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The design and development of the second generation tabletop Kibble balance at NIST

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Abstract
The recent redefinition of the international system of units (SI) shifts the definition of the unit of mass, the kilogram, from a physical artifact to the fixed value of the Planck constant. Utilizing the new SI, mass measurements can be carried out with Kibble balances (KB) which directly realize mass through electromagnetic force measurements ultimately traceable to quantum electrical standards. Recently, calibrations laboratories and metrology institutes have shown interest in directly measuring gram-level masses with a tabletop KB with uncertainties similar to that of International Organization of Legal Metrology (OIML) class E2 weights typically used for calibrating commercial mass comparators. For example, E2 weights from 1 g to 5 g have relative uncertainties from 5 x 10^{-6} to 2 x 10^{-6}, respectively. Building a KB at this level of uncertainty relaxes the demand for direct connection to quantum electrical standards, gravimeters, and high vacuum environments required for more accurate KBs and was proven with KIBB-g1, a first generation tabletop KB capable of directly realizing gram-level masses in air with uncertainties on the order of 10^{-6}. A NIST/US Army collaboration has initiated the design of the second generation tabletop KB, KIBB-g2, for a dynamic range of 500 mg to 50 g with slightly looser uncertainties of 3 x 10^{-5} and focuses strongly on optimizing usability, robustness, ergonomics, and measurement time, to meet commercial requirements for a ubiquitous weighing device. Here, we describe the recent design and developments of the KIBB-g2 tabletop KB.

Keywords: metrology, mass, kilogram, instrument design, Kibble balance

1. Introduction

Gram-level mass determinations have historically been realized via subdividing through a convoluted dissemination chain ultimately traceable to a primary kilogram standard. A tabletop version of an instrument known as the Kibble balance (KB) allows for calibrations labs to truncate this traceability chain and directly realize gram-level masses on site with an alternate path of traceability to voltage and resistance standards. Such an instrument, KIBB-g1, was built as a proof of principle [2].

It is compulsory for calibrations laboratories to regularly calibrate their mass sets by physically shipping them to primary laboratories, such as the National Institute of Standards and Technology (NIST). This infrastructure is a logistically and financially inefficient, time consuming process. The US Army has funded a three year project for NIST to design and build a second generation tabletop Kibble balance, KIBB-g2, aimed to directly realize masses ranging from [500 mg – 50 g] with uncertainties on the order of 3 x 10^{-5}. KIBB-g2 in contrast with its predecessor will be flexure based and much more compact, robust, and user friendly, with ultimate intentions of becoming a commercial instrument.

2. Operational Theory

A conventional beam balance makes relative measurements, comparing the weight of an object to that of a calibrated mass. A Kibble balance, however, makes absolute measurements, comparing the weight of an object to a frequently calibrated electromagnetic force determined by electrical quantities. The experiment involves two modes of operation, velocity mode and force mode. Velocity mode is based on the principle of Faraday's law of induction. A coil of wire length L is moved at a vertical velocity v through a magnetic field of flux density B so that a voltage V is induced. The induced voltage is related to the velocity through the flux integral BL:

$$(1) \quad \boldsymbol{V = BLv}$$

Force mode is based on the Lorentz force. The gravitational force on a mass m is counteracted by an upward electromagnetic force F generated by the same coil, now energized with a current I in a magnetic field:

$$(2) \quad \boldsymbol{mg = BLI}$$

where g is the local gravitational acceleration. An expression that virtually equates electrical and mechanical power leading to a solution for mass is obtained by combining equations (1) and (2):

$$(3) \quad \boldsymbol{m = VI/gv}$$

Since KIBB-g2 strives for relative uncertainties on the order of 10^{-5}, the Planck constant makes a subtle appearance as the means for absolutely calibrating the voltmeter and resistance standard used for the electrical measurements.

3. Balance Design

KIBB-g2 is in the initial design phase with several opportunities identified to optimize the mechanics for usability, robustness, and ergonomics. Special attention has been given to the guidance mechanism of the balance, the process for obtaining the magnet systems, and the method for measuring coil displacements. In the first generation, linear guidance was accomplished with a square cross-section air bearing system acting as a frictionless stage for coil motion coupled to a balance beam pivoting about a knife edge [2]. Though functional, requiring a constant supply of compressed air with small flutter forces directly transmitted to the coil was undesirable.

Recent KBs and electrostatic balances under construction at NIST have been designed with flexure-based guidance systems [3]. Flexure hinges such as those used in these balances require no maintenance, have negligible hysteresis, and demonstrate highly-reproducible motion. NIST in-house design capabilities have been leveraged to produce a similar system for KIBB-g2. The design objective is to achieve repeatable linear translation with minimal parasitic motions while maintaining a tabletop form factor. A prototype flexure mechanism has been designed and is being manufactured for the purposes of initial studies. The performance and ergonomics of the prototype will be verified and used as a basis for optimizing the final design for manufacturing ease, durability, and size.

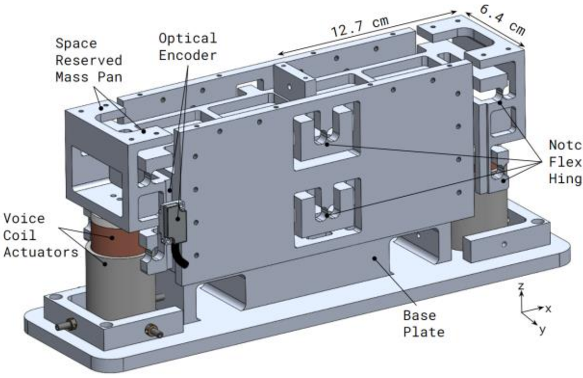

Figure 1. CAD image of the idealized KIBB-g2 concept. The proposed KB is symmetric about the XZ and YZ planes.

Figure 1 shows the conceptual design and proposed locations of all major subsystems, including magnets, mass pan, optics, and other ancillary components. The design occupies a volume of approximate 4000 cm^3, approximately 10 times less than the first generation instrument which fit on a 30 cm diameter optical breadboard and measured 57 cm tall [2].

For KIBB-g1, both magnets were designed and manufactured at NIST, a solution only reasonable for one-off instruments. For KIBB-g2, a commercial company specializing in voice coil actuator (VCAs) will implement minor modifications such as a non-conductive former, smaller wire gauge coil, and SmCo magnet instead of NdFeB to produce a magnet system suitable for KIBB-g2.

Finally, KIBB-g1 utilized a custom-built heterodyne interferometer for measuring coil displacement. With similar reasoning, a commercial solution will take the next-generation instrument one step further. Initial findings are detailed towards the possibility of replacing interferometric sensing with that of an optical encoder.

3.1 Flexure Guidance Mechanism

To create a ubiquitous tabletop balance, a monolithic design for the guidance mechanism has been chosen. This approach offers several advantages: 1) flexure hinges can be fabricated in a single machining setup, 2) no assembly is required, and 3) so long as machining tolerances have a negligible impact on performance, several identical parts can be made.

A compliant four-bar linkage guide mechanism has been designed and optimized using parametric simulation studies to allow repeatable linear motion with a range of +/- 5 mm. Keck et. al found that corner loading is minimal when linkage dimensions are equal and when the flexure is stiff in the cross-wise direction. With these considerations, the mechanism has been designed to be fully symmetric to allow for the option of weighing on either side and for immunity to thermal expansions. To verify manufacturability, the 3D model began as a monolithic block with dimensions of 254 x 63.5 x 88.9 mm^3, with only cutting operations being used to develop the part. The part has been designed with a focus on keeping as much material as possible for the static portion of the structure, while designing the moving structure to be stiff and lightweight. This will allow the static part to serve as a large, stable thermal mass and metrology frame.

The moving parts of the flexure mechanism are hidden in the center of the monolithic piece: two swings which are protected by the static frame and linked to twelve notched-style flexures. A circular geometry is easy to manufacture and allows precise rotation about the center of the hinge. To keep the footprint of the mechanism small, a dual-diameter hinge was chosen to improve compliance without the need to increase linkage length: the center portion of each flexure element follows the geometry of a 75 mm diameter circle, then tapers to a 6 mm circle. The minimum flexure thickness is 0.05 mm and has a total width of 8 mm. Such flexures are able to be reliably machined by electrical wire discharge machine. Shown in Figure 2 is a simplified model of the moving components, with the static structure cut at each of four fixed support constraints.

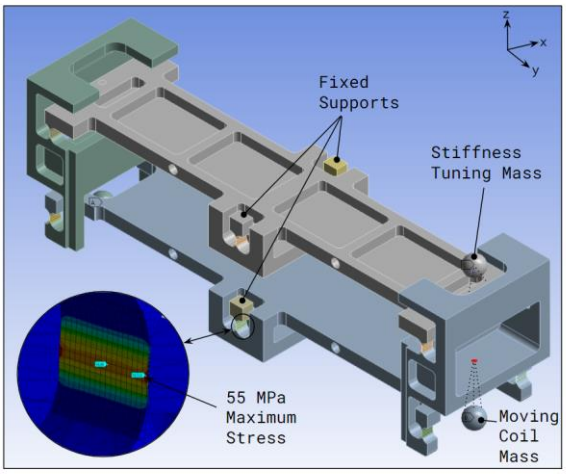

Figure 2. Stress distribution in the hinges as calculated by finite element simulations for Poisson's ratio of $v = 0.33$ and elastic modulus $E = 68$ GPa for the maximum system travel of 5 mm.

Previous iterations of flexure-based balances at NIST have explored the use of materials including titanium, beryllium copper, and different alloys of aluminum. For the combination of cost, machineability, and occupational safety, aluminum is the only feasible option for a monolithic part. Keck et al employed aluminum 7075-T6 for a similar flexure mechanism, referencing its high yield strength [3]. The flexure mechanism for KIBB-g2 must accomodate a magnet actuation system and employ the previously mentioned dual-diameter hinge design to satisfy the large travel requirement. Such a geometry is more difficult to machine and requires a deeper electrical discharge machining operation than similar systems at NIST, opening the door for electrode wire misalignment, taper errors, and tensioning issues at the target tolerance of 0.01 mm. Aluminum 6061-T6 and aluminum 5083-O have been identified as candidate materials that are easier to machine.

Parametric studies have been conducted to set the initial hinge and bar geometries such that: 1) the stress in the mechanism remains below the fatigue limit of either candidate materials and 2) the hinges are loaded only in tension. For the mass measurement range of KIBB-g2, the preliminary geometry has been selected and the mechanism demonstrates a peak stress of 55 MPa at the center of the hinge, shown in Figure 2, for aluminum 6061-T6. Initial characterization of the prototype mechanism and lessons learned during the manufacturing process will allow for further optimization. The final design of the mechanism can be sized even smaller and approach the fatigue limit of the chosen material.

Because of the dominance of the flexure mechanism with respect to design decisions for the rest of the balance, the prototype mechanism has been designed to offer maximum flexibility during initial testing. Mounting has been included to offer several different options for mass pan placement, coil displacement sensing, adjustable hard stops, and other ancillary features which may become necessary as the design matures.

Several tapped holes have been included in the upper swing to allow for adjustable masses to be mounted to reduce the stiffness of the mechanism. Preliminary studies indicate an elastic linear stiffness of the prototype mechanism of 2.8 N/m. Simulations show that loading the upper swing such that the balance acts as an inverted pendulum is possible to obtain a linear stiffness less than 0.1 N/m. For the preliminary geometry, parametric studies indicate that this point occurs with a 125 g weight at approximately 27 mm above the upper swing.

To protect the mechanism during transit and machining, several sacrificial bridges, not shown, are included in the design and lock the motion of the flexures. After delivery of the mechanism, the bridges will be removed using a small rotary cutting tool. After removing the bridges, it is possible to lock motion using four safety pins which pass through the mechanism and expand after installing a long screw.

3.2 Electromagnet

As it was an experimental apparatus, the KIBB-g1 magnet system featured two coils connected in series opposition, wound in-house with a mean diameter of 73 mm, interacting with a SmCo permanent magnet. The mild steel yokes for flux guidance were designed to be adjustable, allowing for tuning of the magnetic field [2].

The design goals of KIBB-g2 include commercial production and minimizing the number of components fabricated in-house. As such, a modified version of a commercial VCA has been purchased. Several changes to commercial-off-the-shelf VCAs are necessary to adapt such a design for KIBB-g2. These include: 1) modifying the bobbin (coil former) to be electrically non-conductive, i.e. plastic instead of aluminum, 2) reducing the wire gauge to maximize the flux integral, and 3) changing the material of magnet from neodymium to samarium cobalt to reduce sensitivity to thermal fluctuations. The candidate VCA to be modified is a BEI Kimco LA15-26-000A[1], chosen for its performance, standard mounting features, and appropriate size.

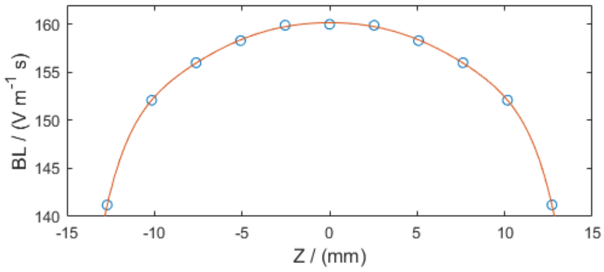

Figure 3. Theoretical BL profile through the air gap of the magnet system as a function of Z, courtesy of the manufacturer. A section where dBL/dZ = 0 exists over a range of a few mm near Z = 0.

Upon implementing these modifications to the commercial VCA, the vendor has provided theoretical performance values. Shown in Figure 3 is a plot of the flux integral BL, with a flat spot within 0.1 % across a range of 5 mm. The design of the flexure guidance system and the operation modes of KIBB-g2 have been optimized to take advantage of this flat region.

The chosen VCA is approximately three times smaller than the diameter and height of the previous generation magnet system, with similar performance characteristics. The peak value of flux density is within 10% of that measured in the KIBB-g1 magnet system. Due to asymmetries in the magnet yoke pieces, we found a slope in the BL profile of the KIBB-g1 magnet system around the weighing position [2]. For the second generation instrument, the manufacturing tolerances and theoretical performance of the modified VCA should be much better than the previous generation and closely match the final part.

The modified VCAs have been purchased and are in the manufacturing phase. Upon receipt, the BL profile of each VCA will be characterized and evaluated, including the leakage of magnetic flux for such an open-top magnet design. Using the magnetic force calculation method described in [2] and preliminary gaussmeter measurements, the initial distance between the mass pan and the VCA has been set as approximately 80 mm. At this distance, an OIML class E2 10 g stainless steel mass would experience an additional force equivalent to a 7.7 µg mass due to the magnetic susceptibility of the material. Finite element simulations and characterization will be performed to optimize this spacing in the final design.

3.3 Optical Encoder

Laser interferometry is generally accepted as the de-facto method for displacement sensing of the coil in KBs. However, this method occupies a large footprint, requires complete design of an optical system, and is costly. The design philosophy of KIBB-g2 relies heavily on reducing the cost, complexity, and footprint of the previous generation instrument. Because of the

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[1] Certain commercial equipment, instruments, and materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

relaxed uncertainty budget for the second generation instrument, it may be possible to replace the heterodyne interferometry with a system based on a commercially-available optical encoder. To characterize how well of an alignment is necessary to achieve 10 ppm-level accuracy, an auxiliary experiment has been constructed and is shown in Figure 4.

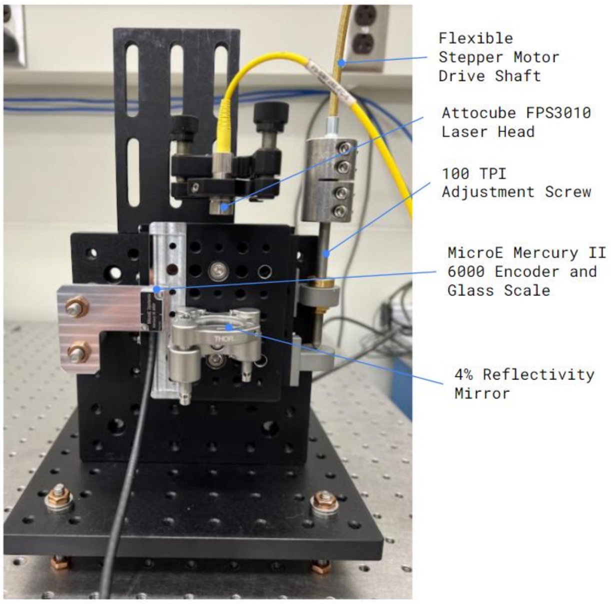

Figure 4. Initial schematic view of the mechanical systems for the optical encoder experiment. Not shown are the electronics, stepper motor, and ancillary equipment used for the test, but described herein.

A literature review and study of high performance commercially-available linear encoders reveals that the interpolated errors are on the order of 15 nm [5, 6, 7]. However, the stability, accuracy, and interpolation errors of such encoder systems are dependent on read head/scale alignment and not traceable to a primary length standard. As such, this experiment will evaluate the short term accuracy and long term stability of the MicroE Systems Mercury II 6000 linear encoder system, with 16384x interpolation, against an Attocube 3010FPS interferometer. Future studies will be performed to compare these results with those of other brands.

A linear stage, with crossed-roller bearings chosen for their repeatability and stability, mounts to a vertically-oriented optical breadboard as shown in Figure 4. An adapter plate provides a platform for both the encoder linear glass scale as well as the 4% reflector for the interferometer. The encoder readhead is mounted rigidly with a slotted adapter bracket and adjusted carefully with ring shims until the system meets manufacturer alignment specifications.

The beam path of the interferometer reference is both aligned to gravity via an alcohol pool as well as the axis of motion of the translation stage. A flex coupler connects a 100 turns-per-inch stage-adjustment screw to a stepper motor, which allows for 32 to 1 microstepping resulting in a final displacement resolution of 40 nm, a technique found in precision microscopy [4]. Such fine resolution is important to evaluate the effect of subdivision error between graduations on the linear glass scale. The stepper motor is mounted on a separate laboratory table nearby, helping to decouple thermal and vibration effects from the breadboard that the apparatus is mounted to. Long-term studies of the stability and accuracy of the system are underway and we expect to report these results at the conference. If sufficiently stable and accurate for our target uncertainties, such a system would greatly reduce the size, complexity, and cost of future tabletop KBs.

3.4 Mass Pan

In KIBB-g1, a gimbal style, self centering mass pan was critical to Force Mode operation. In order to lower the Type A uncertainty to 1 x 10^{-6}, about 100 mass placements and mass removals over 10 hours were necessary for adequate sampling, a procedure best conducted automatically. The gimbal was necessary so that the mass would self center on the mass pan after each transfer. However, analyzing the data, a single Force Mode measurement is already below the target uncertainty, 3 x 10^{-5}, of KIBB-g2[2]. This relaxed accuracy indicates that a much shorter measurement time is necessary, likely on the order of minutes. Thus an automated mass handling system with a delicate gimbal mass pan is deemed unnecessary. A simple static platform should suffice for the end user to directly place and remove the test mass.

4. Discussion

The design and construction of KIBB-g2 focuses heavily on optimizing the system for ease of use, robustness, and commercialization. Improvements to the guidance mechanism, magnet system, displacement sensor, and mass pan described in Section 3 foreshadow an instrument catered towards calibration technicians and end users.

In the coming months, we plan to acquire the hardware for constructing the first iteration of KIBB-g2 and characterize the flexure guidance mechanism. In parallel, we plan to collect data on the short term accuracy and long term stability of the optical encoder based off the auxiliary experiment. Finally, large efforts dedicated to programming the data acquisition and control loop of the instrument will be necessary. Further updates will be presented at the meeting.

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