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FORCE METROLOGY AT NIST

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Abstract: This paper describes the measurement services, the instrumentation and procedures available for force metrology at the National Institute of Standards and Technology, USA. The uncertainty in the forces realized over a range of 44 N to 53 MN is reviewed. The maintenance and the uncertainty of the voltage ratio indicating system for strain gage load cells are discussed.
Keywords: force measurements, uncertainty, deadweight machines

1 INTRODUCTION

The NIST force group provides compression and tension force calibrations by application of deadweight standards over a range of 44 N to 4.448 MN. To cover this wide range, NIST maintains six deadweight machines described in Table 1.

Table 1. NIST deadweight machines characteristics

Capacity, kN	***2.2***	***27***	***113***	***498***	***1334***	***4448***
Min. Load, kN	0.044	0.44	0.89	13	44	222
Min Load Increment, kN	0.022	0.22	0.44	4.4	44	222
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
Deadweight Alloy (AISI Series)	302	302	302	410	410	410
Deadweight Density at 20 °C, kg/m^3	7890	7890	7890	7720	7720	7720

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 traceability of the primary force standards at NIST to the fundamental SI units is shown in Figure 1.

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. Further, except for the 27 kN and the 4.448 MN machines, all are equipped with environmental chambers to allow for the characterization of load cells linearity, repeatability, hysteresis and creep over a temperature range of -10 °C to 40 °C in accordance with legal metrology requirements [1,2].

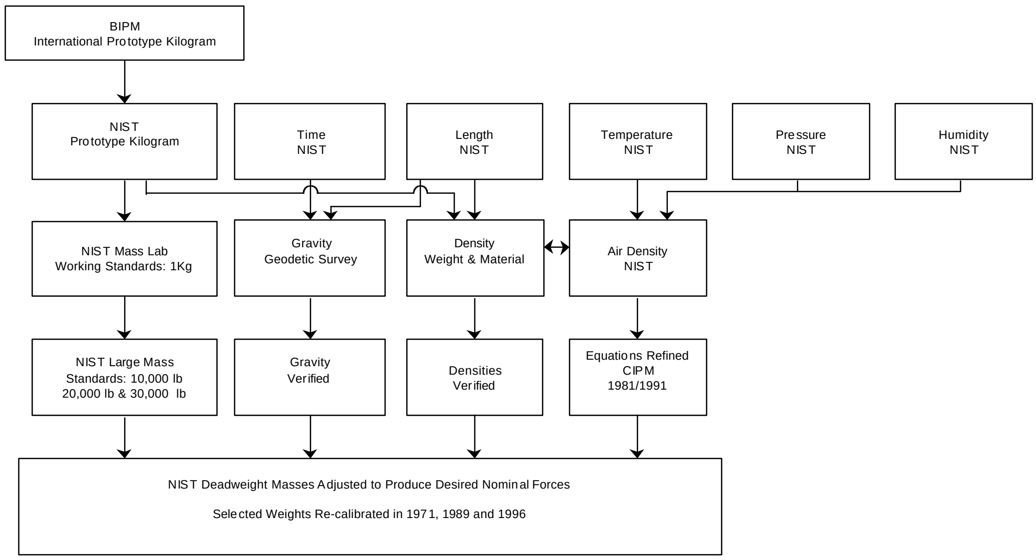

Figure 1. Traceability of NIST primary force standards to fundamental units.

In addition to the deadweight machines, NIST maintains a hydraulic testing machine capable of generating forces up to 53 MN for compression calibrations of large force transducers through comparison with secondary force transfer standards maintained by the force group.

2 INSTRUMENTATION

2.1 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 [3]. A force measurement system has two components: a sensing component, normally called a transducer, and an indicating component, called an indicator. For a conventional proving ring, these components are integrated into a single mechanical device, with the response of the transducer 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. 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, type evaluation tests performed in conjunction with legal metrology requirements [1,2] are conducted with the load cell in the deadweight machine positioned only once, at the beginning of a test. The associated equipment required for legal metrology 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. Accordingly, the tests, which typically take several days, can be conducted around the clock without any manual intervention.

2.2 Voltage Ratio Instrumentation

The force applied to a load cell produces a change in the resistive unbalance in the load cell strain gauge 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 mV 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 8 1/2 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 several times, 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. This is accomplished using one 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.

2.3 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 forces, 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:

$$F = \frac{m.g}{9.80665}\left(1 - \frac{r_a}{r_w}\right) \tag{1}$$

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, r_a is the air density, and r_w is the density of the weight. The uncertainties in the determination of m, r_a and g are the principal sources of uncertainty in the applied force.

The mass of each deadweight was 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 $\pm$ 5 x 10^{-6} m/s^2, and is based upon an absolute determination conducted by Tate in 1965 [4]. All other gravity values were based upon a gravity gradient of –0.000003 m/s^2 per meter elevation. Subsequent gravity surveys at several positions within the force laboratory done by the National Oceanic and Atmospheric Administration 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 yearly 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, $m_{wa} < 0.0003$ %.
(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, is $m_{wb} \approx 0.0003$ %.
(c) The estimated standard deviation associated with the variation in gravitational acceleration with height $m_{wc} \leq 0.0001$ %.

The combined standard uncertainty in the force realized by deadweight application is computed as:

$$m_w = \sqrt{m_{wa}^{\ 2} + m_{wb}^{\ 2} + m_{wc}^{\ 2}} \qquad (2)$$

The combined standard uncertainty in the forces realized at NIST is shown in Figure 2. Observation of Figure 2 shows that over the entire range of 44 N to 4.448 MN the standard uncertainty is 0.0005 %. Above 4.448 MN, NIST provides compression calibrations up to 53 MN by comparison with NIST transfer standard strain gage load cells using a 53 MN capacity universal testing machine. For this purpose NIST maintains a set of three 4.448 MN NIST transfer standards each calibrated in the 4.448 MN deadweight machine, and a set of four 13 MN transfer standards each calibrated by comparison with three 13 MN transfer standards.

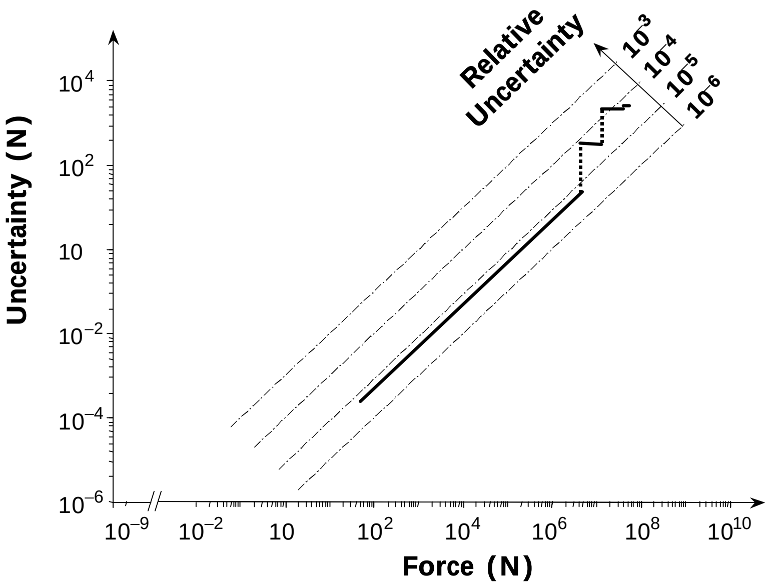

Figure 2. Standard uncertainty in forces realized at NIST.

In the range of 4.5 MN to 13 MN three 4.448 MN transfer standards loaded in parallel are used as shown in Figure 3. The resulting standard uncertainty, computed by combining in quadrature the estimated uncertainties contributed by each of the three transfer standards, is estimated at 1.7 kN, constant over the interval. Thus the relative uncertainty ranges from 0.038 % at 4.5 MN to 0.013 % at 13 MN. From 13 MN to 40 MN three 13 MN transfer standards are used. The resulting standard uncertainty is estimated at 5 kN, constant over the interval. Thus, the relative uncertainty ranges form 0.038 % at 13 MN to 0.013 % at 40 MN. From 40 MN to 53 MN four 13 MN transfer standards are used resulting in an estimated standard uncertainty of 5.9 kN. Thus the relative uncertainty ranges from 0.015 % at 40 MN to 0.011 % at 53 MN.

Figure 3. Setup for a 13 MN calibration.

4 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 $m_{va} \leq 0.0002$ %.

(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 is $m_{vb} \approx 0.0003$ %.

(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 $m_{vc} = 0.0003$ % 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 is $m_{vd} \approx 0.0001$ % of the reference ratio.

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

$$m_v = \sqrt{m_{va}{}^2 + m_{vb}{}^2 + m_{vc}{}^2 + m_{vd}{}^2} \qquad (3)$$

Applying the values given above yields a standard uncertainty for the voltage ratio of about 0.0005 %.

5 FUTURE EFFORTS AT NIST

Two main efforts are emerging within NIST in the area of force metrology. They include:

(a) The development of a research laboratory appropriate for the realization, measurement, and repeatable dissemination of very small forces to address the emergent force metrology needs of a growing class of nanotechnologies, including the atomic force microscopes, nanoindentors, and micro-electromechanical systems (MEMS) that operate in force regions between nanonewtons and millinewtons.
(b) The development of a testing facility to assess the susceptibility of digital load cells to electromagnetic radiation.

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