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Novel Method for Determining the Mechanical Stiffness of Weighing Cells

Martin Wittke, Maximilian Darnieder, Mario André Torres Melgarejo, René Theska
Technische Universität Ilmenau, Department of Mechanical Engineering, Ilmenau, Germany
Institute for Design and Precision Engineering, Precision Engineering Group
martin.wittke@tu-ilmenau.de

Summary:
Weighing cells with electromagnetic force compensation are frequently used in precision balances and mass comparators. The kinematic structure is given by a compliant mechanism with concentrated compliances. Thin flexure hinges enable highly reproducible motion but limit the sensitivity to mass changes due to their rotational stiffness. To achieve the desired sensitivity, the stiffness of the mechanism must be further reduced by mechanical adjustments. To optimize the adjustment parameters, the initial stiffness of the mechanism needs to be characterized accurately.
For this purpose, a novel self-testing method was developed. It allows accurate determination of the elastic stiffness of the weighing cell and the geometric stiffness caused by the masses of the linkages. The method uses static stiffness measurements in three orientations. The gravity vector must be orthogonal to the plane of motion to characterize the elastic stiffness. Determining the geometric stiffness requires the system to be in the working orientation. The upside-down orientation is used to confirm the results. This paper considers the novel method analytically and simulates using a rigid body model and the finite element method. The measurement of the stiffness of a weighing cell prototype is taken to validate the method.

Keywords: weighing cell, electromagnetic force compensation, compliant mechanism, flexure hinge, stiffness measurement

Introduction

Weighing cells with electromagnetic force compensation are frequently used in precision balances and mass comparators due to their high measurement resolution and robust behavior [1]. The kinematic structure of the weighing cell is a compliant mechanism with concentrated compliance. It enables highly reproducible behavior and high sensitivity to mass changes on the weighing pan. Due to technological manufacturing limits [2] of the thin flexure hinges, stiffness adjustment is required to achieve the desired specifications. To optimize the adjustment, the initial stiffness of the mechanism must be known accurately. For this purpose, a novel measurement method was developed. It allows a self-testing characterization of the elastic and geometric stiffness by measurements in three orientations.

State of the Art

There are several methods for determining the stiffness of mechanical structures or compliant systems. They can be divided into three main categories: dimensional methods, dynamic experimental methods, and static experimental methods. The dimensional methods use the dimensions and the material properties of the mechanism to calculate its stiffness. However, they have high overall uncertainty. Dynamic experimental methods measure the natural frequency or thermal noise, from which the stiffness can be determined. As a prerequisite, the moving masses need to be known. Uncertainty in the range of 10% to 25% can be estimated [3]. Static experimental methods achieve the lowest measurement uncertainties of less than 5% [3]. The stiffness can be determined by measuring the force-displacement curve for example with a reference balance [4], a reference spring, or a calibrated actuator [5].

Determination Principle

Trim masses are typically used to reduce the stiffness of a weighing cell [6]. When selecting the adjustment parameters, the intrinsic mass of the linkages is often neglected. This leads to complicated readjustment to achieve minimal stiffness.
The developed method precisely characterizes the elastic and geometric stiffness of the mechanism and enables optimal adjustment. Static

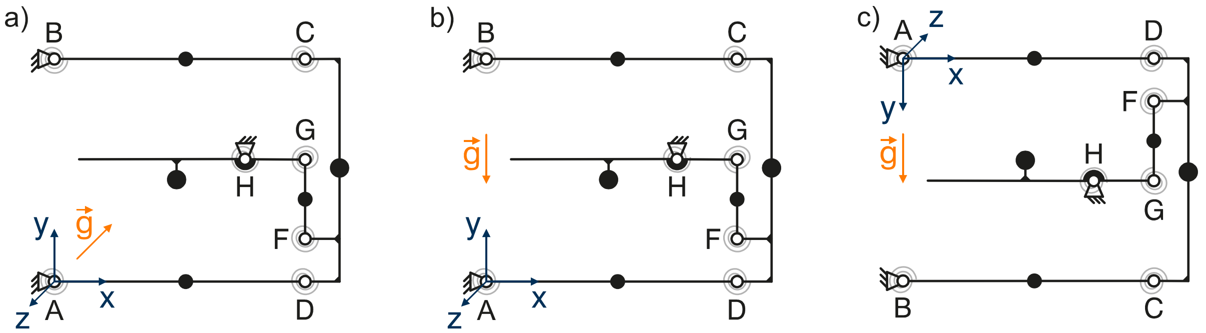

Fig. 1. Orientations required for the stiffness determination method. a) Horizontal. b) Working. c) Upside-down.

stiffness measurements in three orientations of the system are carried out. The horizontal orientation (see Fig. 1. a)) is used to determine the pure elastic stiffness $C_{M,e}$ of the mechanism. The gravity vector $\vec{g}$ is orthogonal to the plane of motion. Thus, there is no impact by linkage masses, i.e. no geometric stiffness. Characterizing the stiffness $C_{M,w}$ in the working direction (see Fig. 1. b)) includes the elastic and the geometric stiffness. The geometric part $C_{M,g}$ of the stiffness can be calculated from Equation (1).

$$C_{M,g} = C_{M,w} - C_{M,e} \quad (1)$$

The upside-down orientation (see Fig. 1. c)) is used to verify the results. The measured stiffness $C_{M,u}$ includes a reversed impact by linkage masses. Thus, equation (2) can be applied to confirm the determined values.

$$C_{M,e} = \frac{C_{M,w} + C_{M,u}}{2} \quad (2)$$

These equations are valid only for minimal deflections. This corresponds to the applications. Larger deflections would lead to a significant difference in the geometric stiffness $C_{M,g,w}$, in the working orientation and the geometric stiffness $C_{M,g,u}$ in the upside-down orientation due to the nonlinearity of the torque-angle characteristic of the geometric stiffness.

Simulation and Measurement Results

Rigid body and finite element simulations of a demonstrator were carried out to determine the elastic stiffness in the horizontal orientation and geometric stiffnesses in the working and the upside-down orientation. The simulation results (see Tab. 1) verify the analytical considerations.

Tab. 1: Comparison of elastic and geometric stiffness.

	$C_{M,e}$ /(Nm^{-1})	$C_{M,g,w}$ /(Nm^{-1})	$C_{M,g,u}$ /(Nm^{-1})
Rigid body model	50.57	-0.84	+0.85
Finite element method	50.58	-1.29	+1.31
Measurement results*	36.58 ±0.27	-1.84 ±0.26	+1.75 ±0.33

*Standard deviations k = 1.

Deviations in geometric stiffness result from considered deformations of the frame and numerical errors in the finite element model. Experimental results confirm the method as well (see Tab. 1). Differences in the absolute values result from dimensional deviations of the manufactured joints.

Summary and Outlook

This paper presents a novel self-testing method for determining the stiffness of weighing cells. It uses static force-displacement measurements in three orientations to characterize the elastic and geometric parts of the stiffness. The method was considered theoretically and validated by simulations and measurements.

As a next step, a metrological model will be elaborated using the guide to the expression of uncertainty in measurement (GUM). The measuring setup used will be optimized to further reduce uncertainty. Additionally, the investigations will be repeated with comparable force measurement applications.

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