

Excitation frequency dependent deviations during the “velocity mode” of Bl measurements in the Planck-Balance

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Abstract – The Planck-Balance is a table-top device that utilizes the concept of a Kibble balance. In contrast to a standard electromagnetic force compensated balance, the force factor Bl is not determined by calibration with mass pieces. Instead of this static calibration, the Planck-Balance applies a sinusoidal motion on the coil and determines the Bl based on measurements of induced voltage, displacement and frequency. In order to obtain valid force calibration for the weighing experiment, one has to ensure that the determined factor does not depend on the excitation frequency of the coil. A linearization of the control loop is established in order to reduce the harmonic distortion of the measurement signals. This work presents a method for reducing the frequency dependency caused by mechanical tilt oscillations and proposes a set-up to reduce the standard deviation of the determination of the Bl .

Keywords – Planck-Balance, ac voltage, electromagnetic parameters, frequency measurement

I. INTRODUCTION

As in other Kibble balance set-ups, the Planck-Balance utilizes a dynamic mode for the determination of the force factor Bl [1]. In this mode of the Planck-Balance, two independently functioning and quasi-identical custom assembled electromagnetic voice coil actuators are used. One of the actuators is used to move the coil of the second actuator relative to the magnetic field of its magnet. This second coil as well as the measurement mirror necessary for measurements of the displacement is rigidly attached to the load carrier of the balance. This load carrier is guided by a compliant mechanism, which is set up

monolithically using flexure hinges. The displacement s of the mirror is measured by a laser interferometer, while the moving coil is connected to a digital multimeter that measures the induced voltage U_{ind} . With knowledge of the signal frequency f_{sig} , which is provided by the signal processing system and corrected by a measurement of the clock frequency of the signal processing system, the Bl can be calculated as follows:

$$Bl = \frac{U_{ind}}{2 \cdot \pi \cdot f_{sig} \cdot S}, \quad (1)$$

where S denotes the amplitude of the displacement and U_{ind} the amplitude of the induced voltage. In the following sections of this work we will present several improved measurement aspects on the induced voltage, the displacement and their dependence on the excitation frequency.

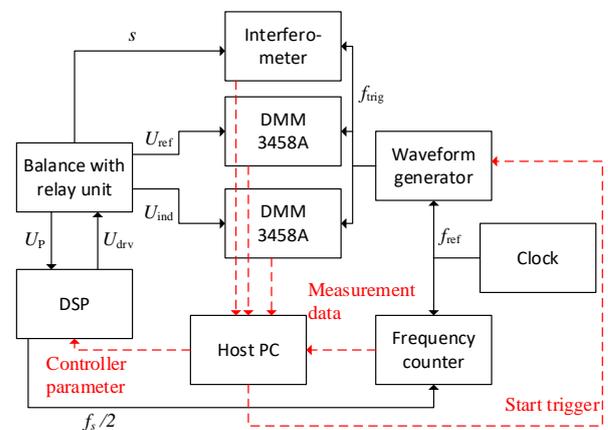


Fig. 1. Signal processing set-up of the Planck-Balance.

II. SIGNAL PROCESSING SYSTEM

In the current set-up of the Planck-Balance (Fig. 1 and Fig. 2), which consists of several custom-made circuitries as well as a customized set-up of commercially available devices, the controller is implemented on a digital signal processor (DSP) system provided by dSPACE GmbH.

The control algorithm runs on processor board of type DS1006, which is enhanced by an analog to digital converter (ADC) board of type DS2004 and a digital to analog converter (DAC) board of type DS2102. The available DACs and ADCs all possess a resolution of 16 bit.

The current $PIDT_1$ -controller is implemented with sampling frequency f_s of 10 kHz and provides an output voltage U_{drv} in order to control the measured position sensor voltage U_P to a given set point value. The output voltage of the DSP is converted by an amplifier circuit into a controlled current that is proportional to U_{drv} . When applied to the internal balance actuator, the output current can be utilized to excite the load carrier with a sinusoidal motion that is necessary in the dynamic mode for calibration of the force factor of the external coil. After this calibration mode, the output current is connected via latching relays to the external coil and is then used to balance the system in the static weighing mode.

In addition to the control algorithm, several different signal generators are implemented on the DSP, which provide chirp signals for testing purposes and the sinusoidal modulation of the set point position in the dynamical operation mode “velocity mode”. Since the internal clock of the DSP represents the time base for the excitation frequency, one of the DACs outputs a square wave that changes its voltage level at each sampling period of the DSP and therefore yields a frequency of $f_s/2$. The actual frequency of this signal is measured by a frequency counter of type Keysight 53220A that receives a reference frequency $f_{ref} = 10$ MHz from a reference clock. The reference clock is an oven stabilized quartz oscillator of type RSGGO100 provided by RF Suisse, which is disciplined by GPS signals.

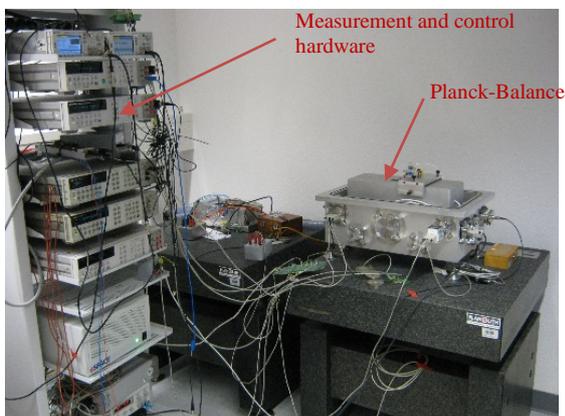


Fig. 2. Planck-Balance measurement set-up.

The same reference frequency is supplied to waveform generator of type Keysight 33521B that provides a square wave signal with the frequency f_{trig} . The square wave signal is used to trigger the measurement of the laser interferometer and the digital multimeters (Keysight 3458A), which are triggered with a sampling frequency of 1 kHz. One multimeter measures the induced voltage during the velocity mode, while the other one measures the necessary compensation current during the force mode as a voltage drop U_{ref} across a pre-calibrated reference shunt resistor that is connected in series with the coil and the current amplifier output.

III. DISPLACEMENT AMPLITUDE

In order to achieve low uncertainties of the determination of the Bl , the displacement of the coil inside the magnet system has to be determined. Since the usage of a closed magnet system does not allow to fix the mirror directly on the coil, one has to rely on a rigid frame that is connected to the coil and interferometer mirror. Additionally, in the existing Planck-Balance set-up, the laser spot is not located on the center axis of the coil, yielding an Abbe error of the coil displacement determination.

A. Set-up of tilt angle determination

To determine the angles of this tilt error occurring during the sinusoidal motion of the load carrier, a three beam interferometer is used to measure the displacement of three points of a mirror that is attached to the load carrier surface (see Fig. 3). By means of the spatially separated three laser spots, the tilt about the x-axis (later referred as “Torsion”) and about the z-axis (referred as “Nodding”) can be calculated along the measured displacement in y-direction.

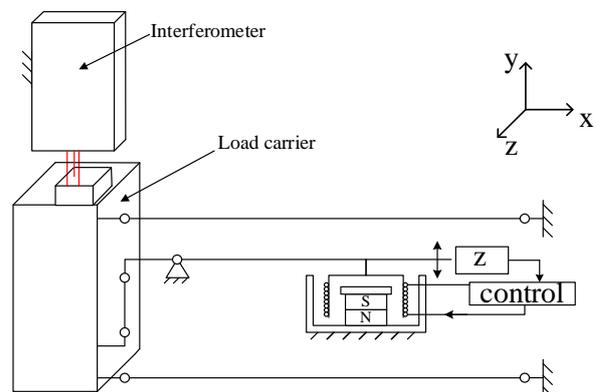


Fig. 3. Schematic representation of the tilt angle measurement set-up.

The lever position and therefore the displacement of the load carrier is controlled by the internal voice coil actuator of the balance and its position sensor. Since the position sensor yields a nonlinear relation between the displacement in measures of meter and the position voltage,

a polynomial that represents this relation is identified in a preliminary experiment in the same set-up. The obtained polynomial can be used to linearize the position control of the load carrier displacement in order to reduce the harmonic distortion of the measured sinusoidal signals.

B. Tilt angle correction

The three displacement signals l_i are utilized to calculate the complex amplitude of the mean displacement \underline{S}_m located in the middle of the three laser spots and the amplitudes of nodding and torsion angles φ_n and φ_t , respectively:

$$\varphi_t = (l_1 - l_2)/b \text{ and } \varphi_n = (l_3 - l_2)/b, \quad (2)$$

where $b = 12 \text{ mm}$ represents the distance between two adjacent laser spots and all complex amplitudes are calculated from the measurement data by applying a sine fit as proposed in [2].

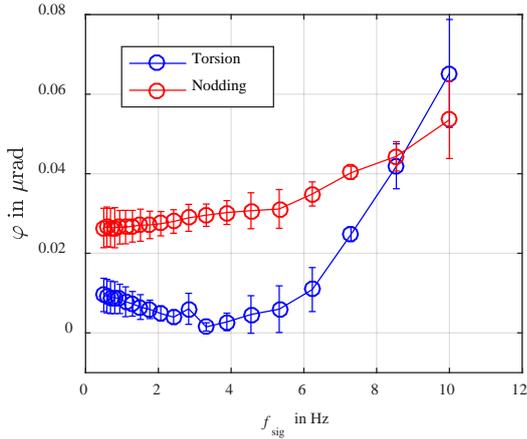


Fig. 4. Tilt angle amplitudes during sinusoidal excitation.

As depicted in Fig. 4, tilt angle amplitudes of up to 80 nrad occur in the current setup. The shown graph represents two days of measurement data from Bl determinations with alternately increasing and decreasing signal frequency.

Thus, with knowledge of the distances a_t and a_n between the center axis of the coil and laser spots of the interferometer, the complex displacement amplitude \underline{S} will be corrected as

$$\underline{S}' = \underline{S} + a_t \cdot \underline{\varphi}_t + a_n \cdot \underline{\varphi}_n. \quad (3)$$

Applying this correction to the determined displaced amplitude, the dependency of the Bl calculated with (1) is significantly reduced in the range of 2 Hz up to 10 Hz (see Fig. 5). In the lower frequency range, frequency dependent changes occur, the origin of which is not clear. It cannot be corrected by the tilt measurement and needs further investigation.

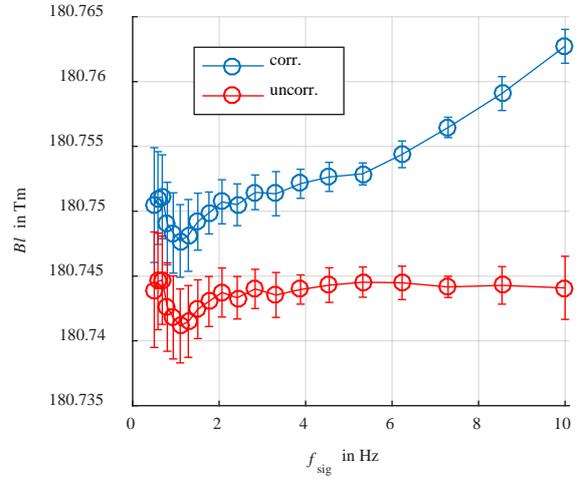


Fig. 5. Bl determination with (red) and without (blue) tilt correction.

IV. INDUCED VOLTAGE

As shown in the previous section, the frequency dependency of the Bl determination still exists in the low frequency range even after a correction of the tilt angle of the load carrier. However, the effect yields a similar magnitude as the standard deviation of the Bl determination, since the standard deviation increases in this frequency range. The main reason for this increase is the fact, that the amplitude of the induced voltage decreases with decreasing signal frequency and a mechanically limited displacement amplitude of $40 \mu\text{m}$. For further investigations of the signal frequency influence on the Bl determination, a reduction of the standard deviation of the induced voltage amplitude measurement is necessary.

A. Differential ac voltage measurement set-up

A viable approach reducing the standard deviation and uncertainty of the induced voltage amplitude determination is to utilize a well-known sine signal provided by an accurate signal generator (e.g. HP 3245) or in best case by a programmable Josephson array with sufficient settlement time as presented in [3].

A reasonable method of a differential measurement of u_{ind} relative to a reference sine signal requires, that the induced voltage would preferably yield the same amplitude and phase as the reference signal (blue sine block in Fig. 6).

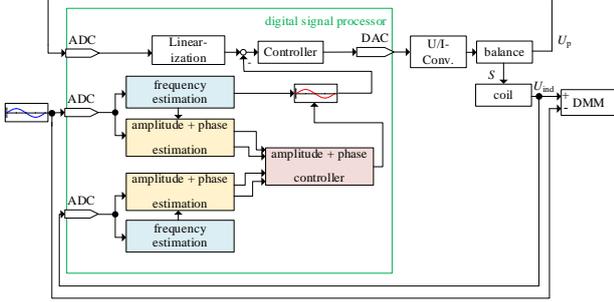


Fig. 6. Proposed set-up of differential measurement of induced voltage relative reference sine signal.

The induced voltage, thus, can be adjusted deliberately by the system consisting of the controlled balance and the external actuator that is fixed to the load carrier. In the system, the set point of the position controller is considered to be the system input, while the induced voltage acts as a system output (see Fig. 7). Considering the transfer function shown in Fig. 7, it can be observed that the system is also influenced by the elastic properties of the transmission of displacement at the internal driving actuator to the external driven voice coil. In case of an ideally stiff connection between driving and driven coil, one would expect a transfer function that resembles a differentiator with a gain, since the induced voltage is proportional to the velocity of the coil. This ideal differentiator would yield a constant phase shift of 90° and a linear increase of 20 dB/decade.

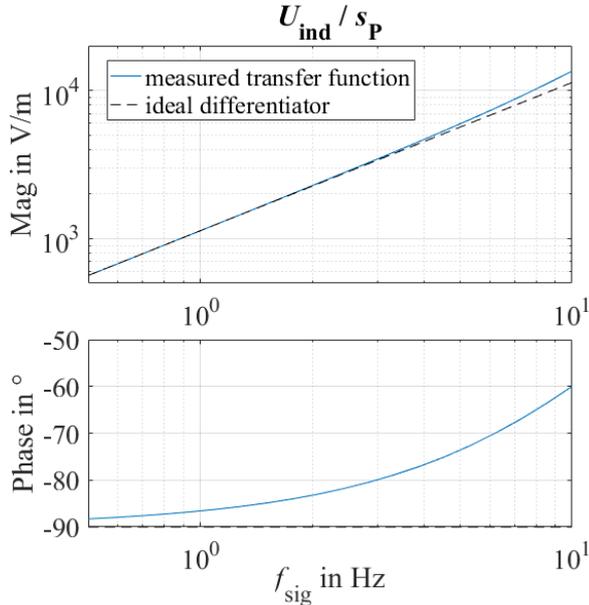


Fig. 7. Transfer function of induced voltage divided by lever position.

Since the phase shift and magnitude of this system are expected to vary over time and with changing environment conditions, the actual phase and amplitude of the induced voltage should be measured and adjusted such that the sine parameters fit to the external reference signal. Therefore, a controllable oscillator (red sine block in Fig. 6) is implemented on the DSP system and routed to the set point value of the position control loop.

B. Amplitude and phase estimation

The properties of the external reference signal are analyzed for data sets that represent several seconds of measurement data to receive smooth and stable values, while the actual time span is chosen inversely proportional to the nominal value of the excitation frequency f_{sig} . The frequency of the signal is obtained by detecting the crossing points of the filtered signal with its mean value.

Phase and amplitude of the reference signal are determined by a digital Fourier transform (DFT) algorithm that was proposed by Goertzel [4]. The algorithm computes the complex amplitude of a signal for the given frequency f_{sig} without the necessity of computing the amplitudes for other frequencies as in most of the fast Fourier transform implementations. In the first step the forward and the backward filter coefficients c_{fw} and c_{bw} are determined according to

$$c_{\text{fw}} = e^{j2\pi\frac{k}{N}} \text{ and } c_{\text{bw}} = 2 \cos\left(2\pi\frac{k}{N}\right), \quad (4)$$

where N denotes the number of samples used for the calculation and $k = \text{round}(N \cdot f_{\text{sig}}/f_s)$ denotes the chosen frequency bin of the DFT. These coefficients have only to be calculated when the nominal value of f_{sig} and therefore also N is changed. For a given series of signal values u_i , the output sequence y_i of the first Goertzel filter stage can be calculated as:

$$y_i = u_i + c_{\text{bw}} \cdot y_{i-1} - y_{i-2}, \quad (5)$$

where y_0 and y_{-1} are chosen to be zero. The last filter stage has only to be calculated once, in order to retrieve the complex amplitude \underline{u} as

$$\underline{u} = y_N + c_{\text{fw}} \cdot y_{N-2}. \quad (6)$$

With an appropriately chosen time span, this algorithm provides a smooth and stable estimation of the signal amplitude and phase, which can be used to adjust the controllable oscillator.

V. CONCLUSION AND OUTLOOK

In this work, the measurement set-up of the Planck-Balance and additional modifications for the identification of frequency related deviations were briefly described. The deviations caused by mechanical tilt oscillations can be

identified and corrected, however there are remaining deviations, which require further improvements of the voltage amplitude determination. In order to reduce the uncertainty of the investigations on the frequency dependency of the force factor Bl , an improved measurement scheme for the measurement of the induced voltage during the dynamic calibration mode is proposed. Based on a detailed analysis of the system transfer function, a control and measurement set-up is designed in order to adjust the frequency, amplitude and phase of the induced voltage in accord to an external reference signal. Currently, this measurement scheme is at active stage of testing and validation.

VI. ACKNOWLEDGMENT

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REFERENCES

- [1] Rothleitner, C., Schleichert, J. et al., *The Planck-Balance—using a fixed value of the Planck constant to calibrate $E1/E2$ -weights*, Measurement Science and Technology, vol. 29, no. 7, 2018, p. 074003.
- [2] Hilbrunner, F., Rahneberg, I. & Fröhlich, T. (2017). *Wattwaage mit Hebelübersetzung auf Basis eines kommerziellen EMK-Wägesystems*. tm - Technisches Messen, 85(11), pp. 658-679
- [3] Lee, J. Behr, R. et al., *An ac quantum voltmeter based on a 10 V programmable Josephson array*, Metrologia, vol. 50, no. 6, 2013
- [4] Goertzel, G., *An Algorithm for the Evaluation of Finite Trigonometric Series*, The American Mathematical Monthly, Vol. 65, No. 1 (Jan., 1958), pp. 34-35