Force Measurement Services at NIST: Equipment, Procedures, and Uncertainty

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Abstract

The facilities, instrumentation, and procedures currently used at the National Institute of Standards and Technology (NIST) for force measurement services are described. The uncertainty in the forces realized by the NIST primary force standard deadweight machines is reviewed. The maintenance and the uncertainty of the voltage ratio indicating system for strain gage load cells are discussed.

1. Introduction

The NIST Force Group provides a force calibration service featuring the application of deadweight primary force standards from 0.5 kN to 4.448 MN for elastic force-measuring devices. In addition, a hydraulic testing machine capable of generating forces up to 53 MN is available for calibrating large capacity force transducers through comparison with secondary force transfer standards maintained by NIST. The force calibration relates the forces applied to a force measuring system to the response of that system, usually by means of a second or third order polynomial equation that is derived from the calibration data. The sensor response may be determined by means of an electrical indicator, as is the case for strain gage load cells, or a mechanical deflection indicator such as those built into proving rings.

Force calibrations are usually performed according to the procedures specified by ASTM E 74-95, *Standard Practice of Calibration of Force-Measuring Instruments for Verifying the Force Indication of Testing Machines*[1]. A minimum of 30 forces are applied during the course of each calibration. These forces are applied in two or more calibration runs with, at a minimum, two positions of the sensor in the deadweight machine. The applied forces are selected at approximately every 10 % in the calibration range. Upon request, a device may be calibrated by modified procedures tailored to meet particular end uses.

Force calibrations are distinct from mass calibrations; adjustments for the local gravitational acceleration at the Gaithersburg force laboratory and for air buoyancy have already been applied to

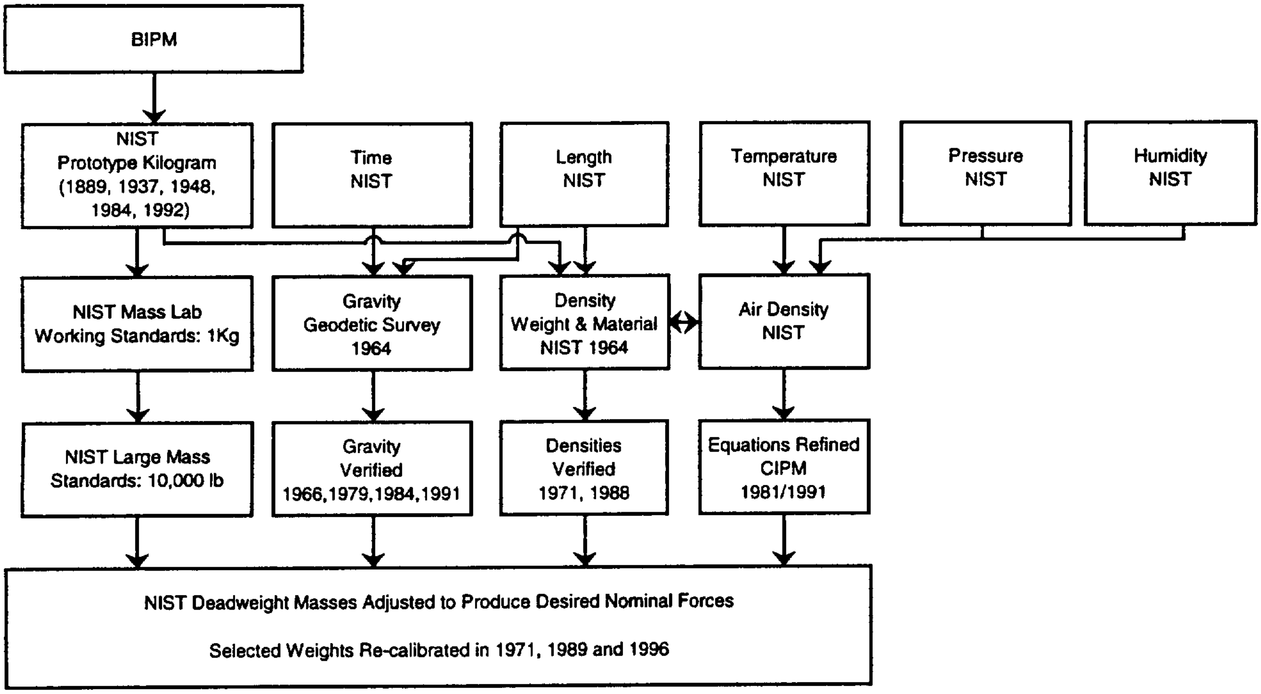

Figure 1. Traceability of the NIST primary force standards to the basic unit of mass.

the masses of the NIST deadweights in order to determine the actual forces exerted by these deadweights. If the customer were to use a NIST calibrated force-measuring device to determine the mass of an object, the local gravity and air buoyancy in the laboratory of the customer would need to be taken into account. The traceability of the primary force standards to the basic units is shown in Figure 1.

In addition to performing calibrations, the Force Group serves as the technical arm of the National Conference of Weights and Measures in the load cell area. In this capacity, the group performs pattern evaluation testing of load cells used in electronic systems. These tests are performed in accordance with the specifications of the National Conference of Weights and Measures Publication 14, denoted in this paper as NTEP[2]. The International Organization of Legal Metrology[3] has adopted a similar standard, OIML R 60. While there exist some differences between the national and the international standards they are minimal. Both procedures prescribe deadweight loading tests of prototype load cells for linearity, repeatability, hysteresis and creep over a temperature range of -10 °C to 40 °C. These prototype load cells are submitted by manufacturers desiring to certify their load cell families as compliant with accuracy class requirements specified either in NIST Handbook 44[4] or OIML R 60.

Improvements have been made in recent years to the facilities, instrumentation, and calibration procedures used by the Force Group. This paper describes the current NIST force measurement capabilities, thereby supplementing information given previously [5,6], and provides an accounting of the uncertainty in the forces exerted.

Table 1. Characteristics of the six NIST deadweight machines.

Capacity,						
kN	2.2	27	113	498	1334	4448
(klbf)	(0.505)	(6.1)	(25.3)	(112)	(300)	(1000)
Min. Load,						
kN	0.044	0.44	0.89	13	44	222
(klbf)	(0.01)	(0.1)	(0.2)	(3)	(10)	(50)
Min. Increment						
kN	0.022	0.22	0.44	4.4	44	222
(klbf)	(0.005)	(0.05)	(0.1)	(1)	(10)	(50)
Compression setup space:						
Vertical, m	0.25	0.61	0.76	1.02	1.65	1.98
Horizontal, m	0.29	0.47	0.50	0.71	0.91	0.86
Tension setup space:						
Vertical, m	0.56	0.76	0.91	2.16	2.49	4.45
Horizontal, m	0.29	0.64	0.66	0.71	0.91	1.17
Alloy						
AISI Series	302	302	302	410	410	410
Density at 20 °C						
kg/m^3	7890	7890	7890	7720	7720	7720

2. Facility

Primary force calibrations are performed in both tension and compression over a range of 44 N (10 lbf) to 4.4 MN (1000 klbf) using the six NIST deadweight machines described in Table 1.

The deadweights of all NIST deadweight machines are made of stainless steel. This material was chosen because of its well-known long-term stability, machinability and availability. Moreover, the working mass standards used by the NIST Mass Group to calibrate the deadweights are also made of stainless steel. Therefore, the errors associated with air buoyancy adjustments are minimized. The particular alloy used for each deadweight machine is listed in Table 1. The design principles involved in the three smallest deadweight machines are shown in Figure 2 while the design of the larger machines are shown in Figure 3.

Today all NIST deadweight machines are able to apply forces in ascending and descending fashion. Originally, actuation of the deadweights of the 113 kN and 2.2 kN deadweight machines was such that the weight frame needed to be unloaded from the device under test, permitting only return-to-zero loading sequences. During the automation of the force facility, this limitation was overcome by installing pneumatically operated stabilizing mechanisms on these two machines, enabling their deadweights to be changed while the frame is loaded without incurring either excessive wear on the deadweight seats or swinging of the weight frame. These mechanisms retract from the weight frame shafts after each deadweight change. Ascending and descending force sequences can now be applied in these machines.

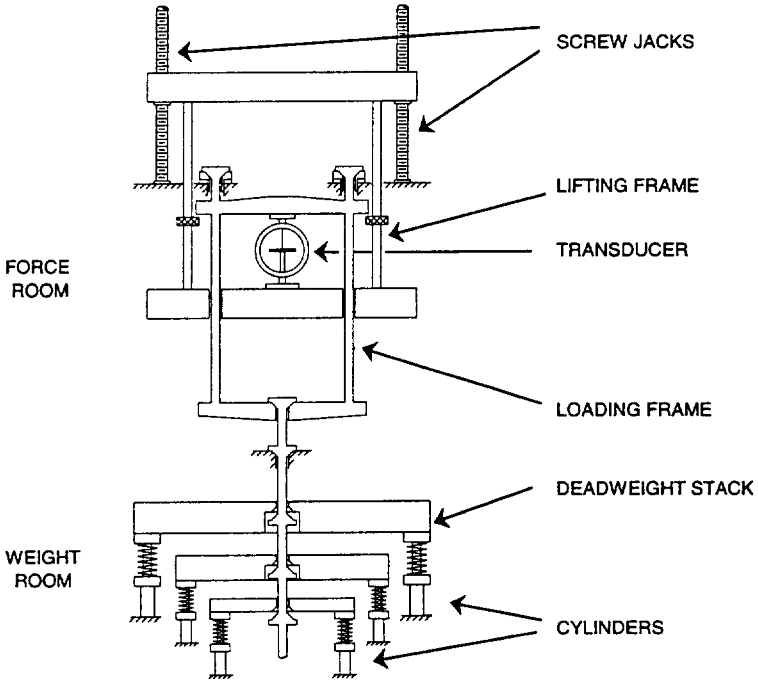

Figure 2. Design principle of the three smaller NIST deadweight machines.

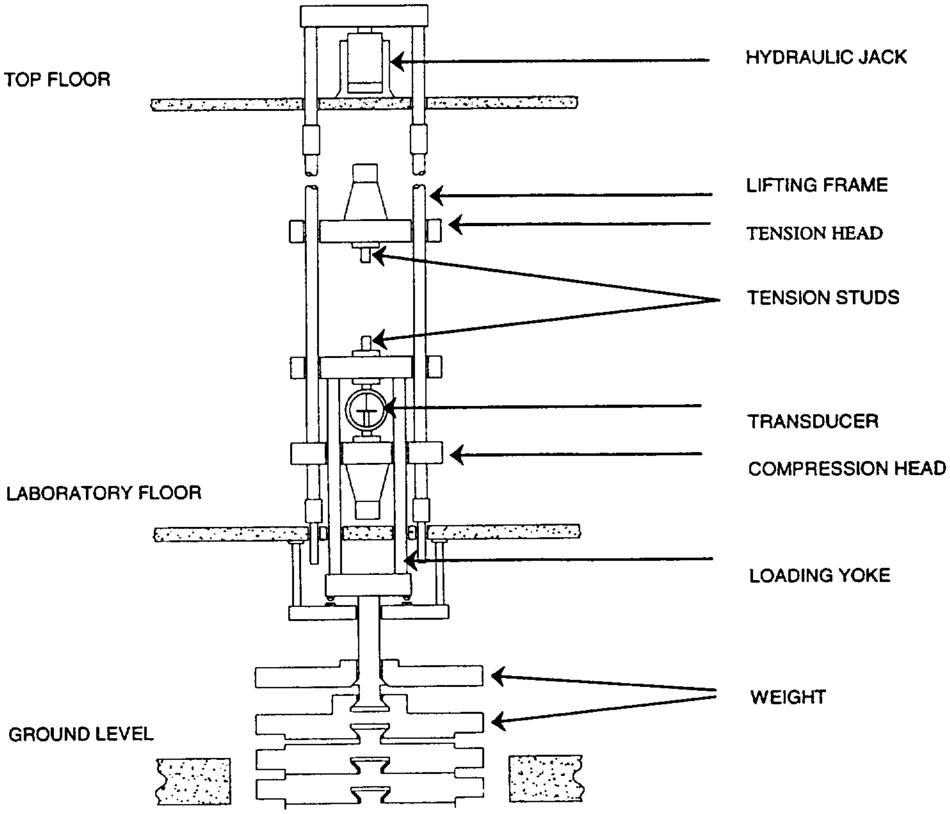

Figure 3. Design principle of the three larger NIST deadweight machines.

With the exception of the 27 kN (6.1 klbf) machine, the NIST deadweight machines are now fully automated. Further, except for the 27 kN and the 4.448 MN machines, all are equipped with environmental chambers to allow NTEP and OIML testing.

2.2 kN (505 lbf) deadweight machine

Air-powered cylinders manipulate lifting bars that allow the individual deadweights to be applied or removed from the main shaft of the machine at any time during the measurement.

27 kN (6.1 klbf) deadweight machine

Hydraulic cylinders raise and lower deadweights individually onto the main shaft usually only while the machine is in the unloaded position. When the required deadweight complement is selected, the main shaft is positioned to allow force application to the unit under test. Limited ascending and descending loading is possible in this machine under special circumstances. A unique feature of this deadweight machine is that nominal metric forces can be applied by activating an auxiliary deadweight set. This deadweight machine is operated manually.

113 kN (25.3 klbf) deadweight machine

The deadweight positioning system consists of a pair of hydraulic cylinders for each deadweight. These cylinders allow application or removal of every deadweight to the main shaft at any time. A manually placed set of auxiliary metric conversion deadweights is available for this machine which produces nominal forces in 4.903 kN increments up to 107.873 kN. These conversion deadweights are used only in non automated measurements.

498 kN (112 klbf) deadweight machine

Calibration forces are generated in this machine by serially applying deadweights from two different stacks. The minimum force is 13.3 kN (3000 lbf) which consists of the calibrated frame and main shaft of the machine and is always included as the first applied force. All other applied forces must be added to this minimum. The main stack consists of ten 44.4 kN (10,000 lbf) deadweights. The second stack consists of nine 4.44 kN (1,000 lbf) deadweights. The deadweights are removed or added to the minimum 13.3 kN (3,000 lbf) frame in increments of 4.44 kN (1000 lbf). An examination of the available deadweight combinations reveals that in some cases it is necessary to unload part of the small stack in order to reach a particular ascending force without first overshooting it.

1.33 MN (300,000 lbf) deadweight machine

All deadweights in this machine are applied sequentially with no further individual manipulation possible. The deadweights are of three different sizes. There are thirteen 44 kN (10 klbf) deadweights, four 89 kN (20 klbf) deadweights and three 133 kN (30 klbf) deadweights. This arrangement allows the sequential calibration in ten equally spaced increments of nominal 444 kN (100 klbf), 890 kN (200 klbf), and 1.33 MN (300 klbf) force transducers.

4.45 MN (1,000,000 lbf) deadweight machine

This deadweight machine simply applies twenty 222 kN (50,000lbf) forces sequentially. The main lifting frame raises hydraulically to pick up additional deadweights in the stack. This machine has been fully automated.

3. Instrumentation

3.1. Deadweight Machine Control Instrumentation

Except for the 27 kN deadweight machine, all the NIST deadweight machines have been instrumented for automated control. With the exception of the mounting and positioning of the force sensor into the deadweight machine, all machine operations can be done under computer control. Details of the automation have been described in reference 7.

A force measurement system has two components: a sensing component, normally called a transducer, and an indicating component, called an indicator. For example, if the transducer is a conventional proving ring, the response of the transducer, that is the change in diameter as the ring distorts under an applied force, is indicated by a vibrating reed and a spherical button mounted on the end of a micrometer. For conventional load cells, the change in strain at one or more points along the surface of the sensing element is indicated by a change in the output signal relative to the voltage applied to the load cell bridge. Only the reading of load cell indicators has been automated. Accordingly, measurements on proving rings are performed manually while measurements of most load cells are performed automatically.

The benefits to be derived from the automation implemented in the force group are numerous. They include the ability to perform measurements with complex loading sequences, precise control of the loading time intervals, and more consistent indicator readings. In addition, in contrast to calibrations, the NTEP and OIML type evaluation tests require positioning of the load cell in the deadweight machine only once, at the beginning of a test. The associated equipment required for these tests have also been automated. Thus, the thermal bath units used to heat and cool the environmental chambers and the sensors used to monitor conditions, including the temperature of the load cell, are also under computer control. Thus, the tests, which typically take several days, can be conducted around the clock without any manual intervention.

3.2. Voltage Ratio Instrumentation

The force applied to a load cell produces a change in the resistive unbalance in the load cell strain gage bridge. For most load cell measurements performed at NIST, this resistive bridge unbalance is measured with a calibrated NIST voltage-ratio indicating system.

The NIST indicating system supplies direct current excitation to the load cell, through the use of a specially built power supply which applies DC voltages to the load cell excitation input leads of ±5 V relative to the load cell ground wire, yielding 10 V difference between the leads. This excitation voltage is stable to within ± 5 μV over a time period of 15 s. This power supply was designed to switch internally the wires going to the load cell terminals by means of a computer command, thus reversing the polarity of the excitation signal to the load cell. This action makes it possible to cancel out small thermal biases in the strain gage bridge and connecting wires, as well as any zero offsets in the rest of the indicating system. The switching is not done if the load cell is not designed to accommodate reversed polarity excitation.

The excitation voltage and the load cell output voltage are sampled simultaneously by an 8½ digit computing voltmeter operating in voltage-ratio mode; the voltmeter calculates the corresponding voltage ratio internally and returns that value in digital form to the computer. The voltmeter is read twice, with the excitation voltage polarity reversed between readings; the final voltage ratio is taken as the average of the voltage ratios measured at each polarity. The sampling time at each polarity, and the delay after switching polarity before resuming the sampling, are specified by the operator through the computer control/acquisition program. A typical time for one complete voltage ratio reading is 10 s. This time can be shortened or lengthened as appropriate for the measurement being conducted.

Calibration of the voltmeters in voltage-ratio mode is done by providing calibrated DC voltage signals simultaneously to both inputs, with the DC calibrated signals derived from a 10 V Josephson-Junction reference voltage array maintained by the Electricity Division of the NIST Electronics and Electricity Engineering Laboratory. The NIST Electricity Division calibrates the Force Group voltmeters each year. The Force Group maintains the calibration of all of its voltmeters by monthly comparison with the voltmeters most recently calibrated by the Electricity Division, through the use of two devices: a precision voltage reference divider having a 100:1 ratio and a load cell simulator that is stable to within ± 5 nV/V over a 24-hour time interval.

4. Measurement Uncertainty

4.1 Uncertainty in the Applied Force

In 1965 when the NIST deadweight machines were designed and built, a decision was made to adjust the deadweights to exert standard pounds force, the standard pound force being defined as the force acting on a one-pound mass under the influence of a gravity field of 9.80665 m/s^2. Deadweights were adjusted for the local values of the gravitational acceleration and air density at the NIST Gaithersburg site to generate a standard pound force given by:

$$F = \frac{m \cdot g}{9.80665}(1 - \frac{\rho_a}{\rho_w}) \ , \tag{1}$$

where F is the generated standard pound force, m is the mass of the weight, g is the local acceleration due to gravity at the elevation of the center of gravity of the weight, ρ_a is the air density, and ρ_w is the density of the weight. The uncertainties in the determination of m, ρ_a, and g are the principal sources of uncertainty in the applied force.

The mass of the deadweights of the NIST machines were determined by the NIST Mass Group. These calibrations were performed in 1965 prior to the assembly of the deadweights into the machines. Over the years, some of the deadweights were re-calibrated. The 498 kN deadweight machine was partially disassembled in 1971 and 1989, with some of its deadweights removed and re-calibrated each time. The 2.2 kN machine was completely refurbished in 1996, and all of its deadweights were re-calibrated at that time. No significant changes in the mass of the deadweights were detectable in either machine, confirming the long-term stability of the stainless steel alloys used in the construction of both the smaller and larger NIST deadweight machines.

For each of the larger machines, the values of gravity were estimated at the approximate center of gravity of the major components and at the center of gravity of the deadweight stacks. The gravity reference is located on the concrete slab of the first floor of the building where the deadweight machines are located. The assigned absolute value of free-fall acceleration of gravity at this location is 9.801018 m/s^2, and is based upon an absolute determination conducted by Tate[10] in 1965. All other gravity values were based upon a gravity gradient of $-0.000003/s^2$. A subsequent gravity survey at several positions within the force laboratory done by the Office of Ocean and Earth Sciences of the National Oceanic and Atmospheric Administration in September 1991 confirmed the results obtained in 1965.

The air density at the Gaithersburg site varies over a range of 1.145 kg/m^3 to 1.226 kg/m^3 throughout the year. In 1965, when the facility was built a decision was made to use an average value of air density equal to 1.185 kg/ m$^{3.}$

The standard uncertainty in the force applied by the NIST deadweight machines incorporates the uncertainties associated with the determination of the mass of the deadweights, the acceleration due to gravity and the air density as follows:

(a) The uncertainty in the determination of the mass of the deadweights is $u_{wa} \leq 0.0003$ %.

(b) The maximum error caused by the use of an average air density is the largest systematic error in the applied force and is equal to 0.0005 %. The estimated standard deviation, assuming a rectangular probability distribution[9], is $u_{wb} \approx 0.0003$ %.

(c) The estimated standard deviation associated with the variation in gravitational acceleration with height, assuming a rectangular probability distribution, is $u_{wc} \approx 0.0001$ %.

The standard uncertainty in the applied force is computed as:

$$u_w = \sqrt{u_{wa}^2 + u_{wb}^2 + u_{wc}^2} \ . \tag{2}$$

Using the values listed in (a), (b) and (c) above yields a standard uncertainty in the applied force $u_w \approx 0.0005$ %.

4.2 Uncertainty in Voltage Ratio Measurement

The standard uncertainty associated with the digital voltmeters used by the NIST Force Group for voltage-ratio measurement incorporates the following:

(a) the uncertainty in calibration of the voltage-ratio of the voltmeters as determined by the NIST Electricity Division using a Josephson-Junction voltage array as a primary standard; the standard uncertainty in the voltage ratio over the range from 1 mV/V to 10 mV/V is $u_{va} \leq 0.0002$ %.

(b) differences between voltmeter calibrations performed by the NIST Electricity Division and comparisons to a 10 mV/V reference ratio obtained with a precision reference divider used by the Force Group to track the voltmeter drift. The estimated standard deviation of these differences assuming a rectangular probability distribution is $u_{vb} \approx 0.0003$ %.

(c) the repeatability in measurements for each voltmeter (made at one-month intervals) of the 10 mV/V response relative to the precision reference divider; the standard deviation for an individual voltmeter is $u_{vc} = 0.0003$ % of the reference ratio.

(d) the nonlinearity in the voltage-ratio measurement response of the voltmeters in the range of 1 mV/V to 10 mV/V; the estimated standard deviation based on Electricity Division data assuming a rectangular probability distribution is $u_{vd} \approx 0.0001$ % of the reference ratio.

The standard uncertainty in the voltage-ratio instrument is given by:

$$u_v = \sqrt{{u_{va}}^2 + {u_{vb}}^2 + {u_{vc}}^2 + {u_{vd}}^2} \quad . \tag{3}$$

Applying the values given above yields a standard uncertainty for the voltage ratio $u_v \approx 0.0005$ %.

4. 3 Uncertainty in the Calibration Data

The calibration data acquired for a force sensor consists of the values of the forces applied to the sensor and the associated readings of the indicating system. These data usually incorporate two or three orientations of the sensor in the deadweight machine. To obtain the actual deflection, the indicator reading observed during the force application is corrected for the reading observed without any force application. The calibration equation is derived by fitting a polynomial to the data using the method of least squares. The calibration curve is of the from:

$$D = A_0 + \sum A_i F^i \ , \tag{4}$$

where D is the deflection, F is the applied force, A_i are the coefficients yielded by the least-squares fit, and the summation is generally carried to an order of 2 or 3.

ASTM E 74 -95 standard specifies a standard deviation that is calculated from the differences between the values observed during the course of calibration and the corresponding values computed from the calibration curve. This standard deviation is given by:

$$s = \sqrt{\frac{\sum {d_j}^2}{(n-m)}} \ , \tag{5}$$

where s is the standard deviation, the d_j are the differences between the measured and calculated deflections, n is the number of measured deflections, and m is the number of degrees of freedom in the polynomial, the degree of the polynomial plus one. This standard deviation is one of the terms used in estimating the combined uncertainty as reported in the NIST calibration reports where it is denoted as u_r.

The errors contained in u_r are ordinarily much greater than the uncertainty in the applied load [6]. The two major sources of systematic errors are mechanical misalignment and load-time effects. In addition, the response of the transducer is also dependent upon the loading sequence, the loading rate, the duration and stability of the load. A detailed statistical analysis that yields separate estimates of uncertainty resulting from various sources of error can be found in reference[8].

The combined standard uncertainty stated in NIST force calibration reports is computed using the following equation:

$$u_c = \sqrt{u_w{}^2 + u_v{}^2 + u_r{}^2}\,, \tag{6}$$

where u_c is the combined standard uncertainty as defined in NIST Technical Note 1297[9], u_w is the standard uncertainty in the applied deadweight forces (discussed in section 4.1), and u_v is the standard uncertainty in the calibration of the voltage-ratio measurement instrumentation (discussed in section 4.2), and u_r is the standard deviation calculated accordingly to ASTM E 74-95. It should be noted that the term u_v applies only in calibrations involving voltage ratio measurements performed using the NIST voltmeters.

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