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Investigation of the sensitivity of a high-precision weighing cell to disturbances caused by the adjustment system

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Abstract

The achievable performance of high-precision weighing cells is often hindered by manufacturing limitations and mass imbalances on the mechanical structure. Full performance is only achieved by means of fine mechanical adjustments. These are performed before setting up the device for operation in a sealed chamber. A further improvement in the performance can be achieved by conducting the adjustments in situ under working conditions. However, due to the high sensitivity at the adjustment locations, parasitic effects of remotely-controlled systems negatively affect the quality and stability of the adjustment. Limiting the disturbances caused by adjustment systems can significantly increase the achievable performance. Setting appropiate limit values to their negative parasitic effects requires accurate knowledge of the disturbance sensitivity of the weighing cell at the adjustment locations.
The following contribution focuses on the investigation of the systematic deviations caused by disturbances on the adjustment locations of a high-precision weighing cell. Mechanical and thermal effects on the mechanical structure are investigated using finite element models. Sensitivity coefficients are determined based on the observed behaviour. Based on the sensitivity coefficients and the targeted properties of the weighing cell, limit values for the parasitic effects of novel adjustment systems are established.

Keywords: weighing cell, adjustment, disturbance sensitivity, systematic deviations

1. Introduction

Highest precision weighing cells base currently on the principle of electromagnetic force compensation (EMFC) [1]. The weight of the measurand is applied to a compliant mechanism to induce a deflection, which is counteracted by an electromagnetic force. The electric current at the actuator is controlled by means of a position indicator and serves as indirect measure of the mass.

The achievable resolution is limited by the inherent restoring forces of the mechanism. Systematic deviations are also induced by ground tilting due to mass imbalances. Full performance can only be achieved by compensating these effects through fine mechanical adjustments [2]. These are performed manually before setting it up for operation in a sealed vacuum chamber. Due to the sensitivity at the adjustment locations, remotely-controlled systems cannot be implemented. Their disturbance effects, e.g., parasitic forces and torques due to electric cables, negatively affect the device function and the adjustment itself.

Further increase in the performance of EMFC weighing cells can be achieved by limiting the disturbances introduced by the adjustment systems. Setting appropriate limit values requires accurate knowledge of the disturbance sensitivities. This paper investigates the systematic deviations caused by disturbances at the adjustment spot of an exemplary weighing cell.

2. Adjustment of an EMFC weighing cell

The working principle of an adjustable EMFC weighing cell is shown in Figure 1. Compensation of elastic restoring forces is partially achieved by the change of the lever arm $\overline{HG}_x$ during deflection due to the difference in height of joints G and H, h_{HG}. To counteract the remaining elastic restoring forces as well as the parasitic torques due to ground tilting, height-adjustable trim masses (m_{T2}, m_{T3} and m_{T8}) are built into the compliant mechanism. These serve to displace the centre of mass of their respective links, which generate deflection-dependent torques in the sense of rotation, i.e., inverted pendula. The vertical position h_{T8} of mass m_{T8} has the highest sensitivity in the adjustment of both the stiffness and the tilt sensitivity [2]. However, adjusting of h_{T8} for zero stiffness and zero tilt sensitivity simultaneously is not possible. The effective centre of mass of the balance beam should locate exactly on its idealised centre of rotation for zero tilt sensitivity but above it to compensate the elastic stiffness. Trim masses m_{T2} and m_{T3} are, thus, used to adjust the tilt sensitivity while minimally affecting the total stiffness value.

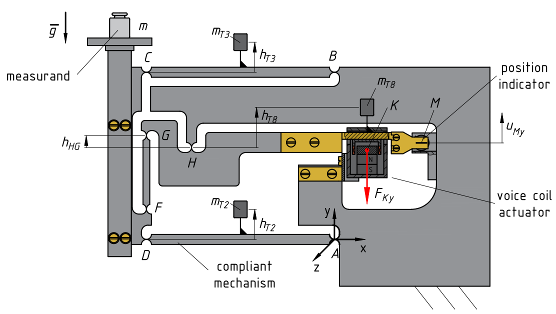

Figure 1. Working principle of adjustable EMFC weighing cell [3]

In this work, particular emphasis is placed in the adjustment of the stiffness via trim mass m_{T8}. The adjustment process consists in changing the position h_{T8} and measuring the change in the compensation force $F_{K,y}$ from the non-deflected position to a deflected position $u_{M,y}$. The total mechanical stiffness at point

K is defined as $C_K = (F_{K,y}(u_{M,y}) - F_{K,y}(u_{M,y} = 0))/u_{K,y}$, where $u_{K,y}$ is proportional to $u_{M,y}$. The adjustment is completed when the measured stiffness is below a certain targeted value.

Due to the very high sensitivity of the mechanical structure at the adjustment spot (point K), disturbance effects by the adjustment system required to displace m_{T8} are critical. Parasitic displacements of the aperture at point M $u_{M,y}$ resulting from deformations induced by parasitic forces, torques and temperature gradients due to heating leads to a variation in the required compensation force $F_{K,y}$. This results in deviations of the measured mass as well as of the adjusted stiffness value.

3. Model-based investigation

To evaluate the influence of disturbance effects at point K, finite element (FE) analysis are conducted. Deviations of the required electromagnetic force to maintain zero deflection $F_{K,y}(u_{M,y} = 0)$ and of the total mechanical stiffness C_K produced by parasitic forces f_x, f_y, f_z, torques m_x, m_y, m_z and heat flux $\dot{q}$ are evaluated using structural and thermal 3D-FE models. Figure 2 shows the FE model and the considered boundary conditions. Accuracy in the calculations is ensured by refining the mesh on the flexure hinges where the highest stress and heat flux gradients are located. The meshing strategy bases on the method presented in [4]. Quasistatic and steady state behaviour are assumed for the structural and thermal models, respectively. In the structural model, linear material behaviour and geometric nonlinearities are considered. Structural loads are applied through remote nodes and multi-point constraints. Due to the expected operation inside a vacuum chamber, convection effects are neglected while only radiation to the environment is considered in the thermal model. Temperature gradients resulting from the thermal analysis are imported as thermal loads in the structural model.

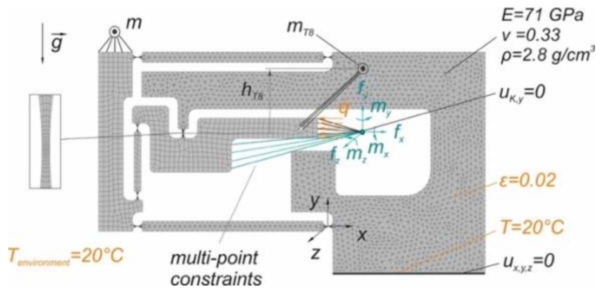

Figure 2. FE model and boundary conditions: black – structural model; green - mechanical disturbances ; orange - thermal model

The simulations are conducted by applying each individual disturbance effect X and evaluating the change in the reaction force $F_{K,y}$ at non-deflected state $u_{K,y} = 0$, and at deflected state $u_{K,y}$. Disturbance sensitivities are defined as the quotient of the change of $F_{K,y}(u_{M,y} = 0)$ and C and of the disturbance effects, i.e., $\delta F_{K,y}/\delta X$ and $\delta C/\delta X$, respectively. Correlations between disturbance effects have been neglected. For nonlinear correlations between the investigated parameters and the disturbance effects, e.g., for f_z, a linearization has been done considering the target values of $\delta F_{K,y}(u_{M,y} = 0)$ and δC_K.

4. Results and discussion

The sensitivities of the weighing cell to disturbances at the spot of the stiffness adjustment are summarized in Table 1. Maximum target values for the deviations $\delta F_{K,y}(u_{M,y} = 0)$ and δC_K are set to 12.6 pN and 6.6 μN/m, respectively. Taking these values into consideration, limit values for each disturbance effect $\delta X_{\max}$ of the adjustment system can be determined.

Table 1 Theoretical disturbance sensitivities of the EMFC weighing cell

X	$\delta F_{K,y}/\delta X$	$\delta X_{\max,F_{K,y}}$	$\delta C_K/\delta X$	$\delta X_{\max,C_K}$
f_x	4.73×10^{-4} N/N	2.69×10^{-8} N	9.53×10^{0} N/m/N	6.93×10^{-7} N
f_y	1.00×10^{0} N/N	1.27×10^{-11} N	8.66×10^{-4} N/m/N	7.62×10^{-3} N
f_z	7.88×10^{-8} N/N	1.61×10^{-4} N	1.02×10^{-3} N/m/N	6.50×10^{-3} N
m_x	3.29×10^{-7} N/Nm	3.86×10^{-5} Nm	1.68×10^{-3} N/m/Nm	3.92×10^{-3} Nm
m_y	7.58×10^{-7} N/Nm	1.68×10^{-5} Nm	7.27×10^{-3} N/m/Nm	9.08×10^{-4} Nm
m_z	9.52×10^{0} N/Nm	1.33×10^{-12} Nm	1.46×10^{-1} N/m/Nm	4.52×10^{-5} Nm
$\dot{q}$	2.27×10^{-4} N/W	5.58×10^{-8} W	3.73×10^{-3} N/m/W	1.77×10^{-3} W

According to the resulting limit values regarding the deviation of the compensation force, avoidance of any disturbance effect during the measurement process is mandatory. The higher limit values regarding the stiffness suggest that disturbances can be allowed up to a certain value only during the adjustment process and must be avoided afterwards. While heat generation can be avoided using zero-power locking mechanisms, permanent cable connections required to transfer electrical energy to the drive element must be avoided due to their highly instable parasitic forces and torques. The results call for new ways to generate the adjustment motion inside the sealed environment without parasitic effects.

The presented theoretical values consider only the vertical deflection of point M due to the disturbances. However, lateral deformations also affect the resulting electromagnetic force. Lateral deflections of point K result in a change in the relative position between the coil and the permanent magnet of the actuator, influencing the actuator sensitivity [5]. Lateral deflections of point M result in a disalignment between aperture and differential photodiode, which affects the sensitivity of the position sensor [6]. In addition, electromagnetic effects related to the selected function principle of the adjustment drive as well as heating affect the function of the actuator. Current investigations are focused on the consideration of these effects.

5. Summary

This paper investigates the sensitivity of a high-precision weighing cell to disturbances at its most critical adjustment spot. The investigated disturbances represent parasitic effects generated by the adjustment system. Multi-domain finite element models are used to determine the deviation of the electromagnetic force for zero deflection and of the stiffness value. Sensitivity coefficients are derived from the simulation results and serve as basis for the definition of limit values for the design of the adjustment system. As a result, the need for novel adjustment concepts becomes obvious. Current research work focuses on the optimization of models, the experimental verification of the sensitivity coefficients, and the development of novel adjustment systems with negligible side effects.

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