ELECTROSTATIC FORCE BALANCE METHOD FOR MILLIGRAM MASS METROLOGY

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Abstract: The impending kilogram redefinition provides an opportunity to realize mass using electrical measurements for traceability to the fundamental constants via the International System of Units (SI). In this work, an approach to realizing mass in the milligram to microgram regime with an Electrostatic Force Balance (EFB) is described. Measurement uncertainty is shown to be smaller than that currently achievable with methods based on subdivision of the kilogram; combined standard uncertainty of $7\text{x}10^{-6}$ has been demonstrated with a 1 milligram mass artifact. A cross check shows the mass value determined with the EFB agrees with that determined using kilogram subdivision within experimental uncertainty.

1. INTRODUCTION

As the kilogram is redefined within the SI, an opportunity arises to realize mass at smaller values using electrical metrology. Work over the past decade at the U.S. National Institute of Standards and Technology (NIST) has shown the feasibility of traceable mass metrology using electrostatic force [1, 2]. In this case, the force is generated by a capacitor in an electromechanical balance. The electrostatic force needed to balance the test mass can then be determined from SI electrical and dimensional units as described below.

2. METHODS

The NIST electrostatic force balance (EFB) uses a concentric cylinder capacitor attached to a compliant 4-bar linkage mechanism to perform a differential measurement of the electrostatic force necessary to balance the gravitational force from a test mass. The mass value of the artifact, m, can be calculated using

$$m = dC/dz\ (V - V_s)^2/2g \qquad (1)$$

where dC/dz is the gradient of capacitance, C, with position, z, in the direction of motion of the free arm of the 4-bar linkage which was aligned to gravity. V is the externally applied voltage used to maintain a null balance position. V_s is a surface potential arising from patch effect and adsorbed surface layers on the capacitor, and is determined by reversing the polarity of V. The quantity g is local gravitational acceleration.

Voltage is measured with commercial digital multimeters (DMMs), and is traceable to a Josephson junction array. Likewise, capacitance is measured with a commercial capacitance bridge and is traceable to the NIST calculable capacitor (and hence also to a quantum Hall resistance standard within the redefined SI.) Position is traceable to the wavelength of a stabilized Helium-Neon laser used for interferometric position measurements. Local gravitational acceleration has been determined using an absolute gravimeter. Each of these measurements are well defined within the current SI, and the SI redefinition as well. It can be shown that the EFB measurement of mass is fundamentally linked to Planck’s constant, the velocity of light in vacuum, and the hyperfine splitting of cesium-133 [1]. Comparison of the EFB measurements to conventional mass metrology therefore further validates the continuity of mass calibration within the redefined SI.

3. RESULTS

A 1 milligram mass artifact was fabricated using aluminum wire then tested on the EFB and using a workdown from the kilogram. Figure 1 shows he results of the most recent comparison between these two methods. More detail on the uncertainty analyses is presented elsewhere [1, 3]. The measurements agree within their combined standard uncertainties, however the EFB uncertainty is substantially lower. Since the EFB measurements were performed in vacuum and the subdivision measurements in air, the effect of adsorbed surface layers may require analysis [4]. It has been shown the change in mass as any surface layers desorb in vacuum is quite small for the comparison shown in

Figure 1. This is due to the surface composition of the aluminum mass artifacts [1]. Note that true mass is reported in Figure 1; a buoyancy correction has been applied in the case of the subdivision results.

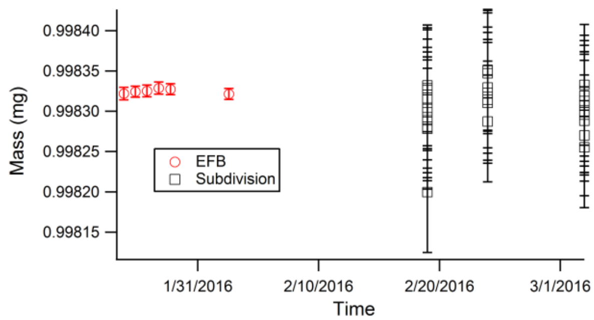

Figure 1. Results of comparison between EFB and subdivision measurements for 1 mg mass artifact. Error bars show combined standard uncertainty for individual measurements.

4. DISCUSSION

The mass values determined using the EFB and subdivision methods agree within the combined standard uncertainties of the measurements for the 1 mg mass artifact tested. The final value produced by the EFB was 0.9983245(73) at k=1. The EFB uncertainties are not dominated by type A (statistical) uncertainty as in past measurements. Rather, systematic effects are now the limiting factor in mass uncertainty, notably the uncertainty in measured voltage, and in the temperature dependence of the capacitance gradient. The automated actuator used to place the mass on the balance inside the EFB vacuum chamber causes a small amount of heating.

Another potential cause for concern is how the mass artifact itself changes over time. The aluminum wire artifact discussed here was monitored over the course of approximately two years in total and showed a decrease of 1 microgram in that time. It will be important to continue to monitor the stability of various kinds of mass artifacts to determine what the optimum conditions are to maintain artifact stability.

5. CONCLUSIONS

The use of SI electrical metrology to perform mass measurement at the milligram level yields mass values identical to those obtained with conventional mass metrology using subdivision from the kilogram within experimental uncertainty. The electrostatic force balance (EFB) method used in the current work reduces the combined standard uncertainty of the milligram by approximately an order or magnitude. This work indicates the use of SI electrical metrology in mass realization provides potential advantages in the scalability of mass within the SI.

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REFERENCES

[1] G. A. Shaw, J. Stirling, J. A. Kramar, A. Moses, P. Abbott, R. Steiner, A. Koffman, J. R. Pratt, Z. J. Kubarych, "Milligram mass metrology using an electrostatic force balance," in Metrologia, submitted, 2016.

[2] J. R. Pratt, J. A. Kramar, "SI realization of small forces using an electrostatic force balance," in Proc. XVIII IMEKO World Congress on Metrology for a Sustainable Development (Rio de Janeiro, Brazil, 17-22 September 2006) 109, 2006.

[3] Z. Jabbour, S. Yaniv, "The kilogram measurements of mass and force," J. Res. Natl. Inst. Stand. Technol., vol. 106, pp. 25-46, 2001.

[4] M. Gläser, M. Borys, "Precision mass measurements," Rep. Prog. Phys., vol. 72, pp. 126101, 2009.