ThP38 THE NIST MICROFORCE REALIZATION AND MEASUREMENT PROJECT

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Abstract

The National Institute of Standards and Technology (NIST) has launched a five-year Micro-force Realization and Measurement project focusing on the development of an instrument and laboratory capable of realizing and measuring the SI unit of force below 5×10^{-6} N using the electrical units as the link to the SI.

Introduction

While force measurements at the micro- and nano-Newton level are commonplace in industry today, no National Measurement Institute supports a direct link to the International System of Units (SI) below 1 N. The smallest mass calibrated by NIST is 0.5 mg which can yield a force realization of 5×10^{-6} N. However the artifact has a relative uncertainty on the order of a few parts in 10⁴ [1]. In principle, there is nothing to prevent further subdivision, but extrapolating the trend in small mass uncertainty leads to a relative uncertainty of a few parts in 10^2 with deadweights producing a force of 10^{-7} N.

A desire for accurate, traceable, small force measurement is emerging within ISO task groups and American Society for Testing and Materials (ASTM) committees working on instrumented indentation standards [2] and the fatigue and fracture of structural films. A central issue addressed by the NIST Microforce Realization and Measurement project is the creation of a viable primary force standard below 10^{-5} N with the goal of realizing force on the order of 10^{-6} N or less with a relative uncertainty of parts in 10^{4} .

To achieve this goal, micro- and nano-Newton level forces can be realized through the highly stable electrical units linked to the Josephson and quantized Hall effects. For example, small forces of known magnitude and direction can be created using a carefully designed capacitor. The work required to change the separation between two electrodes of a capacitor while maintaining a constant voltage is:

$$dW = Fdz = \frac{1}{2}V^2 dC \tag{1}$$

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where dW is the change in energy, F the force, dz the change in separation, V the voltage, and dC the change in capacitance. Thus a force can be realized by measuring the voltage applied across a capacitor and the capacitance gradient, dC/dz:

$$F = \frac{1}{2}V^2 \frac{dC}{dz}$$
(2)

Prototype Electrostatic Force Balance

A prototype electrostatic force balance was constructed to provide a crosscheck between an electrically derived force and a mechanical force via deadweights, at least at the upper end of the device's useful operating range. A schematic of a prototype electrostatic spring balance is shown in Figure 1 and described in detail in [3]. It features a compound-rectilinear leaf spring with a spring constant of 14 N/m that suspends and guides the motion of an inner cylindrical electrode consisting of an inverted, thinwalled cup with a 15 mm outer diameter. This entire assembly mounts to a 5-axis stage for alignment of the motion axis to within 2 mrad of gravity, and for fine positioning of the device with respect to an outer cylindrical electrode that has a 16 mm inner diameter.



Fig. 1. Schematic of a prototype electrostatic spring balance.

With this geometry the capacitance gradient is nearly linear at roughly 1 pF/mm. Relative displacement between the two electrodes is measured with a heterodyned double-pass interferometer. By alternating between 0 and

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10 V across the capacitor 140 times and integrating the position for 1 s, a displacement of $(3.3 \pm 1.8) \times 10^{-9}$ m was measured, corresponding to a force of 5×10^{-8} N. This is the limit of our force resolution using this spring balance and interferometer.

There are two modes involved with performing an electrical-mechanical force comparison: a weighing and a capacitance gradient determination (dC/dz). A weighing consists of applying a bias voltage across the electrodes and recording the relative position with the interferometer. The mass is placed on and removed from the platen while adjusting the voltage to hold the relative position fixed. To eliminate offsets and reduce the effect of linear drifts, the difference between the voltage with the mass on (off) and an average of the two adjacent mass off (on) voltage measurements was taken. The capacitance gradient is determined by scanning the inner electrode over a specific range centered around the weighing position with a given step size. Single dC/dz values are calculated for each single round trip up/down scan to reduce the effect of linear drift in the measurement.

Electrical and mechanical force comparisons were made using 1, 2, 5, and 20 mg mass standards as presented in [4]. Random discrepancies as large as 1% were discovered between the electrical and mechanical force determinations, far exceeding the estimated uncertainties due to length, voltage, capacitance, mass, and gravity metrology, as well as the determination of dC/dz and the corrections due to buoyancy and refractive index [3]. Currently the comparisons are being performed again with real time environmental monitoring, automated switching between the two modes, and dC/dz determinations with and without high voltage present.

Future Progress

Progress is being made toward developing an instrument and laboratory capable of realizing and measuring the SI unit of force below 5×10^6 N. A new laboratory that will provide a clean environment with electric, acoustic, and vibration isolation is nearing completion. To increase the force resolution, a new balance with a spring stiffness of 0.1 N/m has been constructed and is currently being tested. Once a primary force standard below 10^{-5} N is realized, dissemination will be accomplished via transfer to "micro load-cells" that are calibrated against the balance using procedures analogous to those described in [5] and [6].

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