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Mechanical properties of an adjustable weighing cell prototype

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Abstract

Weighing cells based on the principle of electromagnetic force compensation are highly sensitive force measuring devices. A compliant mechanism with thin flexure hinges constitutes the mechanical basis of the balance. The weighing cells are the core components of high-performance vacuum mass comparators, e.g. for the comparison of one kilogram mass standards. According to the mechanical models, the achievable sensitivity of the measurement device is only limited by the adjustment resolution. Without further measures, the vertical adjustment of small trim masses represents a trade-off between resolution and tilt sensitivity. The numerical test of the underlying adjustment concept by finite element models reveals that the objectives of a high sensitivity and a low tilt sensitivity can be achieved simultaneously by a meaningful combination of adjustment measures. This represents a promising concept for the further enhancement of vacuum mass comparators. The prototypes are planar weighing cell structures for a flexible choice of the manufacturing process. The planar mechanism facilitates the comparison between models and measurements. The weighing cells for a nominal mass of 300 g are experimentally investigated. The measurement of tilt reactions is enabled by the use of a precision tilt table as base for the weighing cell. Properties like stiffness and tilt sensitivity are determined as a function of the adjustment parameters. This way the mechanical models are verified, and the property enhancement of the weighing cell is evaluated.

Weighing cell, compliant mechanism, adjustment, stiffness, tilt sensitivity, control

1. Introduction

Weighing cells based on the principle of electromagnetic force compensation (EMFC) have various applications. Designed for the balancing of weights, their measurement capabilities promote the use in various fields of science and economy. Among those are the determination of spring constants of AFM-cantilevers [1], Lorentz force flow meters [2], tiltmeters [3], Planck balance [4], and other applications with high force resolution requirements.

EMFC-weighing cells are position controlled compliant mechanisms which are operated closely around the zero-deflection position. The obtainable force resolution is defined by the mechanical stiffness of the compliant mechanism and the resolution of the position sensor. The latter is in the nanometre range [1].

The joints in the mechanism are realized by semi-circular flexure hinges which are manufactured to very fine minimal notch heights in order to minimize the bending stiffness of the joints.

In weighing applications, EMFC-weighing cells in mass comparators are currently defining the state of the art for mass comparisons of 1 kg standards. In the latest mass comparison campaign at the Bureau International des Poids et Mesures (BIPM) in 2014, a repeatability of the mass comparison of < 0.5 µg has been achieved [5]. In data sheets of commercially available mass comparators a maximum resolution of 0.1 µg is indicated.

2. Electromagnetic force compensated weighing cells

The compliant mechanism of an EMFC weighing cell is typically composed of a parallelogram guide (2-4) and a transmission lever (8) coupled by a coupling element (7) , see figure 1. The weighing pan(s) (5,6) are attached to the load carrier (4) that is part of the parallelogram guide. The components of the EMFC system (counter weight (L), position sensor (M), and voice coil (K)) are attached to the left hand side of the transmission lever (8).

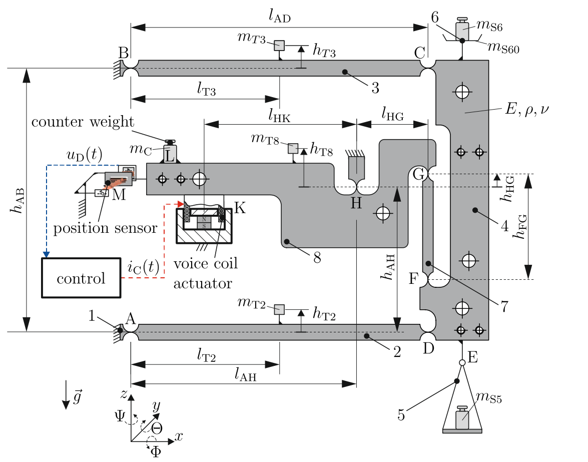

Figure 1. Depiction of the weighing cell mechanism with components attached.

A resolution of the weighing system in the sub-microgram range can be achieved with a mechanical stiffness of the mechanism of approximately 1 N/m in combination with a position sensor having a resolution of 1 nm. The flexure hinge geometry in this paper with a minimal notch height of $h = 50$ µm results in an initial stiffness of about 55 N/m. Consequenty, adjustment measures for a stiffness reduction represent a viable option to achieve the projected resolution.

3. Adjustment concept

The adjustment of the compliant mechanism to a smaller stiffness can be achieved in three ways, assuming that the flexure hinge thickness cannot be further reduced. Available measures for the stiffness reduction are the shift of a mass point in the gravitational field (**A**), the use of geometrical nonlinearities of the mechanism (astatic mechanism) (**B**), or pretensioned elasticities (**C**). The concepts are presented in figure 2:

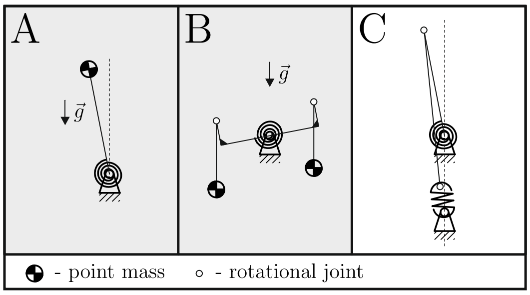

Figure 2. Methods for stiffness reduction: left – mass point vertical shift; middle: astatic adjustment; right - preloaded elasticity.

The astatic adjustment (**B**) and the vertical shift of mass points (**A**) are combined to adjust the weighing cell. The novelty are additional trim masses on the levers of the parallelogram guide (m_{T2}, m_{T3}). In combination with the trim mass on the transmission lever (m_{T8}), the weighing cell can be adjusted to a state where the total stiffness C and the tilt sensitivity D_Θ have a common zero crossing. Without the astatic adjustment h_{HG}, this optimum can only be reached either with large trim masses or large displacements of the masses. Since both options are unfavourable, the astatic adjustment with the parameter h_{HG} is an essential part of the adjustment concept to initially set the stiffness C close to zero.

4. Mechanical model

The mechanical behaviour of the weighing cell is described using the finite element (FE) method. The structure with seven thin flexure hinges is subject to elastic deformation which affect the location of both centers of mass and rotation axes. These complex correlations are covered within the FE model.

The geometry of the mechanical model is based on the geometry of the prototype weighing cell that is experimentally investigated in section 5. Further components attached to the structure like the weighing pan, trim masses or the counter weight are represented by point masses. Their nodes are connected to the structure by contact elements using the MPC-formulation in ANSYS®. The parameters according to figure 1 are defined in table 1.

A particular difficulty is the modelling of the thin flexure hinges with a minimum notch height of less than 50 µm. For the accuracy of capturing the stress gradients in the notch region a fine mesh is only required in a small central zone [6], see detail in figure 3. This strategy enables an exact modelling of the mechanism while simultaneously limiting the number of nodes and the computation time. As it is shown in figure 3, the model includes relevant drilled holes for the attachement of parts since they have a relevant influence on the deformation of the structure.

Table 1 summarizes the relevant model parameters that are carefully chosen to comply with the realized prototype in section 5.

Table 1. Model parameters.

Param.	Value	Unit	Param.	Value	Unit
ρ_{Al}	2800	kg/m³	m_{T8}	0.0804	kg
E	71	GPa	m_{T2}, m_{T3}	0.0057	kg
ν	0.33	-	m_C	0.0484	kg
g	9.81	m/s²	m_{S6}	0.3319	kg
l_{HG}	27	mm	m_{S60}[1]	0.1018	kg
h_{HG}	3.15	mm	l_{AH}	85.5	mm
$l_{AD,BC}$	112.5	mm	l_{HK}	105	mm
h_{AB}	100	mm	h_{FG}	40.0	mm
h_{AH}	55	mm	$l_{T2,T3}$	56.25	mm

[1] – net weight of the weighing pan components

The finite element model with attached point masses and boundary conditions is presented in figure 3:

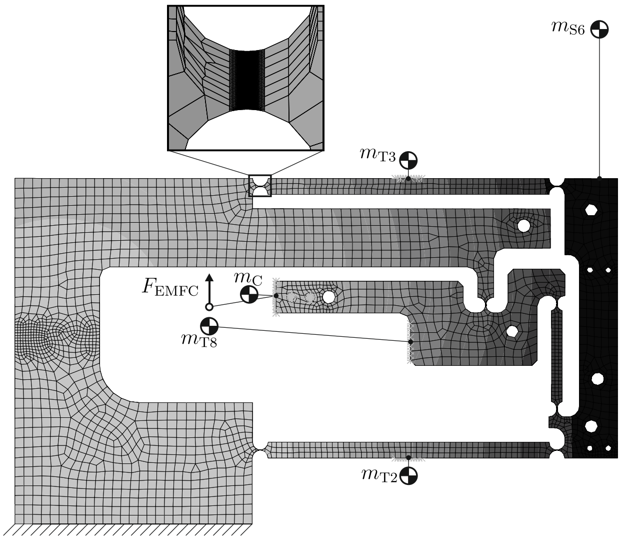

Figure 3. Weighing cell prototype as finite element model in ANSYS®.

Slight changes in the model concerning the minimal notch height of the flexure hinges or the location of the centers of mass have a major influence on the stiffness C and the tilt sensitivity D_Θ of the structure. The force for the determination of the properties is determined at the left end of the transmission lever (8) at point K where the resulting Lorentz force F_{EMFC} of the voice coil is excerted. The force at the lever is converted to a force at the weighing pan using the nominal transmission ratio of the transmission lever (l_{HK}/l_{HG} ≈ 3.89).

The stiffness C is determined by deflecting the mechanism slightly and evaluating the force difference. The tilt sensitivity is modelled by tilting the g-vector and calculating D_Θ from the force difference divided by the respective tilt angle.

5. Experimental investigation

The following section describes the experimental setup, the measuring method and the results including a comparison with the finite elemente model in the sections above.

5.1. Experimental setup

The experimental setup for the investigation of the influence of selected adjustment parameters is located in a quiet surrounding in the basement of a building. The measurement setup is placed on a separate foundation to reduce the impact of small tilings and vibrations caused by wind loads on the building and other disturbances. Vibration damping is ensured by a weighing table with a heavy natural stone.

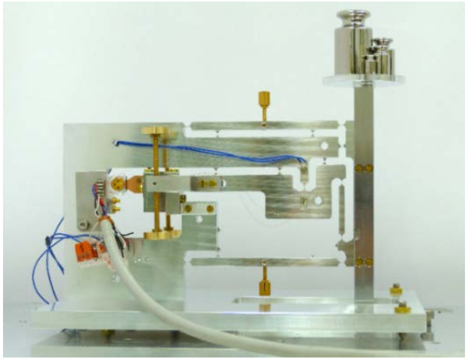

Figure 4. 2D-EMFC weighing cell structure in experimental setup.

For the investigation, the novel monolithic 2D-structure of the electromagnetic force compensated weighing cell (see figure 4) is aligned horizontally to its base on the precision tilt table [7]. The weighing cell is additionally protected by a cover from styrodur for the minimisation of errors caused by air movements. The temperature fluctuations in the controlled laboratory environment are limited to 0.1 K. In long term measurements, a temperature sensitivity of the indication of 896 µg/K is determined.

A schematic overview of the experimental setup with its periphery is presented in figure 5. The optical position sensor (see figure 1) consists of an optical slit aperture on the lever and a combination of an infrared LED and a differential photo diode fixed to the base. As indicated in figure 5, the position sensor is operated by analog electronics and detects movements of the lever with nanometer resolution [1]. The output signal is an amplified differential voltage (u_D) that is zero for one distinct position of the lever. The differential voltage is measured with the digital multimeter Agilent 3458A and is transferred to a computer as the input signal for a digital PID-controller programmed in MATLAB®.

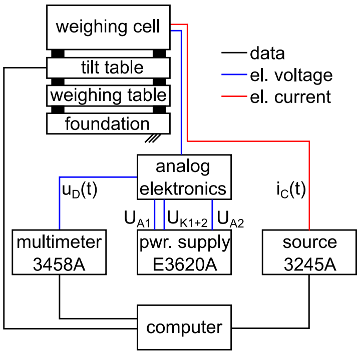

Figure 5. Schematic overview of the experimental setup.

The controller calculates the required coil current (i_C) to hold the lever in its undeflected position and transmits the value to the universal source Agilent 3245A which is connected to the coil. The control process runs due to restricted data rates and required communication times with a maximum frequency of 20 Hz. For the analysis of the static behaviour of the mechanical weighing cell, the control frequency is sufficient.

5.2. Method for the determination of adjustment success

The properties of stiffness and tilt sensitivity can be modified by trim masses, adjustable in its z-position [8]. The adjustable parameters (h_{T2}, h_{T3}, h_{T8}) are the distances between the centers of mass of the trim weights (m_{T2}, m_{T3}, m_{T8}) and the respective center of rotation in z-direction (see figure 1). The parameters are varied to determine their influence on stiffness and tilt sensitivity.

The measurement procedure allows the determination of the stiffness of the configuration (C) and the tilt sensitivities (D_Θ, D_Φ). To measure the stiffness, the lever was deflected in steps by the digital PID-controller. With the deflection and the coil current difference the mechanical stiffness can be calculated.

The current and voltage constants have been determined in previous experiments. The actuator constant K_I (kg/A) is determined by measuring the required current for a mass change of a 1 g-mass standard (E2). The voltage constant K_U (m/V) is determined by deflecting the lever by predefined voltage steps while measuring the movement of the weighing pan with an interferometer.

With the actuator and voltage constants, the stiffness at predefined tilt stages of the tilt table is determined (as presented in figure 6). With the data from all measurements for each tilt setting, the stiffness ($C(\Theta, \Phi)$) and the tilt sensitivity D_Θ and D_Φ is determined.

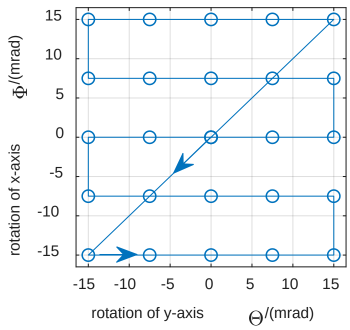

Figure 6. Predefined measuring stages of the tilt table.

5.3. Experimental results and agreement with FE-model

The experimental results show a clear correspondence between the adjustment parameters and the investigated data. It reveals that the stiffness can be adjusted to zero as a function of parameters h_{T8} and $h_{T2,T3}$ as shown in figure 7. The intersection of the planes result in a linear function to which applies $C = 0$. In the same manner a linear function for a tilt sensitivity of zero is determined in the plane $D_\Theta = 0$ (as presented in figure 8).

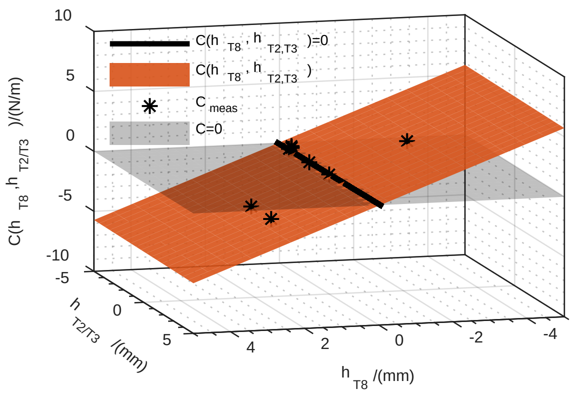

Figure 7. Stiffness depending on adjustment parameters.

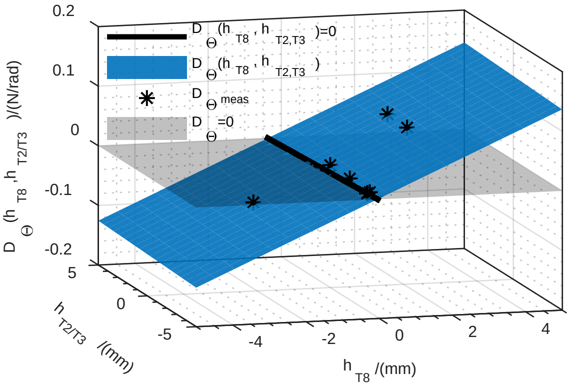

Figure 8. Tilt sensitivity depending on adjustment parameters.

The combination of the linear functions $C(h_{T2,T3}, h_{T8}) = 0$ and $D(h_{T2,T3}, h_{T8}) = 0$ in figure 9 shows the existence of a common zero crossing of stiffness and tilt sensitivity.

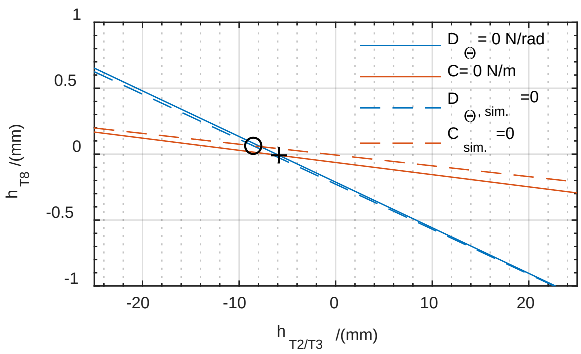

Figure 9. Measurement results (solid lines) in comparison to the FE model results (dashed lines).

The measuring method was repeated for different weights on the weighing pan around 300 grams to find a combination of adjustment parameters close to zero. The best result is presented in figure 9 with a weight $m_{S6} = 335\,\text{g}$. Here, the optimal configuration is determined to $h^*_{T8} = -0.009\,\text{mm}$ and $h^*_{T2,T3} = -5.872\,\text{mm}$ (black cross in figure 9). To test the determined parameter combination, the trim masses m_{T8} and $m_{T2,T3}$ are adjusted in their heights as close as possible to determined parameter combination. In the adjusted state close to $h^*_{T2,T3}$, h^*_{T8}, the stiffness and a tilt measurement under controlled conditions are repeated without changes to the setup. The results are presented in table 2:

Table 2. Experimental settings and results.

Param.	Value	Std.dev.	Unit
m_{S6}	$334.829 \cdot 10^{-3}$	$\pm 3.53 \cdot 10^{-7}$	kg
$m_{T2,T3}$	$5.720 \cdot 10^{-3}$	$\pm 3.00 \cdot 10^{-5}$	kg
m_C	$48.428 \cdot 10^{-3}$	$\pm 2.00 \cdot 10^{-6}$	kg
m_{T8}	$80.448 \cdot 10^{-3}$	$\pm 2.32 \cdot 10^{-4}$	kg
$h_{T2,T3}$	$-5.874 \cdot 10^{-3}$	$\pm 3.47 \cdot 10^{-6}$ (*)	m
h_{T8}	$-0.013 \cdot 10^{-3}$	$\pm 4.86 \cdot 10^{-6}$ (*)	m
$\boldsymbol{C}$	$\mathbf{16.60 \cdot 10^{-3}}$	$\mathbf{\pm 65.94 \cdot 10^{-3}}$	**N/m**
$\boldsymbol{D_\Theta}$	$\mathbf{-5.06 \cdot 10^{-5}}$	$\mathbf{\pm 9.29 \cdot 10^{-6}}$	**N/rad**

(*) – assuming an adjustability of ± 2.5° to parallel structures

6. Conclusions

A novel adjustment concept for EMFC-weighing cells is experimentally investigated based on a planar prototype weighing cell. In the presented mechanical model of the weighing cell prototype, the adjustment concept allows an adjustment to a common zero crossing for the stiffness C and the tilt sensitivity D_Θ. Thus, highest resolutions can be achieved with a simultaneous minimization of the tilt sensitivity.

To experimentally verify the adjustment concept, a measurement regime in combination with a precision tilt table is developed. The parameter h_{HG} is manufactured to 3.15 mm to compensate the entire stiffness in combination with a sample weight of $m_{S6} = 300\,\text{g}$. Due to manufacturing tolerances, especially concerning the minimal notch height h of the flexure hinges, an additional substitution weight of approximately 35 g is required to adjust the initial stiffness to zero. With this initial configuration of the weighing system ($C \approx 0$), the adjustment concept was successfully verified. The common zero crossing of stiffness and tilt sensitivity from the measurement results (black cross) was found in proximity to the position predicted by the FE model (black circle). The existing deviations of the common zero crossing in figure 9, may be caused by deviations between model and prototype setup concerning the exact location of m_{S6} and the position reference for the transmission lever.

The novel adjustment concept for EMFC-weighing cells is successfully verified using a prototype weighing cell and a precision tilt table. The common zero crossing of the stiffness $C = 0$ and the tilt sensitivity $D_\Theta = 0$ is clearly identified from the measurement results and is in good agreement with the predicted values. An adjustment towards the determined optimum resulted in a stiffness of about 17 mN/m corresponding to a theoretical resolution of 1.7 ng. Following this principle proof, the further evaluation of the adjustment concept requires vacuum conditions. This along with the automation of the adjustment is part of the ongoing research activities.

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