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Modeling of very thin flexure hinges considering surface topography

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Abstract

Mechanisms based on concentrated compliances are frequently used in precision engineering and metrology due to highly reproducible motion behavior. The materially coherent joints define the elasto-kinematic properties of the mechanism. In many applications, such as in force and mass measurement devices, low stiffness against deflection and minimum parasitic motions are desired. Notch flexure hinges with high aspect ratios and minimum thicknesses down to about 50 µm are used. For such thin geometries, the manufacturing-related imperfections on the notch surfaces are of a similar order of magnitude as dimensional deviations from the nominal thickness. Thus, they lead to unknown systematic deviations of the real stiffness value. Accurate knowledge of the stiffness of the compliant mechanism requires appropriate modeling of the flexure hinges. However, no consideration of the notch surface topography in the determination of the joint stiffness has been undertaken in the current state of the art.

In this work, the bending stiffness of thin semi-circular flexural hinges is investigated using a numerical model considering the notch surface topography. A mathematical approach is derived to parameterize manufactured surfaces. The notch surface profile parameters of a single flexure hinge specimen are used to determine the impact on the bending stiffness. Simulation results show a decrease in the mean stiffness of 0.22% and a maximum scatter range of 0.22%. Compared to experimentally determined values, it appears that the surface topography is not negligible. In future works, studies will be carried out to determine the impact factors of single parameters describing the waviness and the roughness. The comparison of the modeled stiffness with those measured on manufactured joints will be used to further refine the model parameters and will help tune the machining parameters.

Keywords: compliant mechanism, flexure hinge, bending stiffness, finite element method, surface topography

1. Introduction

Compliant mechanisms with concentrated compliances are frequently used in high-precision force and mass measurement applications. The materially coherent joints enable highly reproducible motion behavior and low stiffness against deflection. To achieve the desired resolution and uncertainty of the application, the initial stiffness of the kinematic structure is minimized by reducing the joint thickness to 50 µm. Further stiffness compensation through adjustment is required. To design the adjustment device optimally, the stiffness of the mechanism must be known accurately.

Experimental investigations show that the elasto-kinematic properties of real prototypes strongly deviate from analytical or numerical models [1,2]. This can be explained by the relatively strong impact of manufacturing deviations on the absolute dimensions of the joint. Studies of the dimensional deviations of semi-circular flexure hinges identify the deviation of the joint thickness as the main factor affecting the difference in the ideal stiffness [3,4]. For these thin geometries, it can be assumed that surface imperfections like waviness and roughness impact the stiffness in the same order of magnitude as shape deviations. However, this has not been considered in the state of the art. For this reason, this work deals with parametrizing characteristic surfaces and modeling materially coherent joints considering the notch surface topography. Numerical studies are carried out to determine the impact on the bending stiffness. The results will be used to further optimize surface topography modeling and joint manufacturing.

2. Flexure hinge modeling

The basis of the research is the numeric ANSYS model of an ideal semi-circular flexure hinge, which defines the state of the art in terms of stiffness [1]. A surface generation method [5] is applied that moves the notch surface nodes considering previously determined profile parameters.

2.1. Surface parameterization

Modeling the topography of a manufactured surface requires a mathematical approach to feature mapping. This is done on the basis of valid standards. DIN 4760 describes a classification that divides geometric deviations into different orders [6]. The 2nd order (waviness) and 3rd order geometric deviations (regularly occurring roughness) are described by a sinusoidal approach. For 4th-order deviations (irregularly occurring roughness), a random displacement between the peak and the valley of the surface section is used. Equation (1) is applied to mathematically describe the topography of a manufactured xz-surface. Periodic characteristics occur along the x-axis.

$$v(x,z) = a \cdot \sin(b \cdot x + c) + d \cdot \sin(e \cdot x + f) + g(x,z) \qquad (1)$$

This approach's limitations are that cracks and micro cracks cannot be modeled and that strongly varying parameters of waviness and roughness have to be averaged.

2.2. Surface modeling

The FE model of an ideal flexure hinge provides the initial geometry. The meshing of this model has to be refined sufficiently to map the profile parameters accurately. Each notch surface node receives a defined displacement generated using equation (1). The nodes are moved successively to create the characteristic topography on the notch surface (see Fig. 1).

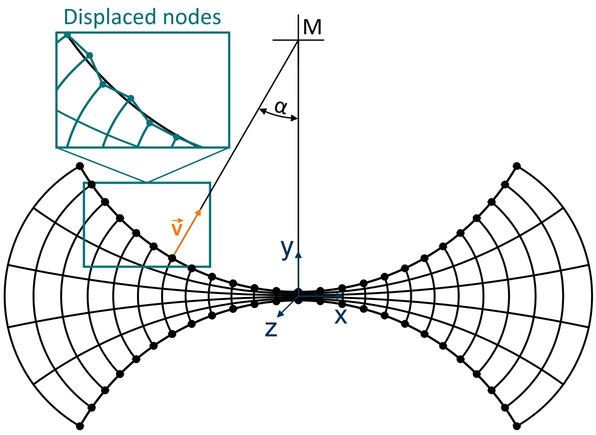

Figure 1. Displacement of the notch surface nodes.

To model the manufactured surface correctly, the nodes are shifted in the direction of the center of the semicircle. Equation (2) is used to calculate the parts of the node displacement for the x and y directions.

$$\vec{v} = v \cdot \sin(\alpha) \cdot \vec{e_x} + v \cdot \cos(\alpha) \cdot \vec{e_y} \qquad (2)$$

3. Numerical investigations

Flexure hinges in high-precision force and mass measurement applications are typically made of aluminum alloys and manufactured by milling, grinding, or wire EDM. The profile parameters of a milled joint specimen were used to investigate the impact on the bending stiffness

3.1. Profile characterization of a milled flexure hinge

Using a laser scan microscope, the notch surfaces of a flexure hinge specimen were examined and evaluated according to ISO 21920-2 [7]. A description of the topography using the approach from section 2.1 requires the waviness depth Wt, the mean period length of the waviness WSm, the roughness depth Rt, the averaged roughness depth Rz, and the mean groove width RSm.

Table 1. Profile parameters of the specimen.

Parameter	Value	Parameter	Value
Wt	1.445 µm	Rz	2.678 µm
WSm	55.195 µm	RSm	3.344 µm
Rt	4.166 µm		

The wave depth and the average roughness depth specify the amplitudes of waviness and regularly occurring roughness. The average period length of the waviness and the groove width are used as period lengths. The phase shifts vary within the period 2π of the sinusoidal function as they cannot be determined exactly. The irregularly occurring roughness is assumed within the difference between the roughness depth and the averaged roughness depth symmetrical to the periodic geometric deviations. This ensures that the peak-to-valley roughness parameters lie within the roughness depth. Equation (3) is applied to describe the surface topography of the specimen.

$$v(x,z) = \frac{Wt}{2} \cdot \sin\left(\frac{2\pi}{WSm} \cdot x + [0;2\pi]\right) + \frac{Rz}{2} \cdot \sin\left(\frac{2\pi}{RSm} \cdot x + [0;2\pi]\right) + [-\left|\frac{Rt-Rz}{2}\right|;\left|\frac{Rt-Rz}{2}\right|] \qquad (3)$$

The measured profile parameters of the specimen (see Tab. 1) were averaged over 10 measurements. The cut-off wavelength was defined at λc = 25 µm.

3.2. Simulation results

The simulation results are based on statistical studies. The phase shifts and the irregularly occurring part of the roughness are randomly varied within the specified limits. This leads to a change in stiffness. The probability density distribution shows a slight left-skewed tendency (see. Fig 2). The mean stiffness value is reduced by 0.04 Nmm/rad (0.22%) compared to the ideal stiffness of 18.23 Nmm/rad. The maximum scatter range amounts to approx. 0.04 Nmm/rad (0.22%).

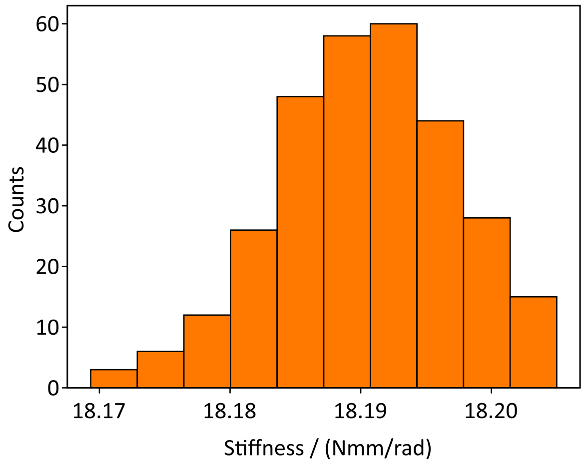

Figure 2. Probability density distribution for 300 simulation runs.

Compared to the experimentally determined stiffness of the specimen of 18.31 Nmm/rad, it appears that the change in stiffness due to surface topography has a non-negligible impact. It becomes obvious that the influence of the 2nd and higher-order geometric imperfections is even more significant due to the limitations of the FE model mentioned in chapter 2.1.

4. Summary and outlook

This paper presents the modeling and investigation of thin materially coherent joints considering surface topography. A mathematical approach was derived to describe manufactured surfaces and a FE model mapping the surface topography was developed. Numerical studies based on the profile parameters of an exemplary specimen revealed a non-negligible impact of higher-order geometric imperfections.

In future work, a more representative number of specimens will be investigated to verify the results of this work. Parameter studies will be carried out to determine the main impact factors on the bending stiffness. An iterative comparison between modeled and experimentally determined stiffness will help to optimize the FE model and tune the machining parameters.

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