euspen's 26th International Conference & Exhibition, Krakow, PL, June 2026
www.euspen.eu

# Challenges in the design of force sensors based on the structure of high-precision weighing cells

Lennart Frentzel[1], Martin Wittke[1], Matthias Wolf[1], René Theska[1], Hannes Scheibe[1]

*Technische Universität Ilmenau, Department of Mechanical Engineering,*
*[1]Institute for Design and Precision Engineering, Precision Engineering Group*

*E-Mail: lennart-ramon.frentzel@tu-ilmenau.de*

**Abstract**
As part of the revision of the International System of Units in 2019, it was decided to also redefine the kilogram. Instead of using die International Kilogram Prototype as a physical reference, the unit is now traced back to Planck's constant. The Kibble principle is one of the approaches used to traceably measure masses, forces, and related quantities. Ongoing research into force sensors is based on high-precision weighing cells, as they enable the highest resolution with the lowest uncertainty.
Unlike weighing cells, force sensors do not operate in a static position in the gravitational field, but must fulfill their function properly in arbitrary orientations. The present work investigates the challenges involved in the design of weighing cell-based force sensors. It was found that not only the orientation but also the deflection of the transmission lever from its controlled position influences the force to be measured. The main impact factors are the mass of the links and the mechanical resistance of the flexure hinges, which inhibit the deflection of the system as stiffness. In order to be able to measure forces reproducible, independent of orientation, with a high resolution and low uncertainty, the design of force sensors must integrate features that minimize system stiffness. Approaches to minimize system stiffness include reducing the links masses or the adjustment of trim masses, optimizing the contour, as well as the geometrical parameters and the material of the flexure hinges, as well as using specific sub-mechanisms for compensating the stiffness.

**Keywords:** force sensor, weighing cell, Kibble principle, Planck balance, stiffness minimization, electromagnetic force compensation, measurement

## 1. Introduction

The revision of the International System of Units (SI) in November 2019 redefined the traceability of the kilogram to Planck's constant as fundamental natural constant [1]. The Kibble principle is one approach to trace the SI unit of mass, the kilogram, back to Planck's constant [1]. Based on this principle, the Planck balance was developed at the Technische Universität Ilmenau in collaboration with the Physikalisch-Technische Bundesanstalt (PTB) to calibrate weights in accordance with OIML [2,3]. The balance uses a mass comparator weighing cell based on a compliant mechanism, that applies the principle of electromagnetic force compensation to counterbalance the weight of a mass artefact ($\Delta F = mg$) with an electromagnetic counterforce ($\Delta F_A = BL \cdot I$) (Figure 1). The product of $B$ and $L$ is determined by calibrating the actuator in Velocity Mode [10].

Current research focuses on the development of force sensors adapting the concept of the Planck balance for precise and reproducible measurement of forces. Application fields are dimensional measurement and manufacturing technology [4,6] or system calibration [8]. In contrast to balances, force sensors do not have a static orientation and position in the field of gravity. Due to permanent changes in orientation, the design of force sensors faces various challenges that are discussed within this work.

## 2. Approach

The goal in designing a force sensor based on a compliant mechanism is to measure forces reproducibly with a minimal uncertainty. If the structure of such a sensor is reduced to its essential elements, the basic model can be described as a frame-supported transmission lever (see Figure 1).

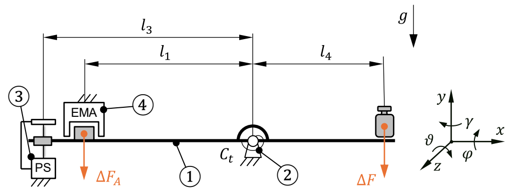


**Figure 1.** Basic model of a force sensor based on compliant mechanisms and the principle of electromagnetic force compensation.

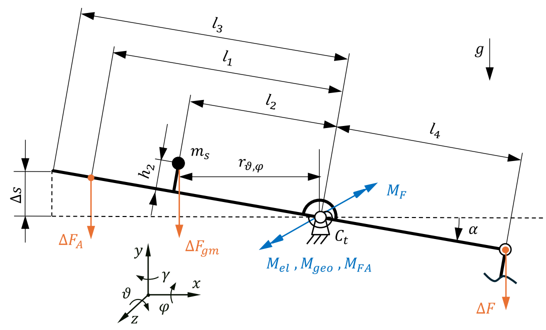


**Figure 2.** Rigid-body model of the transmission lever of a force sensor using electromagnetic force compensation to visualize acting moments and forces in a loaded state.

A force $\Delta F$ acting on one side causes the transmission lever ① to deflect from its controlled position due to the flexure hinge ② (see Figure 2). As a result of the applied force $\Delta F$, the resulting deflection $\Delta s$ is detected by an optical position sensor ③ and compensated by a counterforce $\Delta F_A$ using an electromagnetic voice coil actuator ④. Since the balanced position is always restored during force measurement (see Figure 1), the moment equilibrium can be established by considering the effective lever arms $l_1, l_2, l_3, l_4, h_2$ and $r_{\vartheta,\varphi}$. Based on the set electromagnetic force $\Delta F_A$, the acting force $\Delta F$ can be directly determined (1).

$$\boldsymbol{M}_{\boldsymbol{F}_A}(\Delta F_A) \;=\; \boldsymbol{M}_{\boldsymbol{F}}(\Delta F) \qquad (1)$$

Due to the permanent readjustments of the angle $\alpha$ in the controlled position and its orientation changes in the form of a pitch ($\vartheta$-rotation around the $z$-Axis) or roll ($\varphi$-rotation around the $x$-Axis) motion (see Figure 2), parasitic forces and moments (2) and (3) are generated that effect the actual force compensation (1). The flexure hinges with the known stiffness $c_t$ additionally generate a moment $M_{el}$ due to elastic deformation that counteracts the deflection motion. Furthermore, the individual masses of the systems links result in a combined centre of mass $m_s$, which leads to a geometric moment $M_{geo}$ depending on the orientation in the field of gravity.

$$\boldsymbol{M}_{\boldsymbol{F}_A} \;+\; M_{geo} \;+ M_{el} \;=\; \boldsymbol{M}_{\boldsymbol{F}} \qquad (2)$$

$$\boldsymbol{\Delta F}_{\boldsymbol{A}} \cdot l_1 \;+\; \Delta F_{gm} \cdot r_{\vartheta,\varphi} \;+\; M_{el} \;=\; \boldsymbol{\Delta F} \cdot l_4 \qquad (3)$$

## 3. Results

The resistance of a system to deformation can be expressed by the stiffness $C_\alpha = \frac{M}{\alpha}$ or $C = \frac{\Delta F}{\Delta s}$. Equations (1) and (2) can be used to establish stiffness equations (4) and (5) which form the basis for evaluating the force measurements.

$$C_{sys} \;=\; C_{geo} \;+\; C_{el} \qquad (4)$$

$$\frac{\boldsymbol{M}_{\boldsymbol{F}}}{\alpha} - \frac{\boldsymbol{M}_{\boldsymbol{F}_A}}{\alpha} = \frac{M_{geo}}{\alpha} + \frac{M_{el}}{\alpha} \qquad (5)$$

For the rigid-body model shown in Figure 2, the system stiffness $C_{sys}$ (4) consists of an effective geometric component $C_{geo}$ and an elastic component $C_{el}$. This relation is illustrated in Figure 3. The sinusoidal curve of geometric stiffness is caused by the size and position of the centre of mass $m_S$ on the transmission lever ①, as well as its orientation in the gravitational field ($\vartheta$ and $\varphi$). Meanwhile, the constant shift of the graph on the stiffness axis by the amount of elastic stiffness results from the resistance of the hinges to elastic deformation.

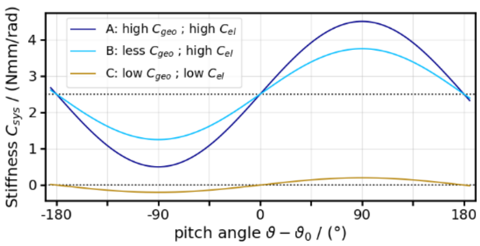


**Figure 3.** Visualisation of the impact of several methods for the minimization of system stiffness as a function of the pitch angle $\vartheta - \vartheta_0$. (There is no quantitative reference for the stiffness values.)

In order to be able to measure force effects $\Delta F_A$ reproducible, independent of orientation and with a high resolution and low uncertainty, the stiffnesses $C_{geo}$ and $C_{el}$ must be minimized when designing balance-based force sensors (6). This indicates that the stiffness characteristic curve needs to be smoothened and then shifted to zero stiffness (see Figure 3, C).

$$\boldsymbol{\Delta F}_{\boldsymbol{A}} = \boldsymbol{\Delta F} \cdot \frac{l_4}{l_1} - \left(C_{geo} + C_{el}\right)\frac{\alpha}{l_1} \qquad (6)$$

## 4. Discussion

Various design and manufacturing methods are available to reduce system stiffness $C_{sys}$ and its components $C_{geo}$ and $C_{el}$.

### *4.1. Minimization of elastic stiffness*

A reduction in the constant proportion of elastic stiffness $C_{el}$ can be achieved by optimizing the flexure hinges and thus cause a shift of the stiffness curve toward zero (see Figure 3, A and C). Minimizing the elastic stiffness is achieved by optimizing the contour and geometry of the hinges, with a special consideration given to the thickness, as well as by selecting a material with a minimal Young's Modulus.

Although the joints cannot be manufactured any thinner than 50 µm due to manufacturing constraints [9], research results from [7] demonstrate, that optimising the joint contour can reduce stiffness even further.

### *4.2. Minimization of geometric stiffness*

A reduction in the sinusoidal proportion of geometric stiffness $C_{geo}$ can be achieved by adjusting the centres of mass of the frame-beared components or the overall centre of mass $m_S$. The position of the centre of mass needs to be shifted into the main rotational hinge ② so that there is no geometric moment $M_{geo}$. On the other hand, a reduction in geometric stiffness $C_{geo}$ can be achieved by minimizing the masses of the links, which cause a reduction in amplitude (see Figure 3, B). [6]

The research results from [6] show that reducing the total mass led to a decrease in rotational dependence and stiffness.

### *4.3. Stiffness compensation*

An additional method to minimize stiffness as a whole, rather than just individual components ($C_{geo}$ and $C_{el}$), is to implement a compensation mechanism. The principle is based on generating a compensating stiffness that increases proportionally to the deflection of the transmission lever ①. [4]

Theoretical investigations have shown that implementing a compensation mechanism can eliminate geometric and elastic stiffness components [4]. However, in practice, its effectiveness has only been partially demonstrated [5].

## 5. Summary and Outlook

The current work has shown that the orientation in the gravitational field of force sensors based on compliant mechanisms, has an influence on the measured forces $\Delta F_A$. Since orientation dependence, reproducibility of results and the measured forces are directly related to system stiffness, design features should be incorporated into force sensors to actively minimize stiffness. This can be achieved by reducing and adjusting the individual masses of the mechanism's links, by optimizing the contour, geometry or material of the flexure hinges, and by implementing compensation sub-mechanisms.

Ongoing studies deal with the implementation of these principles for the next generation of SI-traceably measuring force sensors. Initial results have already been presented.

## References


[1] Kibble B P 1975 *5th International Conference on Atomic Masses and Fundamental Constants* Paris 545–551
[2] OIML R 111-1 2004 Weights of classes E1, E2, F1, F2, M1, M1–2, M2, M2–3 and M3 - Part 1: Metrological and technical requirements
[3] Rogge N 2023 PhD thesis Technische Universität Ilmenau
[4] Wittke M, Torres Melgarejo M A, Wolf M, Fröhlich T, Theska R 2026 EUSPEN's 25th ICE, Zaragoza
[5] Wittke M, Torres Melgarejo M A, Wolf M, Fröhlich T, Theska R 2026 EUSPEN's 26th ICE, Krakow
[6] Wolf M, Wittke M, Torres Melgarejo M A, Theska R 2024 EUSPEN's 24th ICE, Dublin
[7] Wolf M, Wittke M, Torres Melgarejo M A, Theska R 2024 EUSPEN's 25th ICE, Zaragoza
[8] Dannberg O 2020 PhD thesis Technische Universität Ilmenau
[9] Darnieder M 2024 PhD thesis Technische Universität Ilmenau
[10] Rothleitner C, Schleichert J, Rogge N, Günther L, Vasilyan S, Hilbrunner F, Knopf D, Fröhlich T, Härtig F 2018 Measurement Science Technology **29** 7 074003