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# Actuator design considerations for the Planck-Balance

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**Summary:**

The paper presents crucial design considerations for the actuators in a table-top Kibble balance, especially its influence on the uncertainty contribution by the voltage measurements. The resulting contribution is exemplary shown for the PB2 version of the Planck-Balance and constraints are discussed that limit the possibilities to optimize the geometric factor of the measurement actuator.

**Keywords:** Kibble balance, uncertainty evaluation, mass metrology, electromagnetic force compensation, dynamic force measurement

## Motivation

The Planck-Balance is a tabletop Kibble balance that was developed in a joint project of PTB and TU Ilmenau. Both versions of the Planck-Balance – the PB1 for calibration of class E1 weights and the PB2 for class E2 – utilize a commercial load cell for carrying the load, but have an additional voice coil actuator to carry out the Kibble experiment (measurement actuator). However, the internal voice coil actuator (drive actuator) of the electromagnetic force compensated (EMFC) load cell is used to move the load carrier of the balance in order to excite the coil of the measurement actuator relative to its magnetic field. From the ratio the induced voltage $U_{\mathrm{ind}}$ in the measurement coil and its velocity $v$, which is measured by an interferometer, the geometric factor $Bl$ can be determined (velocity mode) as

$$Bl = \frac{U_{\mathrm{ind}}}{v}. \qquad (1)$$

This factor also equates the ratio of force, which is used to counterbalance the gravitational force $F_{\mathrm{G}}$ of the weight, and the current $I_m$ through the measurement coil (force mode), which is measured as voltage drop $U_R$ over a shunt resistor with the known value $R$.

$$Bl = \frac{F_{\mathrm{G}}}{I_m} = \frac{m \cdot g \cdot R}{U_R} \qquad (2)$$

Combining the measurements of velocity mode and force mode, the mass $m$ of the weight can be determined with

$$m = \frac{U_R \cdot U_{\mathrm{ind}}}{v \cdot g \cdot R}, \qquad (3)$$

and a known local gravitational acceleration $g$.

This allows a mass calibration that is independent from a calibration weight and traceable to natural constants like Planck's constant $h$ via the electrical quantities.

### Influence on uncertainty

The value of the geometric factor $Bl$ can be influenced by the cross-section area $A_{\mathrm{W}}$ of the coil wire and therefore the Number of turns $N$ that are immersed into the air gap of the magnet system, which provides a flux density $B$. The flux density and the air gap volume $V_{\mathrm{W}}$ are less convenient for a tuning process of the actuator, supposed that the geometrical constraints are already used to full capacity and an extensive redesign of the system should be omitted. However, he ratio between power dissipation and the compensation force is independent from the wire diameter and must not be taken into account during its optimization [1].

Even though, the geometric factor $Bl$ is canceled out due to combination of the results of both measurement modes, the value of $Bl$ is crucial to the uncertainty contribution of the voltage measurements. Assuming a lower absolute limit $\Delta U$ of the uncertainty of the voltage measurement, the best relative uncertainty is achieved with higher voltages. In the velocity mode the induced voltage is increased with a high value of $Bl$, while a high value of voltage drop is generated for small values of $Bl$ in the force mode.

Therefore, the sensitivity coefficient $c_{U;\mathrm{rel}}$, which equates the contribution of the voltage measurement uncertainty to the relative uncertainty of mass determination, has a minimal value for a geometrical factor $Bl_{\mathrm{opt}}$ of

$$Bl_{\mathrm{opt}} = \sqrt{\frac{m \cdot g \cdot R}{v}}\,, \qquad (4)$$

If the same voltage uncertainty is assumed in both modes [2].

This minimum is valid for given values of the other parameters, but one has to keep in mind that this also applies to the sensitivity coefficient

$$c_{U;\mathrm{rel}}(Bl_{\mathrm{opt}}) = \sqrt{\frac{2}{v \cdot m \cdot g \cdot R}}\,. \qquad (5)$$

In contrast to the value of *Bl* that minimizes the coefficient, the coefficient for this optimized geometric factor itself decreases with increasing gravitational force or resistance of the shunt.

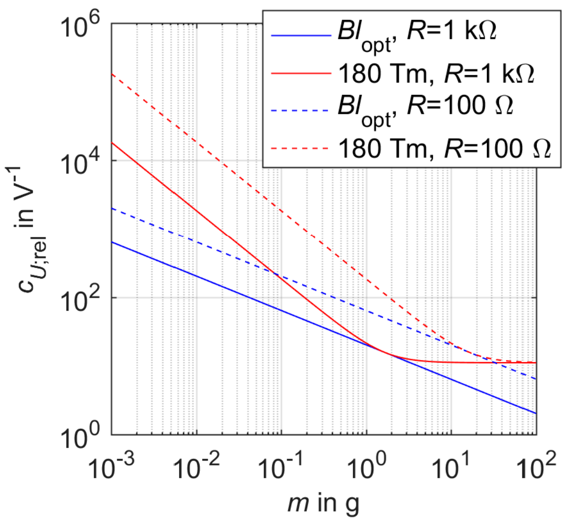


*Fig. 1. Sensitivity coefficient of the contribution of voltage measurement uncertainty.*

For illustration, the calculated sensitivity coefficient is shown in Fig. 1 in the measurement range of the PB2 system and its current design and uncertainty parameters that are taken from [3]. Since it is not reasonable to exchange the coil of the measurement actuator for every mass value within the measurement range in order to have the optimal *Bl*, the sensitivity coefficient is also shown for the fixed value that was chosen in the PB2 system. With an appropriate choice for the value of shunt resistor, the sensitivity coefficient can even be smaller than with an optimized *Bl*, but a lower resistance.

## Constraints of optimization

The shown example illustrates the possibility to optimize the achievable measurement uncertainty with the choice of the coil parameters and the shunt resistor. However, these possibilities are limited by several additional aspects.

Voltage measurements with very low relative measurement uncertainties can only be done within a measurement range of up to 10 V with devices like the Keysight 3458A that represent the current state of the art. In a similar way, this provides also a lower limit for the *Bl*, but also an upper limit for the geometric factor *Bl*, since the induced voltage should not exceed this measurement range. Furthermore, it also provides an upper limit for an optimization with the shunt resistance in order to avoid a too high voltage drop in the force mode.

The choice of the shunt resistance is further limited by the factor that also an appropriate current source that provides the coil current in force mode has also a limited supply voltage $U_{\mathrm{max}}$. This voltage needs to be bigger than the sum of voltage drops over the shunt and the actuator coil, which is not independent from *Bl*, if it is mainly optimized due to the choice of the cross-section area $A_{\mathrm{W}}$ of the wire. This constraint provides an upper limit for the shunt resistance that equates to

$$R_{\mathrm{max}} = \frac{U_{\mathrm{max}} \cdot B \cdot A_{\mathrm{W}} - \rho_{\mathrm{W}} \cdot m \cdot g}{v \cdot m \cdot g \cdot B^2 \cdot A_{\mathrm{W}}{}^2}\,. \qquad (6)$$

## Drive actuator

In addition to the obvious necessity to optimize the measurement actuator, also the characteristics of the drive actuator need to be considered.

In the PB2 system, this actuator is used to excite the system in the velocity mode and therefore its ac characteristics are relevant for choosing an appropriate current source. These characteristics are composed of the coil's resistance and inductance as well as its geometrical factor *Bl*, which should not be too high in order to avoid back EMF. But since the drive actuator is also used to generate offset forces in the force mode [3], its *Bl* should also not be too small.

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