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Experimental characterization of a force sensor for orientation-independent SI-traceable measurements

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Abstract

Since the revision of the International System of Units (SI) in 2019, the Kibble Principle provides traceability for the measurements of masses, forces, and derived quantities by correlating electrical and mechanical quantities. The application of the principle enables the design of self-contained systems for absolute measurements. In the present work, the initial experimental investigation of a force sensor developed for use in precision technology is described. The sensor operates according to the Kibble principle, utilising spring-based stiffness compensation to realize high-precision measurements irrespective of its orientation within the field of gravity. The measurement data confirm the working principle, including the stiffness compensation by preloading the springs and the measurement window adjustment. However, manufacturing deviations and mounting constraints limit the compensation range.

Keywords: force sensor, load cell, stiffness compensation, Kibble Principle, measurement setup, experimental investigation

1. Introduction

The Kibble Principle [1] ensures traceability in the measurement of masses, forces, and derived quantities according to the revised SI. It is already applied in various fields [2-4] as it enables absolute in-situ measurements. To meet the growing demands for SI-traceable force monitoring in precision technology, a compact force sensor was conceived [5]. The sensor adapts the concept and functions of the Planck balance [6] (see Figure 1).

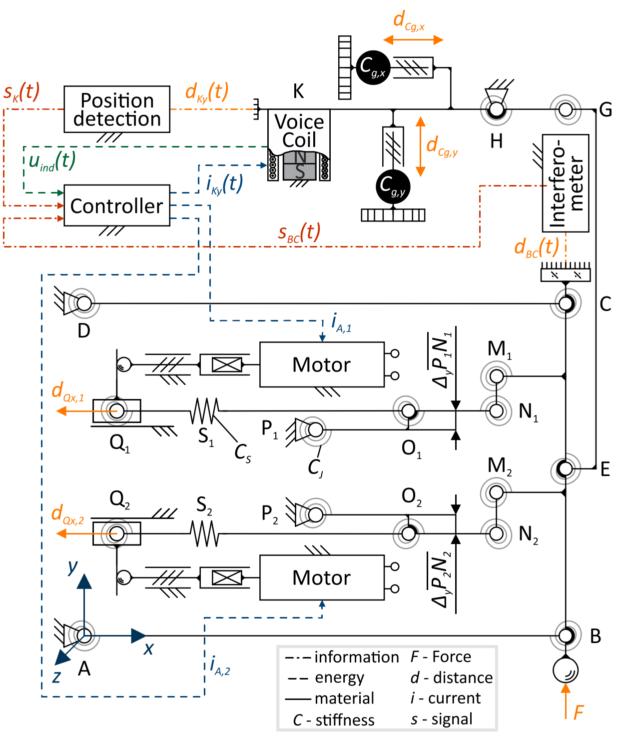

Figure 1. Concept of the developed sensor.

The kinematic structure is designed as a non-monolithic, compliant mechanism with thin, concentrated flexure hinges in order to enable the use of functional materials as well as the interchangeability of components. Spring-based stiffness compensation is applied to increase the resolution and reduce measurement uncertainty regardless of the sensor's orientation in the field of gravity. Two sub-mechanisms are installed to compensate for the stiffness of the mechanism using tunable forces of preloaded springs. The dual configuration also allows for the adjustment of the measuring window. The present work describes the commissioning and experimental investigation of the force sensor. The results are being discussed and deviations to the FE model are identified. [5]

2. Methods

The stiffness of the force sensor is investigated in various orientations using a static experimental measurement method. To identify deviations from the ideal geometry, the etched surface of the flexure hinges in use is measured optically.

2.1. Static-experimental measurement of the stiffness

The stiffness of the force sensor is determined by measuring its force-displacement characteristics. This is achieved with the built-in voice coil actuator and the optical position detection. To be able to align the force sensor in an arbitrary orientation, the measurement setup (see Figure 2) uses two open-beared rotation axes to allow for pitch in γ and roll in α by ±180°.

2.2. Optical measurement of the flexure hinge geometry

The LEXT OLS4100 Olympus 3D laser scanning microscope is used to analyse the etched surface of the flexure hinges. This includes measuring the contour, the length, the width, and the etching depth. The thickness of the hinges is determined using the sheet thickness, which is measured with a micrometer, and the etching depth.

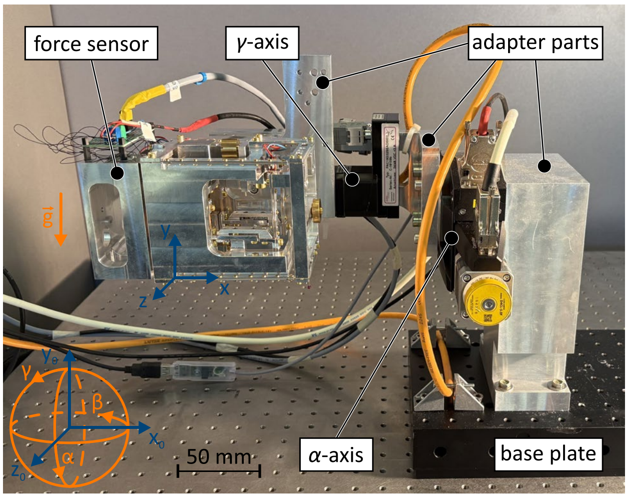

Figure 2. Measurement setup to investigate the assembled prototype of the force sensor. (xyz – local cartesian coordinate system; $x_0y_0z_0$ – global cartesian coordinate system; αβγ – global rotations)

3. Measurement results

For the commissioning, one of the compensation springs had to be preloaded significantly to shift the transmission lever into the measuring window. Subsequently, the curve of the stiffness C was recorded over the roll motion $\alpha = \pm 180°$ for various pitch angles γ (see Figure 3).

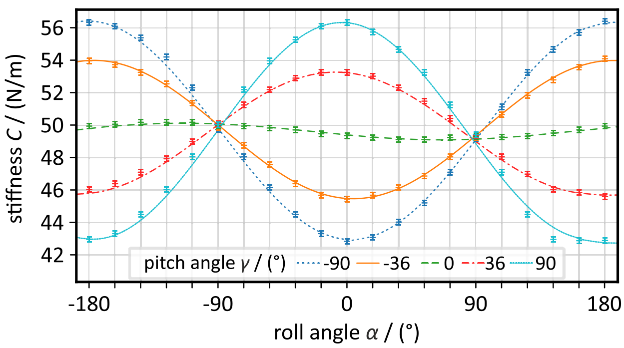

Figure 3. Overall stiffness C for different roll angles α and pitch angles γ.

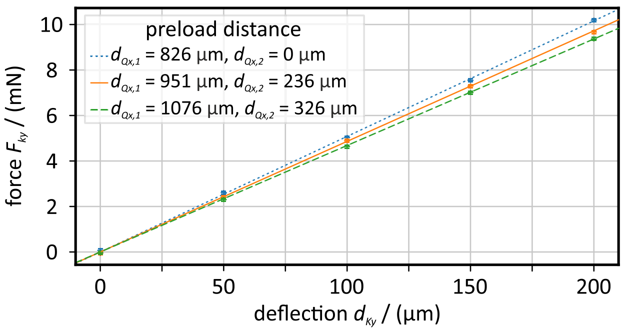

Figure 4. Force F_K across deflection d_K with increasing preload distances $d_{Qx,1}$ and $d_{Qx,2}$ of the stiffness compensation springs.

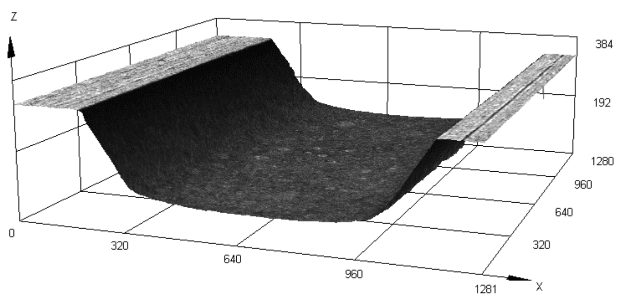

Figure 5. Optically measured topography of the etched surface of a thin copper beryllium flexure hinge.

For the orientation $\alpha = -90°$ and $\gamma = 0°$, the force F_{Ky} was measured across the deflection d_{Ky} for increasing preload distances $d_{Qx,1}$ and $d_{Qx,2}$ of the stiffness compensation springs (see Figure 4). It is evident that the uncertainty of both x-axis quantities is negligible. To detect potential error sources, the geometry of specific flexure hinges was characterized (see Figure 5). An average length of 0.960 mm ± 0.006 mm and an average thickness of 62.612 µm ± 4.233 µm were recorded. It was also determined that the hinges have large etching angles and rounded bending edges.

4. Discussion

The measurement results confirm the anticipated trend in stiffness during roll and pitch motions (see Figure 3). In the unadjusted state, the geometric stiffness accounts for up to 17% of the total stiffness. The absolute value of the total initial stiffness of C = 50.81 N/m for α = 90° and γ = 0° is higher than the stiffness of C = 42.58 N/m of the FE model even though one of the compensation springs is already significantly preloaded. One of the main contributions to this deviation is the substantial discrepancy in the geometry of the built-in flexure hinges. The approximately 4% reduction in bending length and the approximately 25% increase in thickness affect stiffness to the power of three. In combination with large etching angles (see Figure 5), this results in significantly higher elastic stiffness compared to an ideally rectangular hinge contour. During assembly, stresses arose that also increased the elastic stiffness.

The adjustment concept for the stiffness and the measurement window could be validated. The increase in preload leads to a constant reduction in stiffness (see Figure 4). However, significant manufacturing deviations were found in the flexure hinges, as well as residual stresses introduced during assembly. This leads to a substantial disparity in the moment generated by the two compensation mechanisms. One of the preload springs had to be preloaded initially to a significant extent to adjust the force sensor into its measurement window. Consequently, the elastic stiffness could only be compensated by approximately 8%.

5. Summary and Outlook

To meet the growing demand in precision technology, a compact force sensor operating according to the Kibble principle was developed. Spring-based stiffness compensation increases the resolution and minimizes the uncertainty independently of the orientation. Experimental investigations confirmed the adjustment concept for the stiffness and the measurement window. However, manufacturing deviations in the flexure hinges and the frame, as well as assembly-related limitations, prevent the desired minimum stiffness from being achieved.

In future work, the force sensor will be optimized by using a sturdier hinge material, implementing stiffer compensation springs, and compensating for manufacturing deviations in the frame. The experiments will then be repeated.

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