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Precision flexure hinges for high-performance optics

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Abstract

The use of flexure hinges is known from different applications related to the alignment, adjustment, and guidance of optical elements. Depending on the specified optical performance, the design of these flexures can be very challenging. It is more so when they are used for high-performance optics.

In this paper, we will review different kinematic architectures that can be used for the mounting and manipulation of optical elements. We will focus on ultra-precision flexures that aim at achieving accurate adjustment and alignment tasks needed for mirrors, lenses etc. Kinematic and dynamic investigations of the proposed flexures will be addressed to prove their adequacy for the intended tasks. Simple and more advanced modelling approaches will be revisited to quantify the performance of these flexures, i.e. possible motion ranges, natural frequencies, parasitic motions, required actuator forces, thermal resistance and drifts. Furthermore, customized approaches for sensitivity analysis will be carried out to determine the expected variations of the aforementioned performance criteria for given manufacturing and assembly tolerances. The main goal of this analysis will be to guarantee a robust design that will not be affected by environmental conditions, and the manufacturing process, which has to be carefully developed beforehand.

Keywords: Flexure, Hinges, Optics, Kinematics, Precision Engineering

1. Design methodology

The design of flexure mechanisms is a key issue in high-performance optics. The appropriate methodology involves different disciplines that range from kinematics to manufacturing over control theory and thermal aspects. Generally, the design process starts off with the search for appropriate kinematic topologies that meet the needed degree of freedom. The result of this design stage, which is often called topology synthesis, is usually a table of different solutions that have to be assessed (see the generic examples in Table 1). The subsequent design stage consists in deriving kinematic, elastostatic and dynamic models to determine the characteristic dimensions of the selected solutions, i.e. length, thickness, and width of the hinges etc. One crucial issue in the design of compliant mechanisms is the determination of parasitic motions, which should be carefully investigated by means of the derived models. The goal is to meet the major specifications of the task, i.e. ranges for each degree freedom, stiffness, natural frequencies etc. FEA simulations can then be used to carry out slight modifications to avoid local high stress in the hinges. Moreover, we will address the challenging task of assessing different solutions according to performance criteria (e.g. stress, stiffness, accuracy of the actuated motion, parasitic motions, thermal conductivity and drift, stability margins, manufacturing and assembly costs etc.) that have to be chosen adequately.

One crucial issue in precision engineering is the sensitivity of the chosen design solution to manufacturing and assembly tolerances. Different methodologies are known from the literature. Depending on the number of parameters that are affected by manufacturing and assembly, grid-based or statistical variations (monte-carlo method or latin hypercube sampling etc.) of the parameters are better suited. In the current work, latin hypercube sampling is used. One result of this parameter variation is a correlation matrix, with the help of which the relevant design parameters can be identified. Thereafter, one can strive to determine the impact of the tolerances of these parameters on the overall performance of the flexure mechanism.

2. Design verification and validation

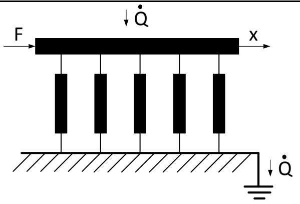
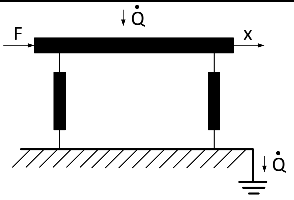
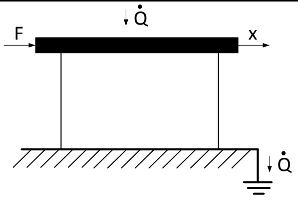
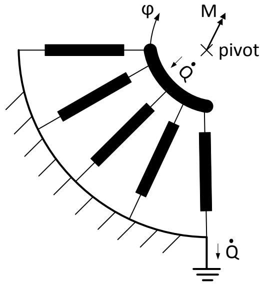
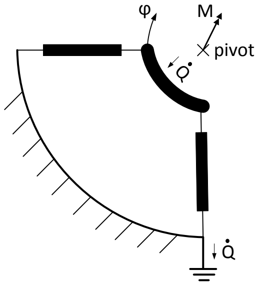
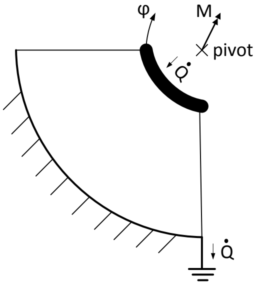
Once the design is completed, different measurement techniques are available to verify and validate the computed performance. Ultrasonic measurements can be used to determine the Young's modulus of the used material. Static stiffness measurements should then be carried out for each degree of freedom. The measurement of frequency response functions enables one to capture the dynamic behaviour of the design solution and to determine the dynamic stiffness. To check the thermal conductivity and drift of the design solution, adequate heat loads are applied. The temperature distribution and 3D thermal drift over time are captured and compared to the specifications.

3. Manufacturing and assembly

The production of flexure mechanisms is often challenging. The biggest driver for the complexity in the production process is usually the flexibility of the elements in combination with the required accuracy.

Apart from the adequate selection of the material, additional treatments are required to avoid stress introduced movements during the manufacturing process. For the right choice of treatments, the focus is put on the required set of material properties.

Table 1. Assessment of different hinge designs.

Examples for 1 translational DOF (all formula apply for this example, see also [1])			
Examples for 1 rotational DOF (see also [2])			
Number of hinges n	n>2	n=2	n=2
Stiffness (same by spec) c_{lat}	$\sim n * 1.2\frac{Eht^3}{l^3}$	$\sim 2 * 1.2\frac{Eht^3}{l^3}$	$\sim 2 * \frac{Eht^3}{l^3}$
Hinge thickness t	min	max	max
Nominal stress $\sigma \sim \frac{3Etx}{l^2}$	less	most	more
Overdetermination	more	middle	less
Accuracy sensitivity to manufacturing errors	less (but more stress)	more (with less stress)	middle (with lowest stress)
Thermal resistance $R_{th} \sim n * t$	lower	higher	highest
Buckling load F_B (similar to z-stiffness)	highest $\sim n * \frac{36\pi^2 EI}{l^2}$	low $\sim 2 * \frac{36\pi^2 EI}{l^2}$	lowest $\sim 2 * \frac{4\pi^2 EI}{l^2}$
Natural frequency of parasitic modes	higher	lower	lowest
Needed volume	more	less	less
Manufacturing cost	more	less	less, even lowest possible

The next step is the choice of the right manufacturing process. Basically, the manufacturing of flexure mechanisms can be achieved by jet cutting, electro discharge machining, selective laser melting and high speed cutting. Relevant evaluation criteria of these processes could be the manufacturing time and costs, the tool positioning accuracy and the expected forces during the manufacturing process.

Another important task is the mounting of the semi-manufactured parts in the production machine, especially when the finished part needs different mounting interfaces, which have to be well aligned to each other after the process to avoid pre-stressed flexure mechanisms and additional adjustment effort. Finally, the transport of the finished and assembled parts could be challenging. Very compliant flexure mechanisms are often needed to reduce the actuator forces. Unfortunately, they are susceptible to vibration and shock excitations during transport that could lead to the damage of very expensive parts. Additional measures are then needed to attenuate and damp the expected excitations. This is usually done by isolation systems that have to be carefully designed.

References:

[1] Herman Soemers: Design Principles for precision mechanics, 2010

[2] Edin Sarajlic et al.: Three-Phase Electrostatic Rotary Stepper Micromotor With a Flexural Pivot Bearing, *Journal Of Microelectromechanical Systems*, Vol. **19**, No. 2, April 2010