MEASUREMENT AND REDUCTION OF ALIGNMENT ERRORS OF THE NIST WATT EXPERIMENT

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Abstract

The effects of uncertainties in the alignment of the NIST watt balance with local gravity and the magnetic field of the balance have been analyzed, and techniques for measuring all misalignment parameters have been developed. The systematic uncertainty in the watt measurement due to alignment has been reduced to 0.04 μW/W.

Introduction

The NIST watt balance [1,2] has been developed to compare the electrical values of the ohm and the volt to the mechanical and time values of the meter, kilogram, and second by measuring the watt in both electrical and mechanical units. Specifically, the force on a current through an induction loop in a magnetic field is measured, as is the voltage induced around that same loop when it moves at some velocity through that same magnetic field. By comparing the force times the velocity to the voltage times the current, the same quantity of power is measured in both electrical and mechanical units.

The watt balance (Figure 1) is designed such that one side has both a pan for a mass and an induction loop in a magnetic field. A known force is applied to that side of the balance using the weight of a 1-kg mass. A current through the induction loop supplies a vertical force to cancel the weight of the mass. The induction loop is then moved with a known velocity (measured by a set of 3 laser interferometers) in the vertical direction by rotating the balance wheel about a knife edge at its center, and the induced voltage is measured. Errors in the measured watt value occur due to a horizontal force component, a horizontal velocity component, or a twisting of the induction loop as it moves vertically. Even with perfect alignment of the balance, misalignment of the velocity measurement system with respect to vertical results in measurement error. These effects, which cause systematic uncertainties in the measured watt value, are collectively referred to as alignment errors [3].

The Alignment Errors and Their Coupling to the Watt Measurement

The specific alignment errors that have been identified are as follows:

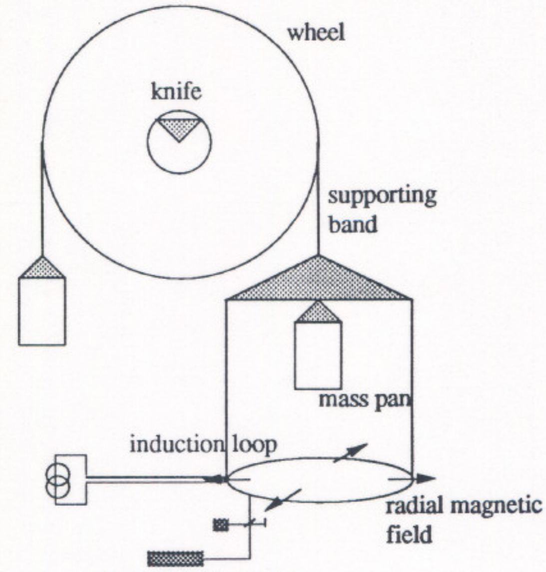

Figure 1: Schematic view of the NIST watt balance.

F_x: horizontal force due to misalignment of either the magnetic field with vertical or the angle of the induction loop with vertical.

v_x: horizontal velocity due to misalignment of the balance wheel.

τ: torque on the induction coil due to a misalignment of the electrical center of the coil and its center of mass or the center of the magnetic field.

θ, ϕ: horizontal and vertical rotation of the induction loop as it moves due to imperfections in the band supporting the induction loop.

d: displacement between the optical center of the interferometers and the center of mass of the induction loop (Abbe offset).

α: uncertainty in the angle between the interferometer laser beams and vertical.

These errors couple to cause the following error in the voltage measurement:

$$\frac{\Delta V}{V} = \left(\frac{F_x}{F}\right)\left(\frac{v_x}{v}\right) + \left(\frac{\tau}{F}\right)\left(\frac{\theta}{l}\right),$$

and the following error in the velocity measurement:

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$$\frac{\Delta v}{v} = d\left(\frac{\theta}{l}\right) + \phi\alpha + \frac{1}{2}\alpha^2.$$

$V, v, F,$ and l, are the measured voltage, velocity, force, and the distance that the induction loop travels during the velocity measurement.

Measuring the Errors

Techniques have been developed to measure each one of the alignment parameters.

v_x can be directly measured by monitoring the position of a vertical laser beam which is reflected from a corner cube attached to the induction loop. Horizontal displacements and velocities in the induction loop become horizontal displacements and velocities of the reflected laser beam. The velocities are minimized by adjusting both the angle of the balance wheel and the position of the knife edge. The sensitivity of the measurement is limited by the uncertainty in the angle of the laser beam of 2×10^{-4} rad, resulting in an error in v_x/v of 2×10^{-4}.

The errors that make up F_x and τ are coupled in a complex manner. The parameters associated with a horizontal force component are the angles of both the magnetic field and the induction loop relative to vertical. The parameters which produce a torque on the induction loop are the positions of both the electrical and mass centers of the loop relative to the center of the magnetic field.

To measure these parameters, first the magnetic field is aligned to vertical using a pickup coil which has been separately aligned to vertical. The pickup coil is then placed in the magnetic field where the induction loop normally rests. The angle of the magnet is adjusted to minimize the mutual inductance between that magnet and the pickup coil.

The relative position of the electrical center of the induction loop and the center of the magnetic field are determined using a pickup coil which measures the radial magnetic field flux at the position of a particular segment of the induction loop. The radial position of that segment of the loop is inferred using the fact that the radial magnetic field is inversely proportional to its radial position. From the position of several different segments of the loop, the position of the electrical center of the induction loop relative to the magnetic field is calculated.

The angle of the induction loop and the position of its center of mass can not be independently measured. Instead they are measured together. If these parameters are misaligned, then a current through the induction loop produces a torque and horizontal force on the induction loop which can be measured as angular and lateral deflections of the wire loop. Because the induction loop is suspended as a pendulum, the motion is constrained, and therefore the lateral and angular motions in response to torques and forces are mixed. By causing known changes in the center of mass and angle and measuring the response of the wire loop to currents, the matrix describing the mixing can be determined. Then the center of mass and wire loop angle are adjusted to minimize the deflections, resulting in uncertainties of 0.1 mm for the relative position of the mass and electrical centers and 1×10^{-4} rad for the static angle of the coil. These errors result in an uncertainty in F_x/F of 1×10^{-4} and in τ/F of 0.1 mm.

θ is determined by examining the difference in displacements measured by each of the three laser interferometers over the distance that the induction loop traveled. θ is a property of the suspending band and is not adjustable. The residual angle of horizontal rotation is 5×10^{-7} rad.

ϕ is determined using a procedure similar to the one used to determine v_x, i.e., by measuring the change in position of two points on the induction loop as the loop moved vertically using light reflected through attached corner cubes. It is reduced using a control system with an electrostatic actuator. The control system is designed such that it does not couple to the watt measurement of the balance and hence can be operated while the balance was making measurements. The residual vertical angle of rotation of the induction loop is 1×10^{-4} rad.

d is determined by swinging the wire loop as a pendulum and measuring the vertical displacement with the laser interferometers. The measurement of each individual interferometer is then weighted to form an average motion in which the first order coupling between the swinging motion and the vertical motion was minimized. The residual error in the optical center is 0.2 mm.

α is measured by reflecting the laser beam from a horizontal mirror and visually making the beam return on itself. The uncertainty of this procedure is 2×10^{-4} rad.

Conclusion

The net systematic error due to alignment errors is 0.04 μW/W. The primary source of the error is our ability to align the reference laser beams to vertical. More sophisticated optical alignment sytems are under investigation. The goal of the watt balance is to monitor the kilogram, which requires a total uncertainty of less than 0.01 μW/W. With these procedures the alignment errors can be monitored and reduced as the overall sensitivity of the balance improves.

References

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