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Orientation-dependent behavior of miniaturized compliant mechanism for high-precision force sensors

Matthias Wolf, Mario A. Torres Melgarejo, Martin Wittke, René Theska

Technische Universität Ilmenau, Institute of Design and Precision Engineering, Precision Engineering Group

matthias.wolf@tu-ilmenau.de

Abstract

Traceable measurement and application of forces with nanonewton resolution and lowest measurement uncertainties over large measurement ranges are fundamental for high precision technologies such as nanofabrication. To increase the range of applications, the main target of this work is a gravity orientation-independent working principle. Furthermore, a miniaturization of the mechanism is being investigated, as it is advantageous due to reduced inertia.The resolution of the measurement in load cells based on compliant mechanisms with concentrated compliance is mainly limited by the stiffness of the hinges, which depends on the hinge geometry. Due to the limits in the manufacturing of the hinge thickness, the geometrical scaling leads to a higher stiffness of the overall mechanism. To achieve lowest stiffness and to avoid parasitic deflections due to the orientation in the gravitational field, the mechanism needs to be further optimized. The investigation has shown that the use of corner-filleted hinge contours results in much lower bending stiffnesses compared to the widely used semi-circular hinge contours. By changing length and corner fillet radius, the hinges are optimized in terms of low bending stiffness and high cross stiffnesses. This provides a compromise between the resolution of the measurement and the amount of parasitic displacements driven by the tilting to the field of gravity. The findings of the investigation were summarised in optimization approaches and verified in a FE Analysis. The result of the tilting analysis shows that an orientation-independent working principle is possible with the optimized mechanism.

Keywords: Force measurement, geometric scaling, gravity independent, compliant mechanism, stiffness

1. Introduction

Orientation-independent, traceable measurement and application of forces with nanonewton resolution are fundamental for high-precision technologies, e.g. nanofabrication. Due to numerous advantages, the use of electromagnetic or electrostatic force-compensated weighing cells based on compliant mechanisms is state-of-the-art for high-resolution force measurement with low uncertainty [1]. However, in weighing systems, even the slightest tilt of the load cell leads to measuring deviations caused by mismatch of the center of mass and the main pivot point H (Figure 1). It causes an astatic state of the stiffness of the mechanism. To achieve the lowest uncertainty, the tilt sensitivity of the load cell has to be compensated. For the typicaly small tilt angles of less than 1° this has been done by means of dead weights [2,3]. A universally applicable principle has to avoid deviations in the measured value even with large angular deflections.

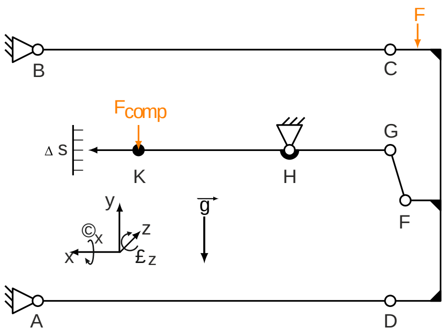

Figure 1 The principle design of the load cell is based on a compliant mechanism. The measured force is applied at the linkage between C and D. Point K serves as the compensation point where the compensation force is applied and controlled using a position sensor.

2. Goals and approaches

The tilt compensation with dead weights needs to be replaced by a more orientation-independent operating principle. The miniaturization of the mechanism will help to reduce the inertial masses. In addition, a more compact design will help to facilitate integration into existing systems. As described in [3], point K (Figure 1) is crucial because it serves as the application point of the compensation force and the position measurement. Any displacement of point K caused by deflections directly influences the relative position of the fixed and moving components of the actuator and sensor located there. To ensure constant properties, these deviations must be minimized by enhanced cross stiffnesses of the overall mechanism. In the previous investigation [4] the behavior of the stiffness of a miniaturized mechanism was considered. The resolution of the force measurement is limited by the bending stiffness of the hinges. A further reduction in the thickness of the bending hinges would be helpful, but is not achievable from a technological point of view, so that the stiffness of the mechanism increases with the degree of miniaturization. Therefore, the miniaturized mechanical structure needs to be optimized for inherently low stiffness in the direction of the force measurement and high cross stiffness avoiding displacements due to tilting. In [4] the scaling behavior of miniaturized hinges was investigated using an FE analysis. It was shown that corner-filleted hinges provide low bending stiffness and high cross stiffnesses even with an increasing grade of miniaturization. The results obtained are used for ongoing optimization approaches.

3. Mechanical model and simulation setup

In the first approach, a 3D FE model was developed and parameterized with the geometrical values from the scaling study in [4]. To simulate gravity, an acceleration was applied to the center of mass. It was divided into the x, y, and z components and was calculated using the amount of gravity and the roll around the x-axis Φ_x and pitch around the z-axis Θ_z. To simulate the position control of point K, it is fixed in the y-direction and the reaction force was observed.

3.1. Simulation results and optimization approaches

The diagrams in Figures 2 and 3 show the results of tilting. Rolling around Φ_x leads to a linear displacement in the z-direction and a negligible displacement in the x-direction. The reaction force is symmetrical to the roll angle Φ_x.

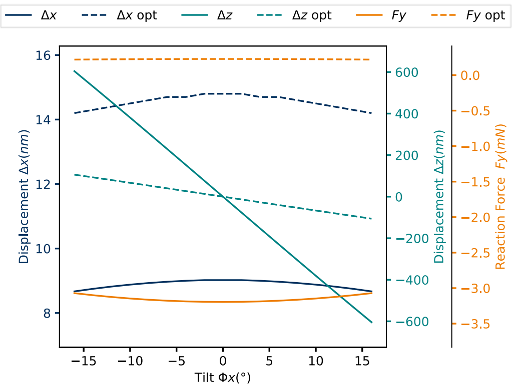

Figure 2 Resulting displacements and reaction force of point K due to tilting the mechanism to gravity around Φx.

Pitching around Θ_z leads to a linear displacement in the x-direction and a negligible displacement in the z-direction. The reaction force is unsymmetrical to the pitch angle Θ_z.

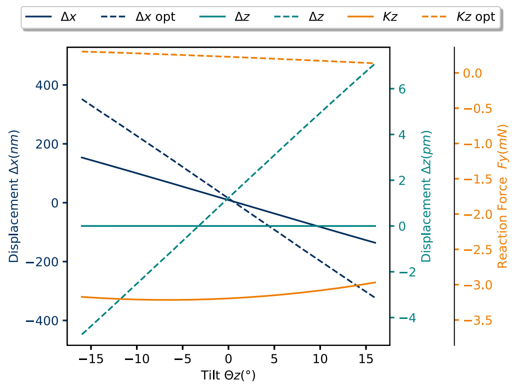

Figure 3 Resulting displacements and reaction force of point K due to tilting the mechanism to gravity around Θz.

The displacement in the z-direction driven by the roll around Φ_x is higher, compared to the x-direction. The behavior of the reaction force can be traced back to the center of gravity, which is not in the center of the pivot point H. This results in a gravity-intended astatic adjustment of the stiffness by tilting.

To provide the tilt-insensitive behavior the following **optimization approaches** were derived:

- expand the structure in z-direction
- place symmetrical cut-outs in the middle to separate the hinges
- reduce the mass of moving parts
- decouple parasitic displacements of the parallel spring guide from the load beam
- place the center of mass of the load beam into the center of pivot H

3.2. Simulation results with geometry optimization

Based on the optimization approaches obtained from the previous analysis, a mechanism with optimized geometry was developed (Figure 4). The load beam (2) and the parallel spring guide (3) are now optimized in terms of mass. The center of mass of the load beam is now located at the pivot point H. In addition, the parallel spring guide and the load beam were decoupled in z-direction, using additional flexure hinges (1).

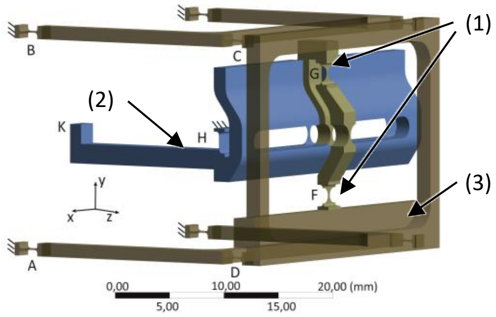

Figure 4 Optimized mechanism with additional hinges (1) to decouple the loadbeam (2) from the parallel spring guide (3)

The mechanism was expanded to 30 mm x 30 mm x 20 mm to enhance the cross stiffnesses while the bending stiffness was reduced by symmetrical cut-outs separating the hinges. The results of the FE-Analysis are shown as the dashed lines in Figure 2 and Figure 3. By decoupling the load beam and the parallel spring guide, the displacement in the z-direction could be reduced by a factor of six. The reduction of the masses, the positioning of the center of mass to pivot point H, and the cut-outs of the hinges led to a reduction of the tilt intended reaction force by almost 30 times. The cut-outs also led to increase the displacement in x-direction by a factor of 2. Tilting around Φ_x has a negligible influence on the reaction force of point K.

4. Conclusion

The investigation showed that the original mechanism is very sensitive to tilting. The defined optimization approaches led to a significantly reduced tilting sensitivity. When tilted by Φx, the reaction force at point K shows a tilting sensitivity close to zero. In addition, the displacements between the fixed and moving components of the actuator and the sensor to the tilting can be neglected. For the further development of the force sensor, a working principle based on tilting around the x-axis and rotating around the gravitational axis is recommended to achieve all force vectors in space.

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References

[1] Marangoni R.R., 2019. Traceable Multicomponent Force and Torque Measurement. diss., Technische Universität Ilmenau

[2] Darnieder M., Pabst M., Zentner, L., Fröhlich T., Theska, R., 2019. Mechanical properties of an adjustable weighing cell prototype. *In Proc. 19th Int. Conf. Eur. Soc. Precision Eng. Nanotech.*

[3] Dannberg, O., 2020. Entwicklung eines Prüfstandes zur rückführbaren Kalibrierung von Cantilevern. diss., Technische Universität Ilmenau

[4] Wolf M., Wittke M., Torres Melgarejo M.A., Theska R., 2023. Scaling of a compliant mechanism for high-precision force measurement applications. *In: Engineering for a changing world: Proceedings : 60th ISC, Ilmenau Scientific Colloquium, Techn. Universität Ilmenau*