a coiled spring in a watch) is released in discrete bursts by the regulating organ, which is comprised of an escapement and an oscillator. The escapement transmits impulses to the oscillator (the balance wheel for the vast majority of mechanical wristwatches). The escapement, in turn, is regulated by the oscillator. Each oscillation, therefore, allows the gear train to advance or 'escape' a determined amount.
For a bit more background on watch principles, see the Slimline Monolithic Manufacture video [V1].

Compliant mechanisms

In watchmaking, compliant or flexible mechanisms are the next big thing, opening a new realm of possibilities. Given the elastic properties of certain materials like silicon, it is possible to create compact, precise monolithic components to replace some of the assembled mechanical parts. Frederique Constant now has used these flexible, jointless structures in the design of its revolutionary oscillator. They have replaced the 26 components of their standard assortment (i.e., assembly of watch components) with a single component fitted with two regulation weights. Made of monocrystalline silicon, the monolithic oscillator also integrates the escapement anchor in its flexible structure.

EDITORIAL NOTE

This article was based on the presentation during the press event for the launch of the Slimline Monolithic Manufacture, a press release by Frederique Constant, and input from Nima Tolou, CEO of Flexous Mechanisms.

Three innovations distinguish the oscillator:

1. A small-size one-piece oscillator.
   Thanks to the geometry of flexures and masses, it is possible to produce for the first time a flexible pivot oscillator in the footprint of a traditional balance wheel.
2. An ultrathin oscillator with a new anchor system.
   The escapement anchor is incorporated into the oscillator and, for the first time, its function is integrated into the flexures allowing a substantial reduction in size while keeping all the functions in one thin silicon layer.
3. Adjustment weights to regulate the flexure oscillator.
   These weights are just like those used on a traditional free-sprung balance. Watchmakers can easily fine-tune the frequency and precision by simply turning two weights.

Monolithic oscillator

Frederique Constant integrated the concept of a monolithic oscillator in its new Slimline Monolithic Manufacture watch design (Figure 1) and developed it in collaboration with Flexous Mechanisms (see the text box on the right). The distinctive technical objectives for an innovative flexure oscillator were straightforward:

1. A size comparable to that of a traditional balance to fit inside a standard movement with minor adjustments.
2. The highest possible frequency.
3. An 80-hour power reserve.
4. A cost-effective formula that would allow the manufacture of significant quantities at a reasonable price.

The engineering of the oscillator's flexures and geometry enabled reduction of its dimensions to the size of a conventional regulator and increased its frequency for enhanced accuracy. The new topology of the flexures and masses constitutes an unprecedented compact size for a flexure pivot oscillator (9.8 mm in diameter and 0.3 mm in thickness). For the very first time, the anchor has been integrated within the flexure. The design combines high frequency with low amplitude (6° versus ~300° for a regular balance wheel), which prevents excessive speeds in the mechanism and increases accuracy. For confidentiality reasons, no more details of the oscillator design can be disclosed.

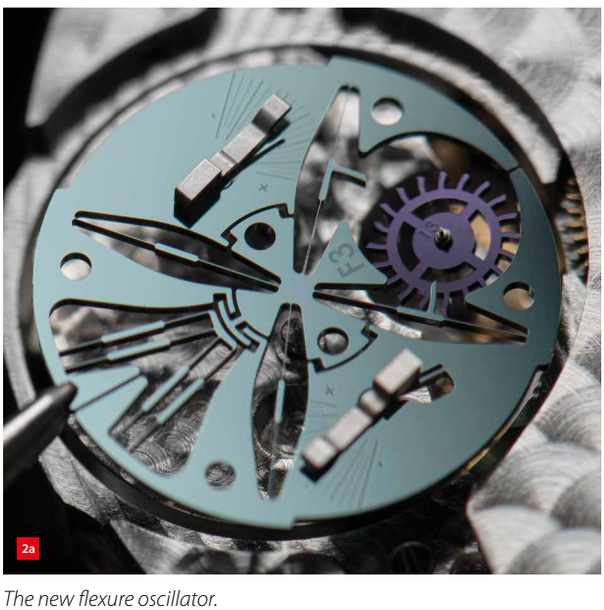
While many traditional mechanical movements operate at a frequency of 28,800 vibrations per hour, the Slimline Monolithic Manufacture represents the first Swiss-made mechanical watch oscillating ten times faster, at 288,000

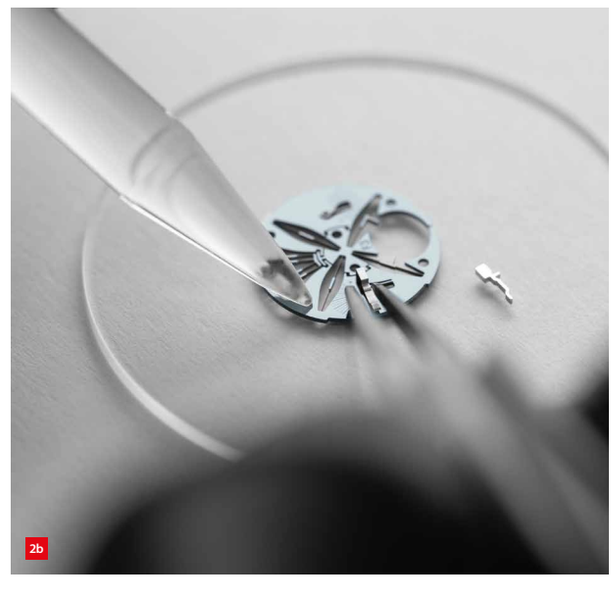
Watch partners

Frederique Constant is a watchmaking manufacture located in Geneva, Switzerland. The maison was founded in 1988, "to offer quality Swiss watches at competitive prices, with the aim of democratising luxury Swiss Made watches".

Flexous Mechanisms is an independent horology technology company specialised in the design and development of flexible watch parts with the focus on mechanical watches. Flexous was founded in 2012 in Delft (NL), as a spin-off of the research in the field of flexible mechanisms at Delft University of Technology. Flexous develops and produces custom-made innovative watch parts from concept to product, "to bridge the fields of traditional watch making and 21st century flexible mechanism design".

WWW.FREDERIQUE-CONSTANT.COM
WWW.FLEXOUS.COM





The new flexure oscillator.
(a) Close-up of the monolithic mechanism, containing a total of six flexures. The escapement wheel is shown in purple.
(b) Mounting of the adjustment weights.

POSITIVE, NEGATIVE OR CLOSE TO ZERO

Compliant ortho-planar mechanisms can be fabricated from a single sheet of material and they can move out of the plane in which they are fabricated. In this work, a design of such a mechanism is proposed in which stiffness compensation is applied. With a finite-element model, the force-deflection relation of the buckled mechanism was modelled and it was shown that by changing the design parameters, the stiffness of the mechanism can be tuned such that it can be positive, negative or even close to zero. The mechanism was prototyped and the force-deflection relation was measured to validate the simulations.

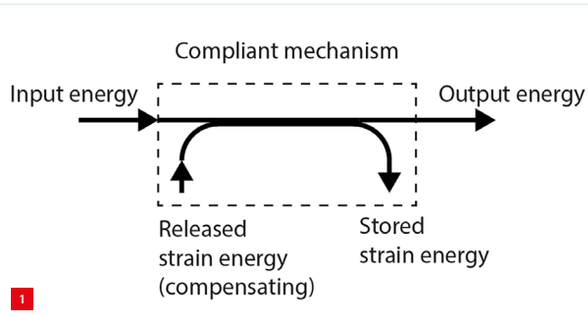
THIJS BLAD, RON VAN OSTAYEN AND NIMA TOLOU

Introduction

Compliant mechanisms are mechanisms in which motion is the result of a deflection of flexible members. These mechanisms have the advantage over their conventional counterparts that they are easier to fabricate, can be more compact and are free of friction, play and wear. Currently, these mechanisms are already applied in for example accelerometers and microphones, and in the future they can be used in applications such as energy harvesters [1].

However, a drawback of compliant mechanisms is their inherent stiffness, a property which describes the extent to which the mechanism resists deformation. Due to this stiffness, a significant part of the input energy is stored as strain energy in the deforming flexible members, and is thus not used for the intended function of the mechanism. As a result, the mechanism may have a poor mechanical efficiency, low range of motion, and high natural frequencies.

In order to overcome this problem, the stored strain energy may be compensated by releasing strain energy in another part of the mechanism [2]. Preloading is a simple way to introduce such compensating energy in the mechanism.



Energy flow in a compliant mechanism where stiffness compensation is applied.

During motion, the energy will flow from preloaded parts to deforming parts of the mechanism. This principle is known as stiffness compensation (see Figure 1) and can be used to achieve zero-stiffness behaviour.

In recent work [3] [4], the principle of stiffness compensation has been applied to a special type of compliant mechanisms called compliant ortho-planar mechanisms (COMs). COMs can be fabricated using planar manufacturing methods and they can move out of the plane in which they are fabricated. Compared to mechanisms that move in-plane, this has the benefit that these mechanisms allow for larger motions while remaining compact, as their parts do not collide.

Design and analysis

In order to apply the principle of stiffness compensation, the mechanism shown in Figure 2 was designed. The mechanism consists of a wide and a narrow section and can be fabricated from a single sheet of material. The energy that is necessary for the stiffness compensation is embedded in the mechanism by preloading, which is done by compressing the mechanism such that it buckles out-of-plane.

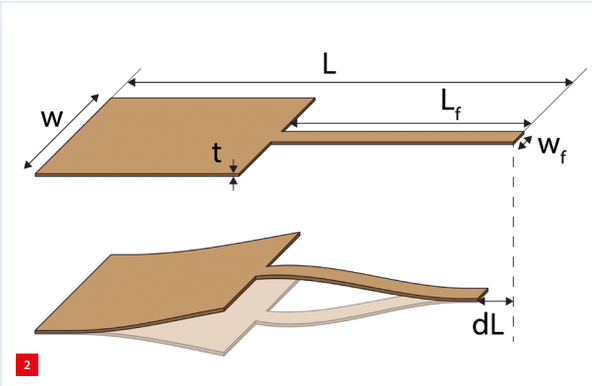
Table 1
Relevant design parameters of the design shown in Figure 2.

Parameter	Value (mm)
L	20
L_f	12.1
dL	0.4
w	2
w_f	0.2
t	0.1

AUTHORS' NOTE

Thijs Blad (Ph.D. candidate) and Ron van Ostayen (associate professor) are members of the Mechatronic System Design research group in the department of Precision and Microsystems Engineering at Delft University of Technology (NL). Nima Tolou is the CEO of Flexous Mechanisms (see also the previous article), located in Delft.

t.w.a.blad@tudelft.nl
www.pme.tudelft.nl



Design of the compliant ortho-planar mechanism before and after preloading.

The design parameters of the mechanism are given in Table 1. The mechanism has a length, L, and a thickness, t, and is compressed over a distance dL. Moreover, the wide and narrow sections have widths of w and w_f, respectively. The narrow section is called the flexure, and the parameter L_f is introduced to identify its length.

When the mechanism is buckled, it takes the shape of a bridge extending out of plane. Two states are shown in Figure 2, which can be identified as 'knee-up' and 'knee-down', and the mechanism can be moved between these states. The stiffness of the mechanism during this motion can be found by analysing its force-deflection relation.

For most compliant mechanisms, the force required to move the mechanism increases with increasing deflection and the mechanism is said to have a positive stiffness. However, in this design the shape of the force-deflection relation can be tuned by the choice of L_f. As a result, the stiffness that can be found for this mechanism can be positive, negative or even (close to) zero.

To analyse mechanical behaviour of the mechanism, a finite-element model was built in ANSYS. In this model, the mechanism was first buckled by constraining one end of the mechanism in all directions, and displacing the other end. Small imperfections were incorporated in the model to prevent the simulation to crash due to singularities in this preloading step. After the buckled shape was achieved, a displacement was applied at the interface of the wide section and the flexure. Over the range of motion of the mechanism, the reaction forces were recorded at regular intervals to determine the force-deflection behaviour. The force-deflection relations were simulated for different variations of the flexure length L_f and the results of this analysis are shown in Figure 3.

From the figure, it can be seen that very interesting force-deflection relations are found for this mechanism. First of all, the force-deflection relations are clearly nonlinear and show a different stiffness at different parts of the curve. It can be observed that for small deflections the mechanism has a low stiffness, as an almost flat force-deflection relation is found. The force-deflection relation rapidly steepens for larger displacements, which is the result of the mechanism being straightened and loaded in tension.

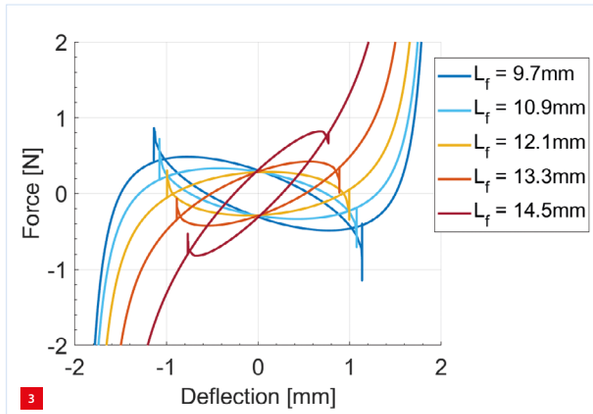
Furthermore, it can be found that the force-deflection relations do not follow a single curve, but make an oval shape. This oval shape actually consists of two load paths, which correspond to the 'knee-up' and 'knee-down' states of the mechanism. When the mechanism is moved from one side to the other, there is a point where the mechanism rapidly changes between these states, a behaviour which is called snap-through.

When looking at the orientation of the oval-shaped part of the force-deflection relation, this part can slope upwards, slope downwards or can be relatively flat. It can be seen that in this mechanism, the slope is dependent on the value of the design parameter L_f. When this parameter is increased, an increasingly upwards-sloping force-deflection relation is found. This means that the level of stiffness compensation can be tuned by changing this parameter. For example, a value of L_f = 12.1 mm was found to result in a mechanism with the flattest force-deflection relation.

Fabrication and experiments

The mechanism was fabricated from a sheet of 0.1 mm thick spring steel (E = 190 GPa) using laser micromachining. For this, a Spectra-Physics Talon 355-15 diode pumped solid-state (DPSS) UV laser system with a wavelength of 355 nm and maximum power of 15 W at 50 kHz was used.

The mechanism was clamped in an aluminium frame consisting of a base plate and two sliding sides. These sides are aligned using dowel pins and can be clamped to the base



Results of the finite-element simulations showing the force-deflection relations of the mechanism for different variations of the design parameter L_f.