The Design of the New NIST-4 Watt Balance

L.S. Chao, S. Schlamminger, F. Seifert, A. Cao, D. Haddad, D.B. Newell, J.R. Pratt
National Institute of Standards and Technology (NIST)
100 Bureau Drive Stop 8171
Gaithersburg, MD 20899-8171
USA
Email: leon.chao@nist.gov, stephan.schlamminger@nist.gov

***Abstract*—The design of the new permanent-magnet driven watt balance and novel mechanical features will demonstrate the high-precision capabilities of a large complex mass measurement system with expected overall uncertainties on the order of 3 parts in 10^8.**

***Index Terms*—mass, watt balance, kilogram, flexure, permanent magnet**

I. INTRODUCTION

A watt balance is a mass measuring apparatus that utilizes a magnetic field and a movable coil to compare electrical power to mechanical power. The NIST watt balance experiment consists of an alternating series of measurement modes called velocity mode and force mode. This instrument measured one of the most recent values of the Planck constant in 2013 and will assist in the realization of the kilogram[2].

NIST-4 is the fourth generation watt balance currently being built at the National Institute of Standards and Technology. The most notable change from the previous apparatus is the shift from a 0.1 Tesla superconducting magnet to a 0.55 Tesla SmCo permanent magnet system. NIST-4 also has a more robust design and will be housed inside a 2 m tall vacuum chamber, significantly smaller than its predecessor which stands past two stories of a building.

II. NIST-4 COMPONENTS

The NIST-4 watt balance contains only a few key components. A monolithic, aluminum spider is suspended and rotationally decoupled from one side of a diamond-turned aluminum wheel [Fig. 1]. Next, a copper coil with 885 turns and a mean diameter of 0.43 m is hung from three identically paired systems of x-y flexures. The coil is suspended in a 30 mm wide air gap and is allowed to translate vertically +/- 40 mm from its nominal position inside of the magnet system.

A main mass stirrup hangs from the center point of the spider but pivots independently from the spider and coil assembly. This main mass stirrup serves as the platform for loading and unloading the main mass and auxiliary mass during force mode and velocity mode [2]. The 600 mm diameter balance wheel pivots about a tungsten carbide knife edge linked to the Extremely Large Flexure (ELF). This monolithic flexure allows pure translational motion in the x-y directions which is essential for positioning the coil accurately inside the magnet.

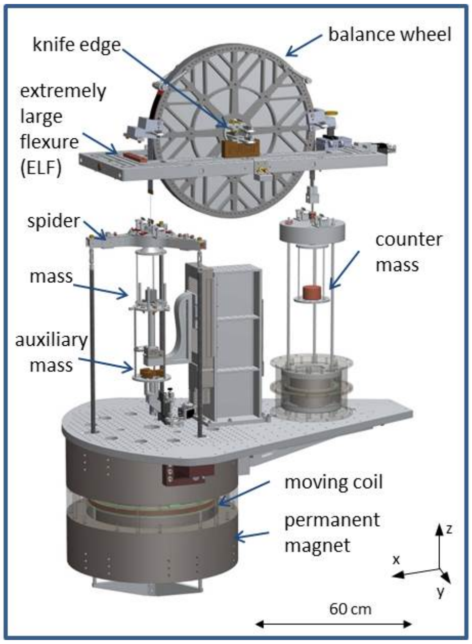

Fig. 1: Drawing of the main components of NIST-4. Vacuum and support components are omitted.

III. THE MOVING COIL

In velocity mode, the moving coil has six degrees of freedom given by three components $(v_\mathrm{x}, v_\mathrm{y}, v_\mathrm{z})$ of its velocity $\mathbf{v}$ and three components $(\omega_\mathrm{x}, \omega_\mathrm{y}, \omega_\mathrm{z})$ of its angular velocity $\mathbf{\Omega}$ about its center of mass [2]. In force mode, the coil can generate a force $\mathbf{F}$ with components $(F_\mathrm{x}, F_\mathrm{y}, F_\mathrm{z})$ and a torque $\mathbf{\Gamma}$ with components $(\tau_\mathrm{x}, \tau_\mathrm{y}, \tau_\mathrm{z})$. Through the combination of velocity mode and force mode, linked by the magnet system's Bl factor, mechanical power is derived and equated to electrical power [1][2]:

$$UI = \mathbf{F} \cdot \mathbf{v} + \mathbf{\Gamma} \cdot \mathbf{\Omega} \tag{1}$$

or

$$UI = F_\mathrm{x} v_\mathrm{x} + F_\mathrm{y} v_\mathrm{y} + F_\mathrm{z} v_\mathrm{z} + \tau_\mathrm{x} \omega_\mathrm{x} + \tau_\mathrm{y} \omega_\mathrm{y} + \tau_\mathrm{z} \omega_\mathrm{z} \tag{2}$$

Of the twelve variables that contribute to the virtual mechanical power, F_z and v_z are the only desired components; all others are deemed as parasitic.

To achieve the precision necessary for realization of mass, the ratio of each off-axis component to $F_\mathrm{z} v_\mathrm{z}$ must be minimized to a few parts in 10^{-9} (ppb). There are essentially three ways to accomplish this: (1) diminish the five off-axis force components, (2) diminish the five off-axis velocity components, or (3) reduce both the off-axis forces and the off-axis velocities to diminish the off-axis product Fv. For example, if

$$\frac{F_\mathrm{x}}{F_\mathrm{z}} = 10^{-4} \quad \text{and} \quad \frac{v_\mathrm{x}}{v_\mathrm{z}} = 10^{-5} \tag{3}$$

then,

$$\frac{F_\mathrm{x} v_\mathrm{x}}{F_\mathrm{z} v_\mathrm{z}} = 10^{-9} \tag{4}$$

The off-axis X-Y force and torque components are minimized by concentrically aligning the electrical center of the coil to the magnetic center of the radial field. By doing this, the minor magnetic flux gradients cancel on opposing sides of the coil. Compliancy in the stirrup system, accomplished by small 2D flexures, allows for monitoring of the parasitic forces and torques during force mode. However, compliant systems result in higher amplitude parasitic motions.

IV. HIGH PRECISION ALIGNMENT

In order to achieve the required level of uncertainty for mass redefinition, the physical alignment of the moving coil's electrical center to the field's magnetic center is important. These two points must be aligned to one micrometer. However, the coil's location traces back to the location of the knife edge, whose 40 kg load must be precisely positioned with a device that is both vacuum compatible and non-magnetic.

The ELF was designed and machined from a monolithic block of 6061-T6 aluminum to adjust the x-y position of the knife edge and everything attached. The ELF weighs 33 kg, is 97 cm x 46 cm x 3.8 cm, and has two symmetry planes. The system contains 24 individual flexures measuring 1.8 mm wide and 8 mm long. These flexures allow the movement of the middle plate with respect to the outer ring.

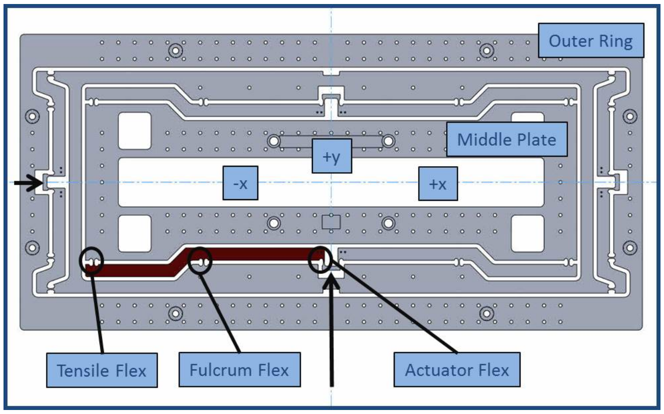

Fig. 2: Top view of the ELF. Pushing on the tabs indicated by the arrows result in X and Y displacements of the middle plate. Desired displacements = +/- 0.5 mm in X and Y.

The symmetric design and the collinear flexures are significant in removing off-axis motions, preserving pure linear motion in X and Y. Focusing only on the lower left quadrant, three collinear flexures are apparent. Pushing on the bottom actuation flexure in the +y direction pivots the whole beam about the fulcrum flexure, resulting in a pulling force applied to the tensile flexure and displacement of the middle plate in the -y direction. The same is conducted with the outer flexures for displacements in the x direction.

V. AUXILIARY MASS

When switching between velocity mode and force mode in the existing watt balance, a $\frac{1}{2}$ kg counter mass is loaded and unloaded from the mass pan hanging from the far side of the wheel. A design flaw is exposed during this process: the knife edge experiences a 1 kg heavier load in force mode than in velocity mode, affecting the hysteresis in the knife edge.

<table>
<tr><th colspan="7">Existing Watt Balance</th></tr>
<tr><td>Mode</td><td>F</td><td>M</td><td>A</td><td>=</td><td>C</td><td>Knife Load</td></tr>
<tr><td>Velocity</td><td>0</td><td>0</td><td>0</td><td>=</td><td>0</td><td>0</td></tr>
<tr><td>Force ($\mathrm{M_{off}}$)</td><td>5 N</td><td>0</td><td>0</td><td>=</td><td>5 N</td><td>10 N</td></tr>
<tr><td>Force ($\mathrm{M_{on}}$)</td><td>-5 N</td><td>10 N</td><td>0</td><td>=</td><td>5 N</td><td>10 N</td></tr>
<tr><th colspan="7">NIST-4</th></tr>
<tr><td>Mode</td><td>F</td><td>M</td><td>A</td><td>=</td><td>C</td><td>Knife Load</td></tr>
<tr><td>Velocity</td><td>0</td><td>0</td><td>5 N</td><td>=</td><td>5 N</td><td>10 N</td></tr>
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<tr><td>Force ($\mathrm{M_{on}}$)</td><td>-5 N</td><td>10 N</td><td>0</td><td>=</td><td>5 N</td><td>10 N</td></tr>
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TABLE I: A comparison between the knife edge load in the existing watt balance and NIST-4: For NIST-4, a 5 N auxiliary mass (A) is inserted during velocity mode to maintain consistency between the 5 N coil force (F) and the 10 N main mass (M) during force mode. Force mode is comprised of a series of main mass insertions and removals ($\mathrm{M_{on}}$ and $\mathrm{M_{off}}$). The counter mass (C) on the far side of the balance wheel becomes a fixed 5 N tare mass.

To remedy this issue for NIST-4, the counter mass was replaced with a $\frac{1}{2}$ kg fixed tare mass. A $\frac{1}{2}$ kg auxiliary mass was introduced to the main mass side to serve as the new counter mass. Using its own on/off system, the auxiliary mass is removed from the system during force mode and reinserted during velocity mode as a novel way to balance the wheel.

VI. CONCLUSION

NIST-4 will be used to realize the kilogram once the redefinition of the SI has occurred with expected uncertainties of 3 parts in 10^8. To disseminate mass with similar uncertainties demands high precision mechanical components capable of sub-micron repeatability and accuracy.

REFERENCES

[1] I.A. Robinson, Alignment of the NPL Mark II Watt Balance, *Meas. Sci. Technol.* **23**, November 2012.
[2] S. Schlamminger, et al. Determination of the Planck constant using a watt balance with a superconducting magnet system at the National Institute of Standards and Technology, submitted to *Metrologia*.