Novel Sensor Principle for High-Precision SI-Traceable Force Measurements

Martin Wittke[1], Mario André Torres Melgarejo[1], Matthias Wolf[1], Thomas Fröhlich[2], René Theska[1]
Technische Universität Ilmenau, Department of Mechanical Engineering, Ilmenau, Germany
[1]Institute for Design and Precision Engineering, Precision Engineering Group
[2]Institute of Process Measurement and Sensor Technology, Process Metrology Group
martin.wittke@tu-ilmenau.de

Summary:
Prior to 2019, force and mass measurements had to be traced back to the International Prototype Kilogram, which realized the SI unit kilogram. This definition required a long calibration chain with a series of relative mass comparisons. By setting Planck's constant to a fixed numerical value of $h = 6.626\ 070\ 15 \cdot 10^{-34}$ J s in the redefinition process, each instance of the calibration chain can now traceably measure absolute forces or masses. However, systems that provide a direct correlation between electrical and mechanical quantities are required. This work presents a novel sensor principle for high-precision SI-traceable force measurements. The sensor is based on the Planck Balance principle. Sub-mechanisms for compensating the stiffness of the compliant kinematic structure are integrated to maximize the resolution and minimize the uncertainty. The compensation mechanisms are based on preloaded springs to guarantee functionality in any orientation. The stiffness can be reduced to at least 0.04 % of the initial value. A force resolution below 40 pN is therefore achieved.

Keywords: force sensor, load cell, force measurement, electromagnetic force compensation, stiffness compensation, Planck Balance, SI, traceability

Introduction

Prior to 2019, the traceability of the SI unit kilogram had to be ensured via a long calibration chain back to the International Prototype Kilogram. By setting Planck's constant to $h = 6.626\ 070\ 15 \cdot 10^{-34}$ J s as a new SI reference, traceable measurements are open to all institutions independently. The sensor principle presented in this work offers a solution for force measurements in a wide field of precision engineering applications. It is based on the principle of a Planck balance and includes spring-based stiffness compensation mechanisms. Thus, the force resolution is increased and the measurement uncertainty is decreased independently of the orientation.

Methods

Planck Balance

The Planck Balance uses the compensation principle to determine the force F_M in Measurement Mode. The force is initiated translationally via a parallel spring guide, which is connected to a measurement lever by a coupling element. Once the force is applied, a position sensor measures the deflection of the lever. A controller processes the signal and energizes the electromagnetic actuator with the current i_{Ky} to keep the measurement lever in balance. To calculate the force F_M using equation (1), the actuator constant $B_{VC} \cdot L_{VC}$ needs to be determined.

$$F_M = i_{ky} \cdot B_{VC} \cdot L_{VC} \qquad (1)$$

The Velocity Mode is used for an in-situ calibration of the voice coil. A second actuator generates specific oscillations. The induced voltage $u_{ind}(t)$ in the voice coil is measured and synchronized with the velocity $v_{BC}(t)$ of the load carrier, which is determined using an interferometer. Therefore, equation (2) can be applied to calculate the actuator constant traceable to Planck's constant and the speed of light.

$$u_{ind}(t) = v_{BC}(t) \cdot B_{VC} \cdot L_{VC} \qquad (2)$$

Stiffness compensation

Due to the high motion reproducibility and negligible material friction, kinematic structures in precision applications are frequently designed as compliant mechanisms with concentrated compliances. However, even minimal hinge thicknesses of approx. 50 µm are still considerably limiting resolution and measurement uncertainty. Therefore, the residual stiffness needs to be compensated. Existing solutions use masses, magnets, or springs. Springs are advantageous since they work independently of their orientation and do not generate magnetic interference fields.

Sensor Principle

The novel force sensor principle (Figure 1) features the fundamental structure of the Planck balance. However, there is only one voice coil actuator. Investigations showed that a single actuator can be used to generate the oscillation for the Velocity Mode and to measure the induced voltage [1]. Spring-based stiffness compensation mechanisms [2] are integrated to compensate for the residual stiffness of the thin revolute joints. To eliminate static imbalances due to manufacturing-related position deviations of the joints and to prevent further function limitation [3], a double configuration of the mechanism is used. The Joints P_1 and

P_2 are purposefully displaced by the distance $\Delta_y P_n N_n$. The two compensation mechanisms thus generate two counter-directed moments about the lever joint H, which cancel each other out. The spring preload distances d_{Qx} can therefore be used to adjust the position d_{Ky} of the static equilibrium and simultaneously to reduce the stiffness to the target value.

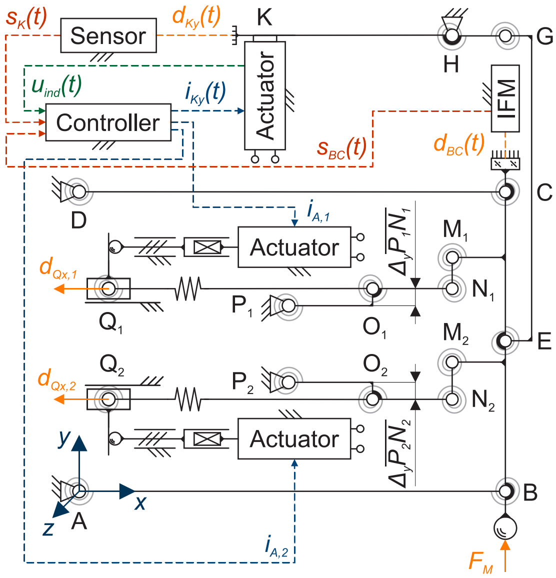

Fig. 1: Principle of the novel force sensor.

Simulation results

The kinematic structure was investigated using the rigid body model. The force-displacement diagrams are shown across the entire compensation range (Fig. 2) and around zero stiffness (Fig. 3).

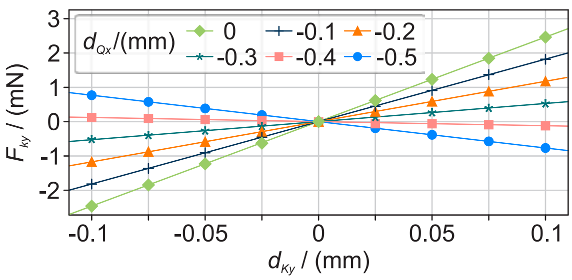

Fig. 2: Force-displacement diagram of the kinematic structure for a range from 0 mm to -0.5 mm for d_{Qx}.

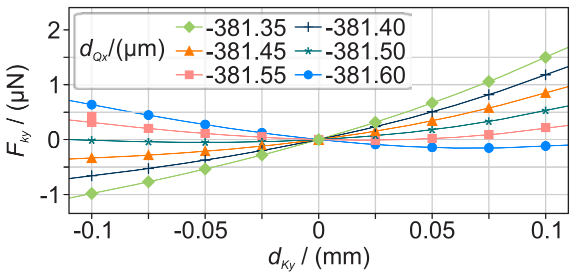

Fig. 3: Force-displacement diagram of the kinematic structure around zero stiffness for preload resolution steps of 50 nm for d_{Qx}.

Discussion

The results of the rigid body simulation confirm the feasibility of the principle. A reduction in stiffness is achieved by preloading the spring elements. There are linear correlations between the stiffness of the mechanism and the preload distance of the springs, as well as force and deflection. In the working range around zero stiffness, the force-displacement curve shows a slightly nonlinear behavior. For the considered configuration, the highest positive residual stiffness is achieved at d_{Qx} = -381.55 µm, if a preload adjustment resolution of 100 nm is assumed. The initial stiffness can thus be reduced from 24.61 N/m to $9.86 \cdot 10^{-3}$ N/m. With a position detection sensitivity of 1 nm at the operation point K and transmission ratio 4, forces F_M of 39.44 pN can be resolved.

Summary and Outlook

The redefinition of the SI unit kilogram allows every institution to perform directly traceable force and mass measurements. This paper presented a novel force sensor principle intended for precision engineering applications. It is based on the Planck balance using two spring-based mechanisms to compensate for the residual stiffness of the compliant kinematic structure. The principle theoretically allows a perfect stiffness reduction, practically down to at least 0.04 % of the initial value. The influences of critical manufacturing deviations are also eliminated by adjustment. The achievable force resolution is below 40 pN.
In future work, the complete kinematic structure will be designed as a compliant mechanism. All actuators and sensors will be specified and integrated into the system. The manufactured sensor will be put into operation and investigated experimentally.

Acknowledgment

The authors gratefully acknowledge the support of the Deutsche Forschungsgemeinschaft (DFG) within the framework of the Research Training Group "Tip- and laser-based 3D-Nanofabrication in extended macroscopic working areas" (GRK 2182) at the Technische Universität Ilmenau, Germany.

References

[1] F. Hilbrunner, I. Rahneberg, T. Fröhlich, Wattwaage mit Hebelübersetzung auf Basis eines kommerziellen EMK-Wägesystems. *tm - Technisches Messen*, *85* (11), 658-679 (2018); doi: 10.1515/teme-2017-0065

[2] M.A. Torres Melgarejo, M. Wittke, R. Theska, Adjustable stiffness compensation for monolithic high-precision mechanisms, *Proceedings of the 22nd International Conference of the European Society for Precision Engineering and Nanotechnology*, 67-68 (2022)

[3] M. Wittke, M. A. Torres Melgarejo, M. Darnieder, R. Theska, Investigation of a novel monolithic stiffness-compensated mechanism for high-precision load cells, *Engineering for a changing world: Proceedings: 60th ISC, Ilmenau Scientific Colloquium, Technische Universität Ilmenau, September 04-08, 2023* (1.3.017). Ilmenau Scientific Colloquium. Technische Universität Ilmenau; 60 (Ilmenau): 2023.09.04-08. Ilmedia; doi: 10.22032/dbt.58735