

Basic Procedures in Force Calibration at NIST

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Abstract

Force calibrations available at the National Institute of Standards and Technology (NIST) continue to focus on achieving the maximum performance from the primary force standard deadweight machines (DWM's), the voltage-ratio electrical readout systems and the environmental factors pertinent to each series of measurements. Basic procedures to be reviewed date from the original series of National Bureau of Standards (NBS) Circulars to current methods of force transducer characterization. Those to be discussed include: accurate alignment of axis of transducer under test, periodic intercomparisons between deadweight machines, voltage-ratio measurement traceability, temperature equilibration, and thorough communications with customers. Much effort still is directed at minimizing force-machine to transducer interaction to isolate the true performance of the device under calibration.

1. Introduction

The provision, measurement and the dissemination of standards through calibrations has been a central mission of the National Institute of Standards and Technology (NIST) since creation of the agency originally as the National Bureau of Standards (NBS). Early research produced new methods of realizing basic standards and their derivatives. An ever-increasing industrial base demanded that measurement standards leave the confines of the laboratory and join with field standards to form a truly unified national measurement system available to all interested parties. It became evident that dissemination of measurement units was best accomplished through calibration services housed in a common facility, hence, the laboratories that comprised NBS.¹ To meet this need, we have developed basic procedures to assure consistent high quality measurements being delivered to our customers. This paper gives a brief history of the establishment of the NIST force calibration laboratories and their capabilities in Section Two. The next five sections describe consecutively the five basic procedural areas we

currently use in our laboratory: (1) accurate alignment of axis of transducer under test to axis of DWM and parallel to gravitational vector; (2) periodic intercomparison measurements between all DWM's; (3) establishment of traceability of the voltage-ratio measurement instruments; (4) careful equilibration of transducer temperature; and (5) thorough communications with customers to determine procedures for transducer calibrations.

2. Background

Evolution of the modern Force Calibration Laboratories of the Mass and Force Group at NIST somewhat parallels that of other NBS labs. The organic Congressional act that created NBS in 1901 specifically charged the new agency with:

“...custody of the standards; the comparison of the standards...with the standards adopted or recognized by the Government; the construction, when necessary, of the standards...the testing and calibration of standard measuring apparatus; the solution of problems which arise in connection with standards; the determination of physical constants and the properties of materials...the bureau shall exercise its functions for the Government of the United States...or for any scientific society, educational institution, firm, corporation, or individual within the United States engaged in manufacturing or other pursuits requiring the use of standards or standard measuring instruments...”²

The act provided the structure to initiate mechanics and materials' standards research at the new facility. Materials' testing based upon NIST (NBS) measurements was and still remains a vital industrial activity much in demand by manufacturers and others. Accurate force measurements became the goal of NBS researchers due to numerous inconsistencies between stated strengths of materials and actual performances in finished structures. Some of the discrepancies resulted in structural failure and loss of life.³ At the very least, efficient engineering designs were impossible to build without accurate material strength data. Consistent delivery of measurement capability to point-of-test locations would be the means of calibrating the numerous materials testing machines already in wide use. Existing force calibration transfer standards such as field weights*, elastic transducers or weights and levers were inadequate for meeting industrial demands of the early 1900's. It was impractical or impossible to carry more than a few thousand kilograms of mass standard into a laboratory, therefore, the 44.5 MN NBS testing machine was initially calibrated by direct reference to the modulus of elasticity of steel columns themselves undergoing materials' testing in the machine. The error was judged to be “well within 1 per cent”.⁴ This lack of precision launched a research process aimed at developing a suitable portable instrument that could be used to calibrate distant equipment. H.L. Whittemore and S.N. Petrenko from the NBS Engineering Mechanics Section filed a patent in September of 1926 for such an instrument.

*Weight is used only to refer to an object. It has a mass in kilograms, which for a given local acceleration of gravity and relative densities of air and object material, produces a force in newtons.

The Proving Ring was to be used to “prove”, or check, various types of materials testing machines, notably the Brinell Hardness Tester and commercial tensile testers.^{5,6}

Following the invention of the proving ring, a large deadweight force machine of 445 kN was designed and built to generate accurate forces which could then be transferred to testing machines via calibration. The ring calibrated by deadweights proved to be an immediate success and rapidly supplanted the other methods of transferring force measurements. As early as 1928, Bureau of Standards (BS) Letter Circular No. 250 provided details on the preferred design and use of the proving ring.⁷ More papers followed while NBS gained experience with this new technology. The efforts culminated with publishing of the definitive NBS Circular C454, *Proving Rings for Calibrating Testing Machines*.⁸ This document remained in use for many years and later became the basis for some of the information found in ASTM E74, *Standard Practice of Calibration of Force-Measuring Instruments for Verifying the Force Indication of Testing Machines*.⁹

During the 1940’s, several industrial researchers developed electrical resistance, strain-gage based “load cells”. NBS began exploring this new application as a means of pushing the transfer of force into the higher ranges. By the early 1950’s, NBS 4.45 MN and 13 MN load cells were in use as standards for large forces.¹⁰ High-capacity load cells allowed calibration of large testing machines and other large force transducers by the build-up comparison method described later. Documentary standards kept pace with hardware development via the wide acceptance of ASTM E74¹¹ to which most US force laboratories conform, including NIST. A new bureau site roughly 20 miles from downtown Washington D.C. was chosen with facilities designed, built and occupied in early 1960’s.

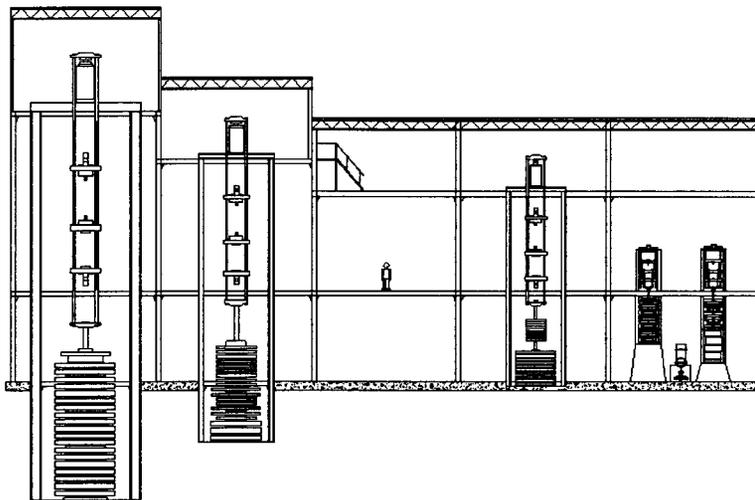


Figure 1. Engineering Mechanics Building cross-section depicting relative sizes of the six NIST Force Deadweight Machines (DWM). Left to right: 4.45 MN, 1.33 MN, 498 kN, 27 kN, 2.2 kN and 113 kN.

Figure one provides a schematic of the facility. Forces are generated by suspending precisely calibrated stainless steel masses in the gravity field and applying a correction for effects of air buoyancy. The uncertainties in the determination of the mass of the deadweights, the variation in the buoyant force of air and, the variation in the gravitational acceleration at NIST are combined by the RSS (root-sum-of-squares) method. This approach yields a combined standard uncertainty of 0.0005% of the applied force for any weight combination.^{12,13} Design and operation descriptions of the deadweight machines (DWM's) are well-documented elsewhere.^{12,13}

Obtaining maximum performance from the six deadweight machines begins with designs optimized to allow great flexibility in fixturing or mounting of the transducers under test. For example, the large compression platens with ample clear working space have allowed the installation of environmental chambers as part of the legal metrology testing program; and, the clear space available in tension allows additional necessary fixtures to be installed in series with the transducer, thus mirroring the conditions that the system may see when in actual use away from NIST.

The decision was made to fabricate nearly all force generating components out of stainless steel to avoid instability problems associated with cast iron and nonstainless alloys, such as corrosion. Subsequent mass recalibrations of selected deadweights have proved the validity of the material choice and machine design. Any changes have been within the uncertainty of the mass determination process.¹³

3. Accurate Alignment of Axis of Transducer Under Test to Vertical Axis of DWM

Accurate alignment of the vertical axis of the transducer under test to the vertical axis of the DWM is the necessary final step before applying calibration forces to the transducer. In addition, the vertical axes of the machine-transducer combination and the DWM itself must be parallel with the gravitational vector. Experience gained since the installation of the first DWM at NBS in 1927 was influential in determining the present designs. Axial alignment of transducer to machine and machine symmetry about the vertical axis was built in as much as possible to minimize eccentric force application to the transducer undergoing calibration. When loaded, the design of a NIST DWM allows a free rotation on a pivot at the top of the calibrated frame in order to effect vertical axial alignment of the working masses to the vertical gravitational vector. The center of gravity of the weight stack is well below the transducer mounting position where force application occurs, thus assuring that the DWM alignment coincides with the gravity vector. Further, on the three largest machines, another pivot point is located at the top of the lifting frame allowing the force generating masses to align themselves with gravity within a lifting frame which is itself aligning to the same vector.

Tension calibrations are performed by coupling the transducer to threaded fittings that are permanently mounted axially in the machines and in series with the calibrated masses. The threaded fittings are free to pivot on spherical shoulders at the machine interface. As the calibration begins, the transducer axis is aligned automatically with the vertical force vector generated by the suspended deadweights and is thus subjected to an axial application of the

desired forces. Compression transducers are placed on a hardened bearing surface on the compression platen and aligned manually with the vertical centerline of the calibrated force-generating head. Forces applied to the top of the transducer must pass through a spherical surface that is either integral to the device or removable. The spherical contact point is designed to optimize axial alignment of the force vector to the transducer.

4. Periodic Intercomparisons Between All Deadweight Machines

Generation of precise forces is monitored within the force laboratory by periodic intercomparisons between all DWM's. This is accomplished via comparison of readings taken from several machines with the same force transducer. Values obtained from one DWM are compared to values obtained at a similar force point in the next DWM within the bounds of the transducer expanded uncertainty interval. Three load cells with capacities of 44 kN, 222 kN and 445 kN are used for these measurements. Data is obtained from at least three DWM's with overlapping capacities with one transducer over a short time span to minimize possible effects of long-term drift in the transducer. The smallest four machines are measured by the smallest transducer; machines two, three, four and five are measured by the 222 kN transducer; and finally, machines four, five and six are measured by the 445 kN load cell. This procedure generates a snapshot of transducer response to applied force between overlapping DWM's within the limitations of transducer uncertainty. Further, the overlap serves to tie all DWM's to those receiving a recent mass calibration.¹³

5. Regular Establishment of Traceability of Digital Voltmeters

Regular establishment of traceability to NIST voltage standards of the digital voltmeters (DVM's) used to measure load cell sensitivity has been implemented by Bartel.^{12,13} Similar to the DWM intercomparisons described earlier, the high-end DVM's that comprise the measurement readout systems are compared on a regular basis with a DVM recently calibrated by the NIST Electricity Division. The comparison is made through a stable passive resistance bridge network. If necessary, a DVM calibration factor is adjusted based upon the comparison results. This practice maintains a reliable measurement trace to the NIST voltage standard.

Electrical strain gage force transducers with dc excitation voltage may be calibrated in a fully automated mode. The change in resistive unbalance in the strain gage bridge, as a function of applied force, is measured as the ratio of the dc output voltage to the input voltage (mV/V). This capability allows the load cell only to be shipped to NIST for force calibration. An automation effort engineered and implemented by Yee and others has allowed complex data logging, precise machine control and long-term unattended testing.¹⁴ In times of heavy calibration volume, this arrangement allows one staff member to perhaps monitor several work stations concurrently. During certain prototype load cell environmental testing procedures the automated systems allow long-term, 24 h a day, runtime of the equipment. Automation also reduces operator fatigue and other human errors. Prior to the start of transducer calibration, customer consultation establishes the exact method of excitation, sensing and wiring to be used. Potential errors due to lead wire resistance, voltage magnitude or waveform and location of voltage sensing are thus avoided.

Calibration data is logged automatically for devices read with the NIST voltage-ratio systems; manual entry is used for data gathered by other readouts. This may include load cell systems mated to an indicator, proving rings or other elastic devices. Data analysis, uncertainty calculations and report generation are automated by the use of custom software developed by the force laboratory. Customer instructions generally dictate the actual calibration procedure and format of reported data. In nearly all cases, the data analysis is that prescribed in ASTM Standard Practice E74.

6. Careful Equilibration and Monitoring of Test Load Cell Temperature

Every NIST force calibration report lists the temperature at which the calibration was performed. Normally, all force transducers require that temperature be uniform throughout with minimal gradient present. In the laboratories that house the six DWM's, care is taken to maintain stable temperature conditions throughout the day. Normal laboratory operating temperature is $23\text{ }^{\circ}\text{C} \pm 0.3\text{ }^{\circ}\text{C}$.¹⁵ The heating/ventilation/air conditioning (HVAC) system has a high rate of air exchange with vents positioned so as to avoid direct drafts on any force transducers mounted in the DWM's. Further, the compression and tension platens and the calibrated heads on the three larger machines are physically massive containing thousands of kilograms of steel that is maintained at the same temperature as the labs. This thermal inertia allows very uniform and stable temperature conditions at the machine heads. Typically, a transducer is placed in the laboratory at least 24 h prior to the start of the calibration, thus permitting ample time for the device to achieve a stable internal temperature. An unusually large transducer or one that has been maintained at an unusually high or low temperature may be given additional time to achieve internal stability. Surface temperature monitoring probes may be applied to provide assurance that proper conditions have been met.

7. Thorough Customer Communications to Determine Procedures for Transducer Calibrations

Transducer calibration procedures are varied and ultimately dependent upon the requirements of the end user. ASTM E74 meets the needs of many users and is widely requested as a specification to be followed explicitly. Other users, perhaps, may determine that customized or modified instructions are to be followed. Thorough communication with the force calibration customer is essential in order to complete the calibration satisfactorily.

End-loading conditions can often affect the performance of a transducer adversely; therefore, detailed instructions regarding system setup are commonly obtained prior to the calibration. For example: in compression, a hardened-top-bearing-block, or a steel ball, may yield a more axial force application than is found by applying forces through a softer, cold-rolled steel block; in tension, certain end fixtures to the transducers, such as flexures, may be specified. Generally, any such addition is made only upon the advice and consent of the customer. Eccentric or off-axis loading has long been recognized as a technical hurdle to obtaining accurate force calibrations and subsequent end use measurements.⁸ Early transducer specifications included advice on quantifying reaction to poor axial conditions. Various studies have been performed by Mitchell and others in an attempt to further quantify and

correct for this anomaly.¹⁶ Fortunately, as described earlier, the designs of the NIST DWM's are inherently conducive to axial transducer alignment. In addition, most calibration procedures specify a rotation of the transducer between runs in order to minimize the potential bias that would be induced by sampling output from one position only. Upon recognizing calibration data displaying severe rotational bias, it is customary to perform a rotation test. Capacity transducer output is logged at numerous rotational positions and plotted versus the calibration data to aid in characterizing the nature of the bias.

Daily technical calibration issues demand a staff willing to attend to exacting details and ascertain the needs of the customer. Experience derived by completing countless calibrations is combined with the proper training and education to produce a staff member able to perform at a sustained high level in the laboratory. NIST force staff is small in number allowing frequent interaction, which promotes problem solving, encourages freethinking and instills a common sense of duty to organizational mission.

8. Other Areas

Compression calibrations above the capacity of the largest DWM, that is, from 4.45 MN to 53 MN, are performed via comparison or build-up method. Three specially designed 4.45 MN load cell standards are calibrated in the NIST deadweight machine and then arranged in parallel to calibrate each of the four 13 MN load cell standards that are stacked in series with the parallel arrangement. The NIST 53 MN universal testing machine¹ applies force to the stack while the calibrated standard cells measure it. The force unit is thus transferred from the largest NIST DWM to the end-use force standard under laboratory conditions. Calibration or verification of the universal testing machine usually occurs simultaneously as a side benefit to the large force measurement.

Environmental testing of transducers can be performed in a variety of dedicated temperature chambers. Under some circumstances, the laboratory temperature itself may be varied over a limited range. In either case, deadweight forces are applied as prescribed by testing requirements or customer directives. Pressure and humidity test chambers are also available. Usually, environmental testing is required as part of the certification process for transducers to be used in legal or trade applications.¹³

9. Summary

NIST Force Calibration and Services described have evolved as necessary to meet changing national requirements and directives. The current facility and institutional heritage have been built upon years of research and untold thousands of calibrations for customers. Equipment and capabilities, particularly in the large forces, are still unique in the world.

References

1. NIST at 100, Foundations for Progress, NIST Spec. Pub. 956, U.S. Dept. of Commerce (2000) pp. 2-4, p. 30
2. Record of Fifty-Sixth Congress of the United States, U.S. Congress. Rec., Sess. II, Chap. 872 (1901) pp.1449-1450
3. Mosley, T.J. and Griffith, J.H., What Our Large Testing Machines Have Accomplished, Engineering News-Record, Vol. 78, No. 4 (1917) pp. 188-190
4. Griffith, J.H. and Bragg, J.G., Tests of Large Bridge Columns, Bureau of Standards Technologic Paper No. 101, U.S. Dept. of Commerce (1918)
5. Petrenko, S.N., Elastic Ring for Verification of Brinell Hardness Testing Machines, Transactions of the American Society For Steel Treating, Vol. IX (1926) pp. 420-429
6. Whittemore, H.L. and Petrenko, S.N., Proving Ring, U.S. Patent 1,648,375 (1926)
7. Specification for Proving Rings for Calibrating Testing Machines, BS Letter Circular No. 250, U.S. Dept. of Commerce (1928)
8. Wilson, B.L., Tate, D.R. and Borkowski, G., Proving Rings for Calibrating Testing Machines, NBS Circular No. C454, U.S. Dept. of Commerce (1946)
9. Marlowe, D.E., A Study of the National Force Measurement System, NBSIR No. 75-929, U.S. Dept. of Commerce (1975) pp. 5-7
10. Tate, D.R., Application of Resistance-Wire Strain Gages to High-Capacity Load-Calibrating Devices, NBS Circular No. 528, U.S. Dept. of Commerce (1951) pp. 121-130
11. Standard Practice of Calibration of Force-Measuring Instruments for Verifying the Force Indication of Testing Machines, ASTM E74-00, Annual Book of ASTM Standards, Vol. 3.01, American Society for Testing and Materials, Philadelphia, PA., (2001)
12. Bartel, T.W., Yaniv, S.L. and Seifarth, R.L., Force Measurement Services at NIST: Equipment, Procedures, and Uncertainty, NCSL Workshop & Symposium (1997) pp. 421-431
13. Jabbour, Z.J. and Yaniv, S.L., The Kilogram and Measurements of Mass and Force, NIST J. of R., Vol. 106, No. 1, U.S. Dept. of Commerce (2001) pp. 37-45
14. Yee, K.W., Automation of Strain-Gage Load-Cell Force Calibration, NISTIR No. 4823, U.S. Dept. of Commerce (1992)

15. NBS Technical News Bulletin Vol. 50, No. 11 (1966) p.218
16. Mitchell, R.A., Seifarth, R.L. and Reeve, C.P., Eccentric Load Sensitivity of Force Sensors, 11th Conf. Of IMEKO TC-3 on Measurement of Force and Mass, Netherlands (1986)