DOI 10.5162/SMSI2023/B6.1

A Kibble balance as part of a quantum measurement institute in one room at NIST

Lorenz Keck[1, 2], Frank Seifert[1, 3], Stephan Schlamminger[1], David Newell[1], René Theska[2], Darine Haddad[1]
[1] National Institute of Standards and Technology, Gaithersburg, MD, USA,
[2] Technische Universitaet Ilmenau, Ilmenau, Thuringia, GE,
[3] University of Maryland, College Park, MD, USA
Lorenz.Keck@nist.gov

Summary:
The new Kibble balance at the National Institute of Standards and Technology (NIST) is part of the Quantum Electro-Mechanical Metrology Suite (QEMMS). Two quantum standards are incorporated directly in the electrical circuit of the Kibble balance for the realization of the unit of mass. This eliminates the need for external calibration in the Kibble balance experiment. The targeted uncertainty is 2 µg on a 100 g mass and a range from 10 g to 200 g will be covered. We introduce the measurement concept of the QEMMS, show the current state of development and publish first measurements proving the performance of the newly designed balance mechanics.

Keywords: quantum measurements, quantum SI, mass metrology, Kibble balance, mechanism

Introduction

Highly accurate Kibble balances today can provide primary realizations of the kilogram with relative combined uncertainties of 2 parts in 10^8 [1]. Until 2019 a worldwide effort has been made towards redefining the kilogram within the International System of Units (SI) to create a definition of this fundamental base-unit traceable to unchanging constants of nature, and not to a physical object. The Kibble balance was developed to fix a value of the last puzzle piece of quantum constants missing for the success of the redefinition: Planck's constant. It was measured based on the current value of the International Prototype Kilogram (IPK). Thus, balances were designed for a 1 kg mass measurement and due to sufficient agreement of various other experiments on the part per billion level, a value for Planck's constant could be agreed upon. Now this value can be used to define the kilogram through the Kibble balance.

The QEMMS

Not only the Planck's constant is important for traceability in the Kibble balance experiment, also the speed of light, charge of an electron, and the definition of the second are vital for operation. Voltage, resistance, time and length measurements are traced back to these constants and thus they build the foundation of calibration of the Kibble balance itself. All quantities except for electrical resistance are typically directly measured by their respective primary standards.

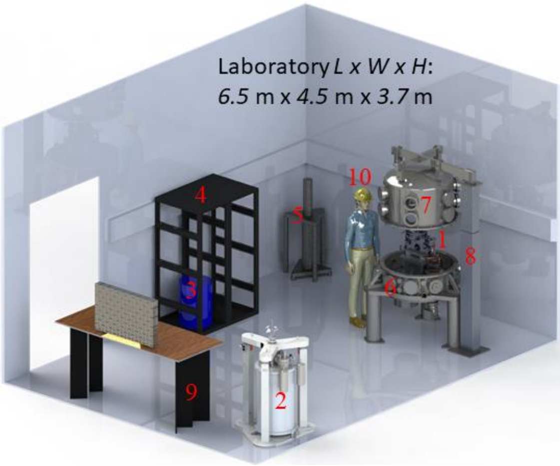

Fig. 1. The QEMMS in the lab at NIST. 1 – Kibble balance; 2 – Cryostat with graphene quantum Hall array standard; 3 – PJVS; 4 – hardware rack; 5 – absolute gravimeter; 6, 7, 8 – vacuum chamber and lift; 9 – desk with PC; 10 – operator

During the weighing mode electric current through the coil needs to be measured to quantify the magnitude of generated electromagnetic force from the magnet-coil system. Here, mostly calibrated resistors are being used and a precisely measurable voltage drop over these can be analyzed to quantify current according to Ohm's law. Recently, scientists at NIST were able to build a graphene quantum Hall array standard capable to maintain quantization during constant exposure with currents up to 0.3 mA [2], which, for the first time, allows for direct implementation of this instrument in the Kibble balance's electrical circuit as a primary reference for resistance. This led to the idea of building a new version of the Kibble balance at NIST, the Quantum Electro-Mechanical Metrology Suite (QEMMS), with the objective to eliminate the calibration uncertainty for resistance by providing full metrological traceability by a metrology institute in one room including all primary references for the measurement. It features an absolute gravimeter, a graphene quantum Hall resistance array, a programmable Josephson voltage standard (PJVS), and the Kibble balance, see Fig. 1. Furthermore, since it is easier and more practical to scale mass measurements up than down, a lower mass range is targeted (10 g to 200 g), but with the same relative combined uncertainty as 1 kg-balances. This tightens the requirements for design especially for subsystems with absolute uncertainty contributions as, e.g., the mechanical system/mechanism.

The new balance mechanics

Another new approach in the QEMMS is the mechanical system, which, for the first time, is based on one single flexure-based mechanism (see Fig. 2) for both modes of operation, the velocity and the weighing mode. A detailed description of the mechanism can be found in [3].

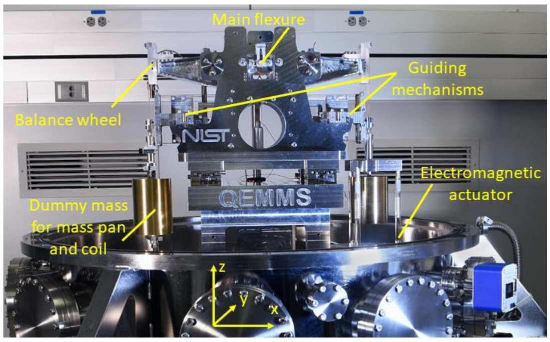

Fig. 2. Picture of the state of construction of the Kibble balance in the QEMMS. The newly designed mechanism is under experimental investigation in the vacuum chamber.

The challenge was to develop a mechanism that minimizes mechanical hysteresis, which is why we use a flexure mechanism over a knife edge one, but also provide sufficient travel during the velocity mode. The latter requires to integrate two functions in the flexure mechanism that are usually separated in flexures: (1) suspending relevant components (15 kg suspended weight), and (2) providing large travel, here ±30 mm. Furthermore, a dedicated sub-mechanism is used to define the trajectory of the coil.

First measurement

A recent success was a measurement of the balance trajectory which indicates that we can use this mechanism to guide the coil in the velocity mode with deviations from the vertical of less than ±3 µm on the whole travel range, see Fig. 3. This is sufficient for the experiment.

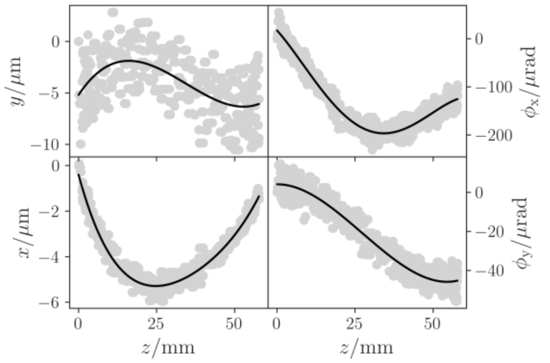

Fig. 3. Preliminary measurement of verticality and angular deviation of balance motion measured with a fully loaded balance mechanism. The mechanism oscillated freely with its eigenfrequency in z.

The result required thorough alignment of the components in the mechanics with respect to both each other and gravity. Currently the quality of alignment is limited by its sensitivity and the types of alignments we can perform with the mechanism in situ. Furthermore, ambiguity remains as to whether one flexure mechanism for both modes of operation is useable from a standpoint of repeatability in mass measurement, especially with views on hysteretic losses in the mechanics.

Conclusion

At NIST a new Kibble balance is under development. Two novelties are featured: (1) all quantum measurements take place directly in the instrument so that there is no need for external calibration anymore, and (2) one single flexure mechanism is used to guide the coil in velocity mode and to perform the weighing phase. The proof of travel quality was given – now a hysteresis/repeatability test of mass measurements is underway for ultimate proof of performance of the concept.

References

[1] S. Davidson, M. Stock, "Beginning of a new phase of the dissemination of the kilogram", Metrologia, vol. 58, 2021.

[2] A. R. Panna, et al., "Graphene quantum Hall effect parallel resistance arrays", Phys. Rev. B 103, 075408, 2021.

[3] L. Keck, et. al, "Design of an enhanced mechanism for a new Kibble balance directly traceable to the quantum SI", EPJ Techniques and Instrumentation, vol. 9, no. 7, July 2022.