High precision flexure hinges – manufacturing-based design optimization

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Abstract

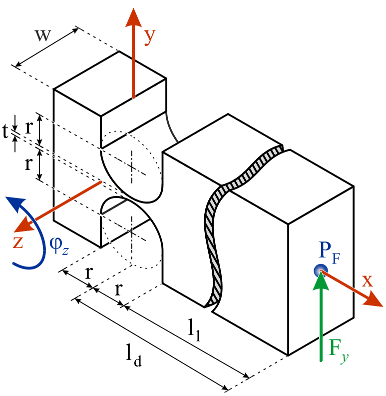
A crucial factor for the accuracy of a flexure hinge based micromanipulator is the performance of its high precision joints themselves. Advanced Wire-EDM technology is ideal for manufacturing flexure hinges due to high geometrical precision and best surface qualities. Although EDM machining with rough and trim cut strategies is nowadays a high-precision process, it is not possible to cut ideal flexure hinges without technological-based imperfections, which result in geometrical deviations within a certain tolerance band. Hence for a comprehensive description of the movement characteristics of real flexure hinges, the limitations of the manufacturing process need to be taken into account. Thus, the geometrical deviations of the hinges due to manufacturing inaccuracies are modelled and analysed in this paper. Based on the results, the actual performance of the flexure hinges is shown and conclusions for a-priori design compensations are drawn.

1. Introduction

Among many advantages such as, insignificant backlash, reduced friction and a significant miniaturization potential, flexure hinges also have some disadvantages in terms of parasitic motion, deviations and a limited range of motion [1]. For high precision parallel micromanipulators with typically a working space in millimetre range the drawbacks of flexure hinges can be compensated using precisely manufactured high precision flexure hinges, which are discussed below.

2. Sensitivity analyses of the geometrical design parameters

The main geometrical design parameters of one degree-of-freedom flexure hinges are the cut-out shape and the hinge width. For example, the cut-out of a right circular flexure hinge is characterised by the radius of the cut-out and the web thickness according to Fig. 1. Technological-based imperfections directly alter the design parameters. The equations for the compliance matrix of a flexure hinge based on the Castigliano's second theorem given in [3] are used to determine the compliance of the hinge for the sensitive axis. The movement in the parasitic axes are not part of this analysis. Thus, two compliance components are sufficient to describe the behaviour of the hinge for a planar motion. The bending as a result of both a force in *y*-direction and a torque about the *z*-axis need to be calculated. In general the compliance components are calculated for $x = 2 \cdot r$. However, the torque about the *z*-axis is replaced by moving the force F_y along the *x*-axis about the length of the lever arm, which is dependent on the distance between the point of symmetry of the hinge shape and the force application point given by design and the cut-out radius. As a consequence of this a bending stiffness C_{φ_z} as a ratio of F_y to the angle of rotation about the *z*-axis can be calculated (for the ideal shape C_{φ_z} is 15.116 N/°). This value is a measure for the necessary force, for example of an actuator, per degree of rotation to bend the flexure hinge in the initial position. The sensitivities of the geometrical design parameters are determined by varying each parameter independently from the others in Fig. 2.



parameters			unit
F_y	force in *y*-direction	-	N
l_d	length giving by design (from point of symmetry of the hinge shape to P_F)	15	mm
l_l	length of lever arm	12	mm
P_F	force application point	-	-
r	radius of cut-out	3	mm
t	web thickness	0.4	mm
w	hinge width	15	mm
φ_z	rotation angle around *z*-axis	-	°
E	Young's modulus (steel)	206	GPa

Figure 1: Shape and load defining parameters of an ideal right-circular flexure hinge.

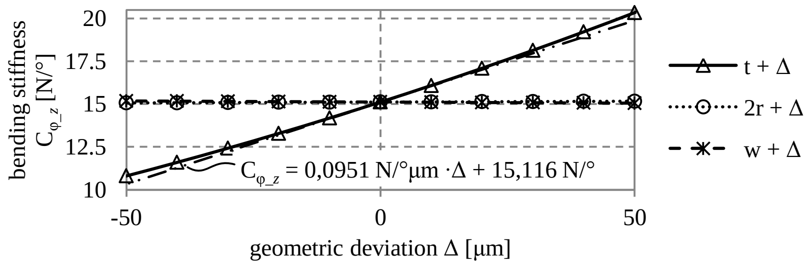
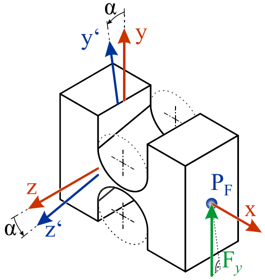


Figure 2: Sensitivities of the geometrical parameters.

3. Clamping errors of the hinge blank

Misalignments of the hinge blank may also affect the motion of the hinge. According to Klocke et al. [2] different kinds of errors are to be considered. A lateral offset of the cut-out causes a shift of the idealised rotating axis. The compliance of the flexible part of the hinge is not affected. As a consequence, the path of a reference point but not mandatory the necessary force is changed by an axis shift. This effect is not explained in detail in this research. The effects on the motion of a flexure hinge caused by a misalignment of the hinge blank as a result of clamping errors on the longitudinal axis according to Fig. 3 is examined both analytically and with finite-element-methods (FEM). Henceforth, the equations for the parasitic axes determined in [3] are considered. With transformation matrices the load on the hinge is transformed and the motion of the hinge itself is calculated in global coordinates. To avoid confusion, only the effect on the global *z*-axis is shown by calculating C_{φ_z}. The out of square face sides of the hinge are neglected in the analytical approach. Hence, FEM calculations are done for verification purpose. The results are shown in Fig. 3.



α tilting angle around x-axis	C_{φ_z} [N/°]	
	analytical	FEM
0°	15.11597	15,63599
0.1°	15.11601	15.63604
1°	15.12057	15.64080

Figure 3: Tilting of the cut-out as a result of clamping errors.

4. Conclusions

The effect of an inaccuracy of the web thickness is eighty to hundred times greater than those of the width and the radius. Linearization of the sensitivity of the web thickness for an ideal geometrical shape shows a ratio for the absolute change in actuation force F_y to the manufacturing tolerance Δ of 0.0951 N/°µm. That means for each micrometre of inaccuracy the necessary actuation force changes with 95.1 mN per degree of rotation. Hence, for high precision applications a manufacturing tolerance in the range of micrometre particularly in regard to web thickness is compulsory.

The comparison between the analytical approach and the use of FEM for calculating the clamping errors on the longitudinal axis show a good correlation of 3.4 %. The effects of this kind of clamping error are eight hundred times less than an inaccuracy of the web thickness. Hence, low clamping errors on the longitudinal axis are permissible as compared to the inaccuracy of the web thickness.

This paper only takes the geometrical deviation into account. For an extensive research the deviations due to changes of the surface layer or other effects of the material itself, also have to be carefully analysed. Thus, this paper can be used as a base for future researches on the material behaviour of high precision flexure hinges.

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