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An enhanced mechanism for a Kibble balance at the National Institute of Standards and Technology

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Abstract

A Quantum Electro-Mechanical Metrology Suite (QEMMS) is being designed at the National Institute of Standards and Technology. It features a graphene quantum Hall resistor, a programmable Josephson voltage system, and a Kibble balance. The QEMMS provides primary standards in the International System of Units (SI) for the units of volt, ohm, ampere, meter, second, and mass directly with one single instrument and thus, is a metrology institute in one laboratory. For the unit of mass, a measurement range of 10 g to 200 g and measurements with relative uncertainties of 2×10^{-8} at 100 g are targeted. Here, essential requirements and features of the new mechanism design are pointed out. Furthermore, measurements that are necessary to verify the performance of the new balance mechanism are introduced. An update on the status of the work and the first pictures of the new mechanism are published.

Conceptual Design, Design, Measuring Instrument, Ultra Precision

1. Introduction

In 2018, a link of the Planck's constant with the mass of the International Prototype Kilogram (IPK), the speed of light and the hyperfine splitting frequency of Caesium 133 [1] has been established using the Kibble balance. Since then, the Kibble balance provides a primary definition of the unit of mass in the International System of Units (SI). The National Institute of Standards and Technology (NIST) was contributing to this redefinition with their fourth generation of a Kibble balance, called NIST-4, which was designed and optimized to measure Planck's constant based on the IPK with a relative standard uncertainty of 13×10^{-9} [2].

In a currently ongoing effort, NIST is designing its fifth version of the Kibble balance for the Quantum Electro-Mechanical Metrology Suite (QEMMS) with the goal to realize mass measurements from 10 g to 200 g with relative standard uncertainties of 2×10^{-8} at 100 g. For such precision, it is necessary to operate the balance in a vacuum. Otherwise, the influence of buoyancy and changes in the refractive index would be hard to quantize at that level of uncertainty. In addition to the Kibble balance, the QEMMS features a graphene quantum Hall resistor array and a Josephson voltage standard directly implemented in one instrument.

Compared to NIST-4, the new Kibble balance will be lighter, smaller, roughly the size of an industrial 1 kg vacuum mass comparator and require fewer auxiliary control systems and adjustments for its high precision operation. The subsystem in the balance that requires special attention during design is the mechanism. For the first time in a NIST Kibble balance, one flexure mechanism for both modes of operation, the weighing mode, and the velocity mode is employed.

In the weighing mode, the balance is held in a defined null position using closed loop position control. Here, the electric current I through the coil of an electromagnetic actuator is adjusted such that the magnetic force compensates the gravitational force of a test mass m according to

$$\boldsymbol{mg} = -\boldsymbol{N}\frac{\boldsymbol{\partial\Phi}}{\boldsymbol{\partial z}}\boldsymbol{I}, \quad (1)$$

where g is the local gravitational acceleration, N the number of turns in the coil and $\partial\Phi/\partial z$ the derivative of the magnetic flux Φ with respect to the z-direction. The expression $N\,\partial\Phi/\partial z$ is further called calibration factor.

A second mode of operation, the velocity mode, is used to determine this calibration factor with a relative standard uncertainty of parts in 10^9 based on Faraday's induction law, i.e.,

$$\boldsymbol{V} = -\boldsymbol{N}\frac{\boldsymbol{\partial\Phi}}{\boldsymbol{\partial z}}\boldsymbol{v}, \quad (2)$$

where V is the voltage induced in the coil by moving it vertically with velocity v through the magnetic field of the permanent magnet. The velocity is typically monitored with a heterodyne interferometer at certain time stamps.

Rearranging and setting the two previous equations equal allows to eliminate the calibration factor which yields the Kibble balance equation:

$$\boldsymbol{mgv} = \boldsymbol{IV}. \quad (3)$$

The following shows how the design of the new flexure mechanism for the Kibble balance in the QEMMS has evolved and emphasizes the requirements and related experiments necessary to proof appropriate performance in the field.

2. Requirements to the new Kibble balance mechanism

For the two separate modes of operation, the mechanism mainly provides the two following functionalities: (1) it serves as a mass comparison/leveling system for the feedback-controlled operation in the weighing mode, and (2) it provides a high precision, vertical guiding of the coil in the magnetic field of the permanent magnet during the velocity mode.

In the weighing mode, it is crucial to maintain a constant length of both balance arms within parts in 10^9 around the weighing position because this directly contributes to a relative mass measurement error. For the mechanism in the QEMMS this translates to an acceptable lateral dimensional error of approximately 250 pm over $1\ \mu\mathrm{m}$ of vertical deflection around the nominal zero position. This is a direct requirement to constant thermal conditions during the measurement and precision in machining and/or assembling of the mechanism. Furthermore, the mechanism is required to have a low force nonlinearity. In flexure mechanisms, nonlinearity shows up as a hysteretic force and stems from anelastic effects in the flexure material after small excitations of the balance from, for example, the placement of a test mass on the mass pan [3]. The overall contribution of the hysteresis to the measurement uncertainty is aimed to be below $0.1\ \mu\mathrm{g}$. Flexure mechanisms as used in industrial ultra-high precision mass comparators can provide the required number for the hysteretic force. A low elastic stiffness in the flexures has positive impact to the hysteretic behavior of metals [4]. For flexures, a minimal notch thickness on the order of $50\ \mu\mathrm{m}$ is the technological threshold value defined by manufacturing processes like wire electrical discharge machining, high speed milling, or chemical etching. A low stiffness of the mechanism is furthermore important to minimize errors to the mass readout derived from positioning errors between mass on and mass off phases. Position errors of approximately one micrometer are expected here. An inverted pendulum for example allows for an adjustment of the stiffness close to zero.

During the velocity mode, a total vertical travel of approximately $\pm 30\ \mathrm{mm}$ needs to be realized for the determination of the calibration factor with a relative standard uncertainty of parts in 10^9. Ideally, the stiffness of the mechanism along the vertical travel should be constant to allow for a precise velocity or voltage feedback control along the travel. Furthermore, the trajectory of the coil in the permanent magnet needs to be a pure linear vertical motion. Lateral deviations of less than $3\ \mu\mathrm{m}$ over the total travel range will keep error influences like voltage bias, velocity bias or beam shear error in the interferometer sufficiently small.

3. Design of the new Kibble balance mechanism

Figure 1 shows different design principles for mechanisms in Kibble balances. Option 1 is used for the new mechanism because it has the advantage of the cancellation of certain trajectory errors by using the same mechanical system in both the weighing and the velocity mode. Furthermore, having only one mechanism for moving and weighing simplifies the design considerably.

The challenge is to find a flexure design to (1) support the load of the entirety of moving parts in the balance ($15\ \mathrm{kg}$) and (2) additionally to move the coil $\pm 30\ \mathrm{mm}$ ($7\,^{\circ}$ angular deflection of the hinges at the defined size). For this purpose, a modified flexure geometry has been studied and chosen by using finite element simulation.

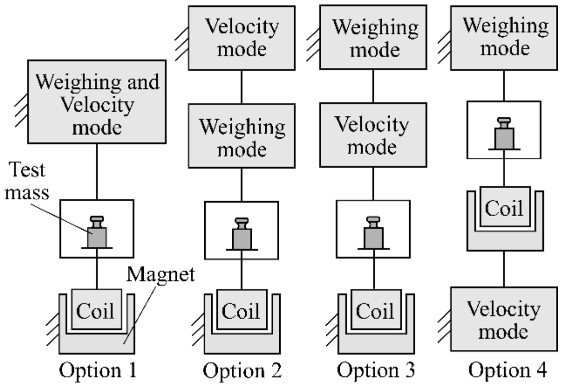

Figure 1. Different design principles for mechanisms used in Kibble balances. These designs can be found in existing versions of Kibble balances around the world. At NIST, option 1 is traditionally used.

Finding a flexure geometry that reduces the stress to an acceptable level and maintains a low elastic stiffness was critical. Normal circular of flat flexure contours as used in [3] would exceed the yield strength of even high strength, hardened material like a hardened Copper Beryllium alloy which will be used in the balance due to its high yield strength ($> 1000\ \mathrm{MPa}$) and low anelastic loss. A representation of a flexure geometry with suitable mechanical properties is shown in figure 2.

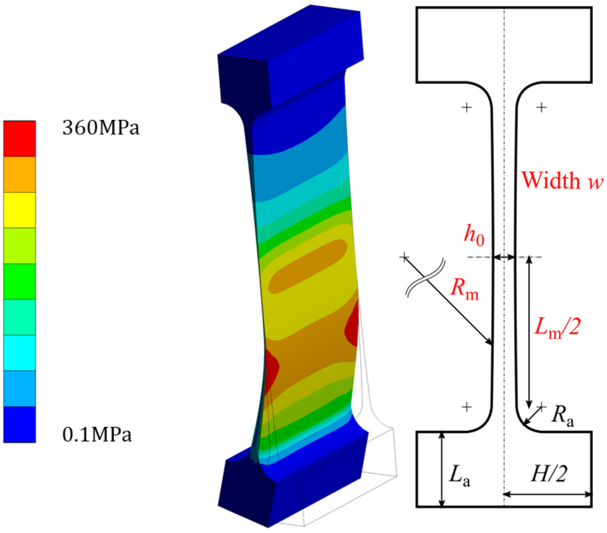

Figure 2. Model and plot of the equivalent von Mises stress from a finite element simulation at a flexure geometry suitable for application in the QEMMS. The geometry has a large radius in the center with characteristic $R_m \gg L_m$. The shown flexure geometry has $R_m = 200\ \mathrm{mm}, L_m = 20\ \mathrm{mm}, h_0 = 50\ \mu\mathrm{m}, w = 10\ \mathrm{mm}, R_a = 1.5\ \mathrm{mm}, \mathrm{L_a} = 3\ \mathrm{mm}$, and $H = 5\ \mathrm{mm}$. The nodes at the top face are fixed supported while a point mass node with a weight of 15 kg is attached to the bottom face via remote constraints and the bottom face is rotated by 7 °. The deformation is exaggerated by a factor of 2.3. The red parameters on the right were subject to investigation for their impact in stress reduction.

The new mechanism design consists of two sub-structures: (1) a dedicated guiding mechanism constrains the motion of the coil and (2) a balance wheel is suspended by the main flexure. Multifilament bands roll off the wheel's surface and connect the balance wheel with the guiding mechanisms.

A wheel-based balance was chosen over a beam-based balance because of kinetic advantages in the velocity mode.

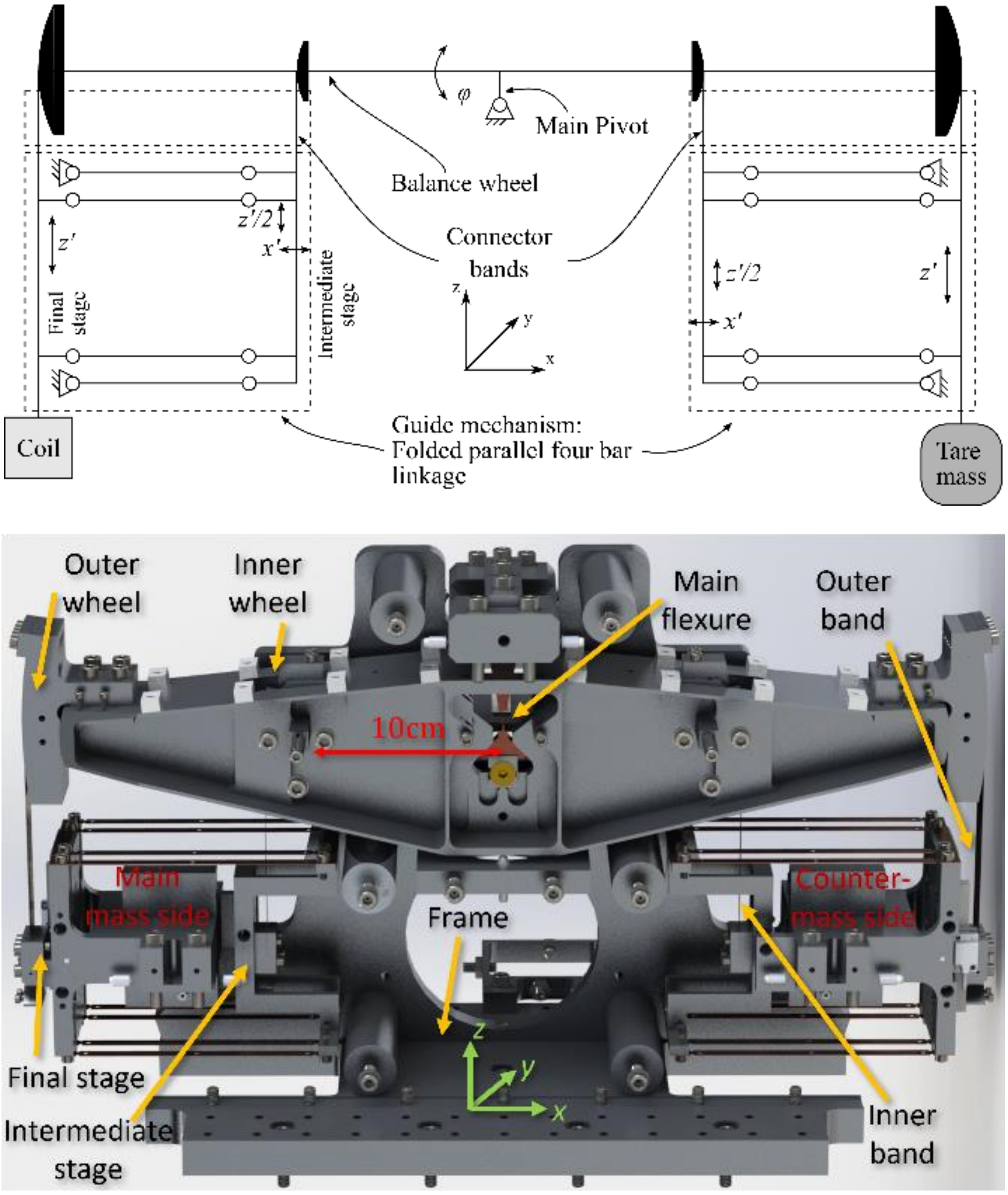

Figure 3. Drawing of the kinematic structure and rendering of the mechanism in the new Kibble balance for the QEMMS. The main mass and countermass side feature the same guiding mechanism to maintain symmetry. The balance consists of an inner wheel which constrains the motion of the intermediate stages of the folded parallelogram linkages and an outer wheel to constrain the final motion of the guides. The output of the guiding mechanism on the main mass side is connected to the coil.

Since the velocity mode requires a relatively large deflection of the mechanism (7 °), the connecting element between the beam and the guiding mechanisms in a beam-based balance would tilt due to the vertical constraint of the guiding mechanism and the shortening of the projected horizontal lever arm length over deflection. Thus, the connectors in a beam-based balance apply a noticeable horizontal force to the guiding mechanism. With larger deflections this parasitic horizontal force causes a stiffening of the mechanism proportional to the suspended masses and also compromises guiding quality. This effect could be reduced by designing the connectors very long ($> 1\ \mathrm{m}$) or compensated by a symmetric compensation design. However, since the need for compactness and simplicity in design make neither of the former suggestions applicable, we employ a wheel-based balance. This avoids a tilt of the connectors in principle by maintaining a constant lever arm over the deflection.

The mechanism is designed symmetric on the main mass and countermass side. The kinematic structure and a rendering are shown in figure 3.

Planar kinematic subsystems are chosen. The guiding mechanism is a folded parallelogram linkage to compensate for the systematic horizontal error in motion of a single parallelogram linkage. Since the folded parallelogram linkage itself is a kinematic structure with two degrees of freedom, two connecting links to the balance wheel have to be used to constrain the mechanism to a defined one-dimensional movement.

The mechanism has been designed, manufactured, and assembled in the vacuum chamber at NIST. Figure 4 shows a picture of the current status of assembly.

Each subsystem in the mechanism can be locked and unlocked repeatedly with minimal over-constraint using expansion pins like in [5], which is necessary for being able to attach, detach and align components within the sensitive compliant structure.

4. Assembling, alignment, and measurements

Assembling needs to be done in a pre-defined sequence with the objective to minimize the number of constraints between the components and parasitic forces in the system deriving from the hanging dead weights. These can cause unwanted deformations in the flexures and thus imperfections to the trajectory – if improperly adjusted.

After assembling and attaching two $6.5\ \mathrm{kg}$ dead weights to the mechanism in the vacuum chamber, it could be shown that the mechanism provides the total required travel while supporting the required load.

A perfect trajectory can only be achieved when all parts of the mechanism are aligned to one another and to the direction of the local gravitational acceleration. This alignment is hard, but not impossible.

The rotation axes of the main flexure and the flexures in the guiding mechanisms need to be aligned horizontal. A high precision bubble level can be used to measure existing misalignments at respective surfaces tolerated for adjustment during machining of the individual parts. Shimming allows for a coarse adjustment of the components. After that, fine adjustments with a more accurate readout than from a bubble level can be done according to the results of an analysis of lateral error motions measured by a position sensitive detector (PSD) and angular error motions measured by an autocollimator.

Special attention should be given to the attachments of the multifilament bands. The bands need to be pre-stressed so that they are hanging straight when unlocking the mechanism after assembling. However, a pre-stress should not cause a pulling force to either the intermediate or final stage of the guiding mechanism such that it biases the zero positions of either stage.

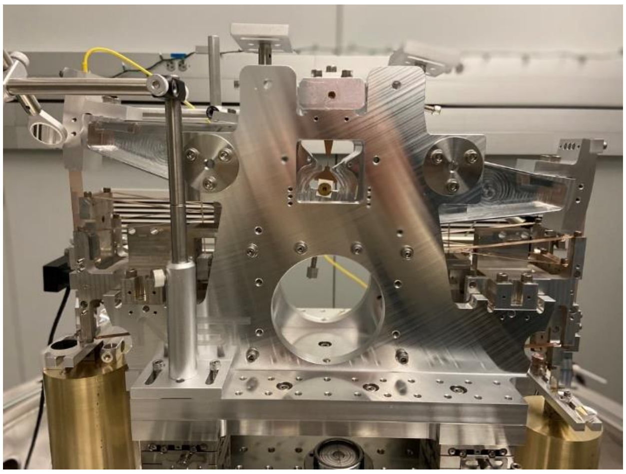

Figure 4. Assembled mechanism in the vacuum chamber. The brass cylinders on both sides simulate the masses of the main mass and countermass assembly. The structure is shown in a fully deflected state.

Optics, sensors, and software are currently being set up to measure deviations of the trajectory of the guiding mechanism. This mainly serves as a proof of concept for the operation of the balance in the velocity mode. Horizontal error motions along the vertical axis are monitored with a PSD, a laser beam aligned parallel to the local gravitational acceleration and a retroreflector moving with the final stage of the guiding mechanism. A change in the readout of the PSD along the travel displays as two times of a lateral error motion due to the reflection characteristic of the retroreflector. During a measurement, the vertical position is monitored with a commercial fiber interferometer.

Additionally, a flat mirror is mounted to the guiding mechanism and an autocollimator measures parasitic rotations of the final stage along the vertical travel.

5. Conclusions and future work

The mechanism for the Kibble balance in the QEMMS has been designed, manufactured, and built inside the vacuum chamber for the new Kibble balance at NIST. Measurements for analyzing the kinematic quality of the mechanism are being set up. A coarse and then fine alignment procedure of the individual components of the mechanism with respect to gravity and in the relative position to each other is meant to minimize lateral error motions of the trajectory. These derive from imperfections in machining, alignment and assembling.

The detailed investigation of the kinematic behavior of the new balance mechanism, which mainly determines the success of the velocity mode, will be followed by a deep analysis of the performance in the weighing mode. Anelastic effects are caused by either small deformations of the flexures due to a mass placement or an after effect of the large excitations of the flexures during the velocity mode. Therefore, the stiffness in the mechanism will be adjusted with an inverted pendulum towards zero and measurements to specify the anelastic nonlinearities in the flexure system will be executed.

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