METROLOGY 101

Force Calibration Guidance for Beginners

Henry Zumbrun
Morehouse Instrument Company

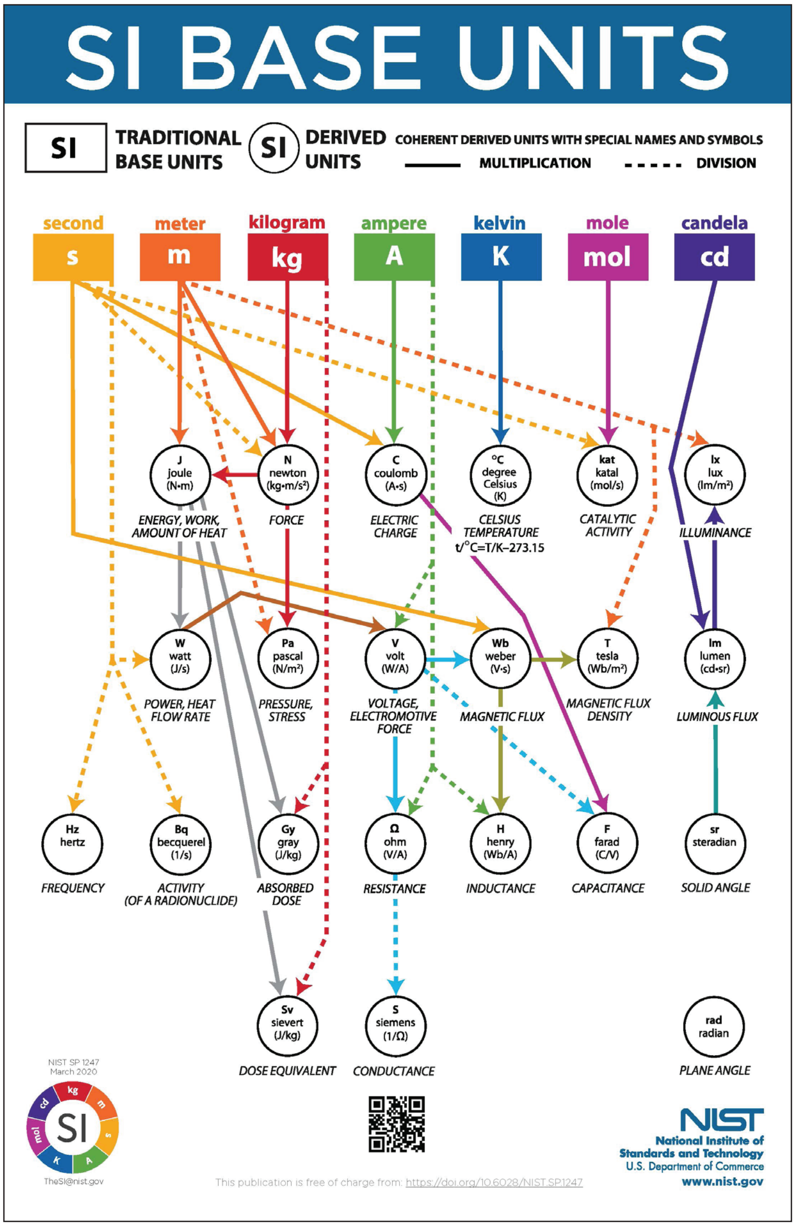

Figure 1. Relationship between SI base and derived units. Download free of charge from: https://doi.org/10.6028/NIST.SP.1247. Credit: NIST

Introduction

Morehouse Instrument Company has shared a tremendous amount of knowledge throughout the years with blogs, technical papers, and webinars. This education aligns with our purpose, to create a safer world by helping companies improve their force and torque measurements.

When someone is new to calibration or metrology, the information can be overwhelming. There is so much to digest that people can quickly become overwhelmed. Some have joked that an introduction to metrology is like trying to drink from a firehouse.

To simplify things, this two-part article was written to help anyone new to force. Even seasoned metrologists or technicians with years of experience may learn something new, or maybe this document can act as a refresher for those who are more advanced. In either case, the knowledge gained will ultimately help you become better.

Force Calibration and Its Importance

What is Force Calibration?

In his second law, Sir Isaac Newton stated that force controls motion; therefore, we must control the force if we are to control the motion. An example of force: I have an egg in my hand and want to break it by squeezing it in my hand. This egg will break at X known force. No matter where I am in the world, the same amount of force will be required to break the egg in my hand. It should not take less force to break this egg in Pennsylvania than in Peru.

A simple physics definition for force is mass times acceleration (F = m x a). As shown in Figure 1, force is a derived unit from the SI base units of Mass, Time, and Length. The International Committee for Weights and Measures in the Bureau International des Poids et Mesures (CIPM/BIPM) defines 1 N as the force required to accelerate 1 kg to 1 meter per second per second in a vacuum.

Calibration is the comparison of an unknown (typically referred to as the Unit Under Test or UUT) to a device known within a certain error (typically referred to as the Calibration Standard or Reference Standard) to characterize the unknown. Therefore, force calibration compares a force instrument to a force reference standard to characterize the instrument.

Why is Force Measurement Important?

The most straightforward answer is that bridges and other objects do not collapse when forces are exerted upon them. When building a bridge, it is essential to get the concrete strength measurement correct. It is essential to make sure the steel is tested, and the cables are appropriately checked for pre-stress or post-tension. When these measurements are not done correctly, bad things happen, as shown below.

Figure 2. Bridge Failure

In the example below, the ripeness of apples is being checked. Why may that be important? If you are in California and want to distribute apples across the country, the harder ones will last longer and ripen during shipment. In contrast, the softer ones might be distributed locally.

Figure 3. Testing Apple Ripeness. Photo provided by Tinius Olsen.

The next example shows fishing line being tested (Figure 4). I am sure any fisherman would not want the line to break as they haul in their prized fish.

In general, the measurement of force is performed so frequently that we tend to take it for granted. However, almost every material item is tested using some form of traceable force measurement.

Figure 4. Testing Fishing Line. Photo provided by Tinius Olsen.

Testing may vary from sample testing on manufactured lots and might include anything from the materials used to build your house to the cardboard on a toilet paper roll.

How a Transducer Measures Force

What is a Transducer?

In the broad sense of the term, a transducer is a device that turns one type of energy into another type. Some examples are:

1. A battery is a transducer that converts chemical energy into electrical energy. The chemical reactions involve electrons' flow from one material to another through an external circuit.
2. A thermometer is a transducer that converts heat energy into the mechanical displacement of a liquid column. As the temperature around the bulb heats up, the liquid expands and rises.
3. A load cell is a transducer that converts mechanical energy into electrical signals. As compressive or tensile force is exerted on a load cell, the mechanical energy is converted into equivalent electrical signals.

Figure 5. Load Cell

How a Load Cell Measures Compression and Tension Force

As force is exerted on a load cell, the material deflects. The deflection is typically measured by a strain gauge, which is placed on the material inside the load cell.

When placed appropriately, the strain gauge will measure the change in resistance as force is applied. The ideal load cell only measures force in defined directions and ignores force components in all other directions. Approaching the ideal involves optimizing many design choices, including the mechanical structure, the gage pattern, placement of the gages, and the number of gages.

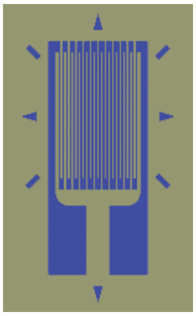

Figure 6. Strain Gauge

When a meter or indicator is hooked up to a load cell, it displays the force measurement value. A load cell may be calibrated at a company like Morehouse using deadweight primary standards known to be within 0.002 % of applied force. The machine's deadweights are adjusted for local gravity, air density, and material density to apply the force accurately. The weights are used to calibrate the load cell, which may be used to calibrate and verify a testing machine.

Compression and Tension Force Calibration

This section covers the terms compression and tension and how they relate to force calibration.

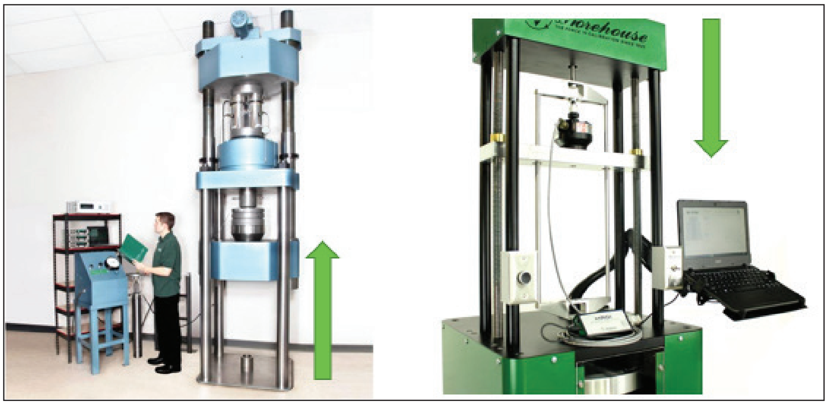

Figure 7. Compression calibration can be thought of as compressing or pushing.

What is a Compression Calibration?

When discussing compression calibration, we should think about something being compressed or something being squeezed. I like to describe compression calibration as pushing or squeezing something.

Figure 7 shows two examples of a compression setup in a calibrating machine. The machine on the left is compressing both load cells by creating an upward force. The picture on the right is a compression setup in the deadweight machine where a downward force compresses the load cell.

The key to this type of calibration is making sure everything is aligned and that the line of force is as straight as possible—I like to say free from eccentric or side forces. The key to proper alignment is using the right adapters in the calibrating machine, from alignment plugs to top adapters.

Morehouse has a technical paper on recommended compression and tension adapters for force calibration that can be found on our website[1].

What is a Tension Calibration?

When discussing tension calibration, we should think of something being stretched. I like to describe tension calibration as a pull.

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[1] https://mhforce.com/wp-content/uploads/2021/04/Recommended-Compression-and-Tension-Adapters-for-Force-Calibration.pdf

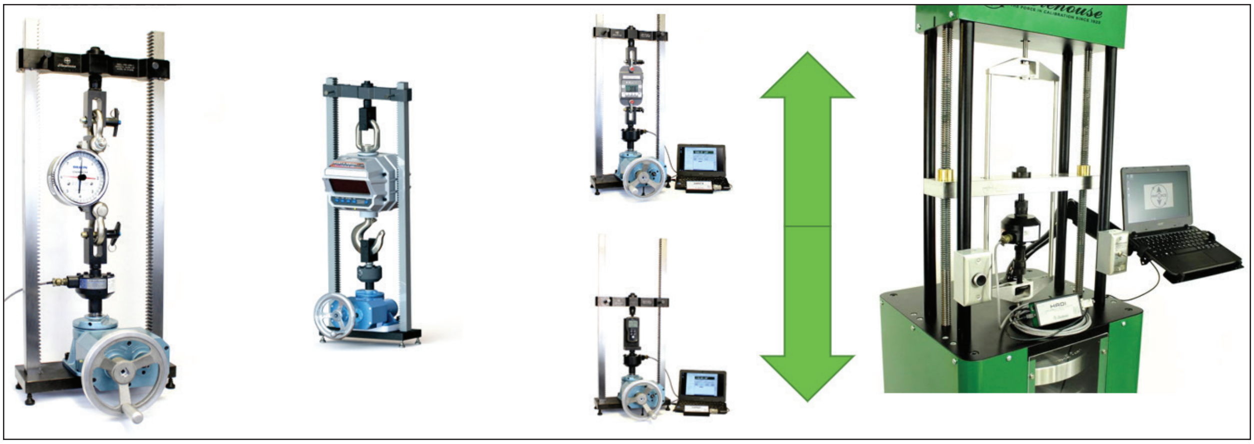

Figure 8. Tension Calibration can be thought of as pulling or stretching the material.

Above are multiple examples of tension setups in calibrating machines. The machine on the left is a benchtop calibrating machine. A dynamometer is fixed to a stationary beam, and force is generated by pulling on the load cell and the dynamometer. More examples are shown with different instruments, from crane scales to hand-held force gauges. The picture on the right shows a load cell fixtured for tension calibration in a deadweight machine. The load cell is fixtured to the frame, and the weights are applied and hung, which stretches the material. The key to getting great results in tension calibration is also adapters.

The ISO 376 Annex gives excellent guidance on adapters that help keep the line of force pure. It states, "Loading fittings should be designed in such a way that the line of force application is not distorted. As a rule, tensile force transducers should be fitted with two ball nuts, two ball cups, and, if necessary, with two intermediate rings, while compressive force transducers should be fitted with one or two compression pads [1]." Morehouse follows the ISO 376 standard for several of our products. We also design adapters to help technicians and end-users to replicate and reproduce calibration results.

Calibration Versus Verification

Calibration and verification are not the same. This section describes the differences between calibration and verification.

What is a Calibration?

Let me start by stating that there are several definitions of calibration across multiple standards. The following are my favorite definitions.

Calibration is the comparison of an unknown (typically referred to as the Unit Under Test or UUT) to a device known within a certain error (typically referred to as the Calibration Standard or Reference Standard) to characterize the unknown. Thus, we are comparing something that we know to some degree of certainty to something that may not be known or that needs to be checked at a time interval to assure drift and other characteristics are kept under control. Thus, in simple terms, calibration can be thought of as validation.

The definition from the International Vocabulary of Metrology (VIM) in section 2.39 is interesting in that many people assume calibration is also an adjustment. It is not. The VIM is clear in Note 2, stating, "Calibration should not be confused with a measuring system, often mistakenly called "self-calibration," nor with verification of calibration [2]." Think about it this way; when you send most instruments to a National Metrology Institute such as NIST, they will only report the value of the device at specific points and the associated measurement uncertainties. Why? Because the end-user can take those values and use those values with the associated measurement uncertainties as a starting point to characterize whatever is being tested. Measurement uncertainty will be explained in the next section.

When an end-user uses a calibrated device, it is often under different conditions than when it was calibrated. For example, if Morehouse calibrates a device in one of our deadweight machines known to better than 0.002 % of applied force, and the end-user later uses this device, then the conditions will vary. It is almost certain that their use conditions do not replicate those exactly of the lab performing the calibration. For example, the temperature, rigidity of the machine, and hardness of adapters could vary, and their machine could introduce torsion, etc. These are only a few of several conditions that can impact the results.

I like to explain that Morehouse calibrates the device and assigns a value that can be considered the expected performance of the device under the same conditions at which it was calibrated. The end-user then varies those conditions, which adds additional measurement uncertainty. Therefore, the end-user can use the calibration data as a starting point to evaluate their measurement uncertainty.

What is Verification?

The VIM in section 2.44 defines verification as the "provision of objective evidence that a given item fulfills specified requirements [3]." Then the VIM goes on to list three examples, followed by multiple notes. I would highly recommend going online to view this page.

When you do check out this page, pay particular attention to Note 5 which states, "Verification should not be confused with calibration. Not every verification is a validation." Verification, per Note 6 "requires a description of the structure or properties of that entity or activity." For example, a 10,000-load cell, like the one shown below in Figure 9, is submitted to Morehouse, and found to be within ± 5 lbf, as per the customer's required tolerance of 0.05 % of full scale.

Figure 9. Morehouse Ultra-Precision Load Cell

In this scenario, verification is more of a conformity assessment and should not be confused with calibration. However, many commercial laboratories perform a calibration by reporting the applied force and the device's corresponding measurement values for calibration. Then they make a conformity assessment, which is a statement to the end-user that the device is either in or out of tolerance. They typically say a device passes calibration or it fails calibration.

The critical detail here is that to ensure measurement traceability, measurement uncertainties must be reported. You should not perform a calibration with a statement of verification without reporting the measurement uncertainty. That uncertainty should be considered when making a statement of conformance to a specification.

Measurement Uncertainty

What is Measurement Uncertainty?

What measurement uncertainty is not is an error. It is imperative to understand the difference between these two terms as they are often confused. Error is the difference between the measured value and the device's actual value or artifact being measurement. In many cases, we try to correct the known errors by applying corrections sometimes from the calibration certificate. These corrections can be all items found in Note 1 of the calibration definition from the VIM: "A calibration may be expressed by a statement, calibration function, calibration diagram, calibration curve, or calibration table. In some cases, it may consist of an additive or multiplicative correction of the indication with associated measurement uncertainty [2]."

Uncertainty, often referred to as 'doubt,' is the quantification of 'doubt' about the measurement result. The VIM in section 2.26 defines uncertainty as a non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used. The VIM goes into further detail with several notes about the included components of measurement uncertainty, such as those arising from systematic effect, components associated with corrections, assigned quantity values of measurement standards, etc. Measurement Uncertainty compromises many components.

OIML G 19:2017 sums the

definition of uncertainty as "the concept of measurement uncertainty can be described as a measure of how well the 'true' value of the measurand is believed to be known [5]."

One of the best guides to uncertainty is JCGM 100:2008 *Evaluation of measurement data — Guide to the expression of uncertainty in measurement*, free to download at https://www.bipm.org/en/publications/guides/gum.html.

In general, when you calculate measurement uncertainties following ISO "Guide to the Expression of Uncertainty in Measurement" (GUM) and ILAC (International Laboratory Accreditation Cooperation) P-14 as required by ISO/IEC 17025 guidelines, you will need to consider the following:

- Repeatability (Type A)
- Resolution
- Reproducibility
- Reference Standard Uncertainty
- Reference Standard Stability
- Environmental Factors

Morehouse has written several published documents on the topic of measurement uncertainty. We have created a spreadsheet tool to help everyone correctly calculate uncertainty for force following accreditation requirements and in line with JCGM 100:2008. That tool can be found at https://mhforce.com/documentation-tools/.

Why is Measurement Uncertainty Important?

The uncertainty of the measurement is required to be reported on a certificate of calibrations if you are accredited to ISO/IEC 17025:2017, as well as several other standards. It is essential if your customer may want you to make a statement of conformance on whether the device or artifact is in tolerance or not. It may need to be considered if you do a test and want to know if the device passes or fails. Measurement Uncertainty is required to establish your measurement traceability, which is defined in the VIM as property of a measurement result whereby the result can be related to a reference through a documented, unbroken chain of calibrations contributing to the measurement uncertainty.

In simplistic terms, the measurement uncertainty is crucial because you want to know that the laboratory performing the calibration of your device or artifact can perform the calibration. If you need a device to be known to be within less than 0.02 %, you must use a calibration provider that gives you the best chance of achieving that result. If the calibration provider has a stated measurement uncertainty of 0.04 %, mathematically, they are not the

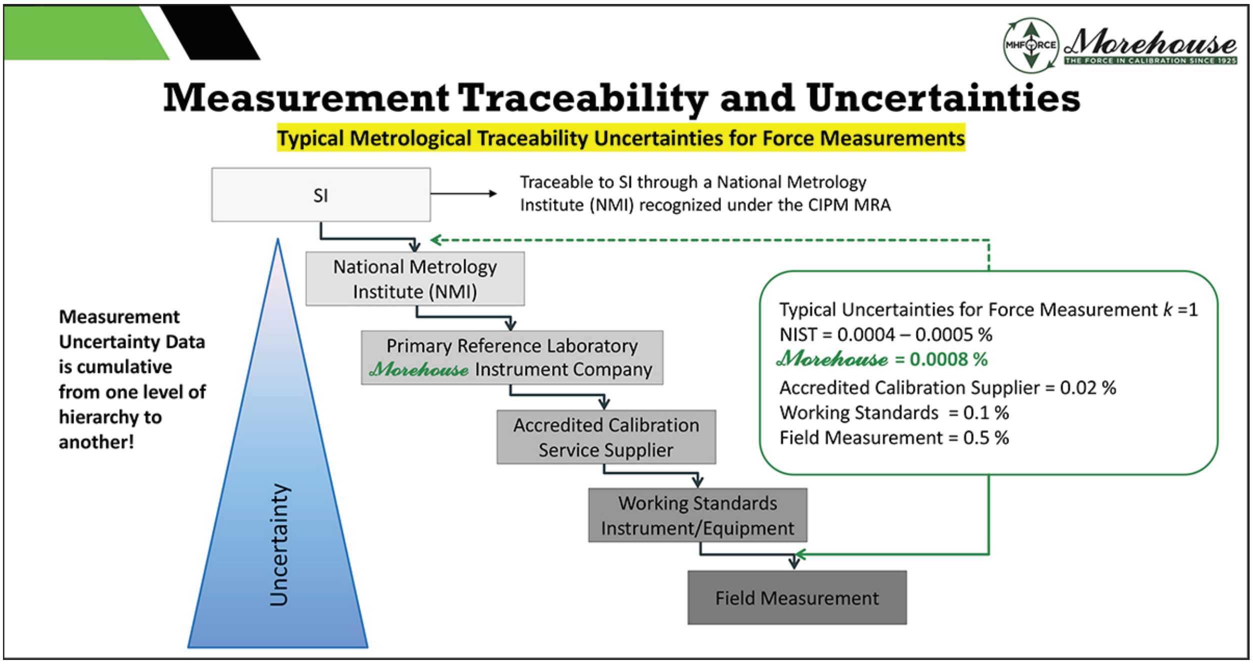

Figure 10. An Example of Measurement Traceability for Force

right calibration lab to calibrate or verify your device or artifact.

Measurement uncertainty also keeps us honest. If a laboratory claims traceability to SI through NIST, the larger the uncertainty becomes, the further away from NIST. The above picture shows this concept as the further away from SI units, the more significant the uncertainty.

Conclusion

In this first part of force calibration guidance, we defined force calibration, its importance, and some devices used to measure force. We differentiated compression and tension in relation to force calibration, as well as defining what we mean by "calibration." Since ISO/IEC 17025 requires a corrective value for measurement uncertainties on certificates of calibration, we covered the documentation to help define these values. And above all, we explained the importance of measurement uncertainties and traceability.

Look for Part 2 in the next issue, where we talk about load cells: terminology, types, and trouble-shooting. We'll also explain what a digital indicator does and provide a glossary of terms often used in force calibration.

Additional Information

Our purpose is to create a safer world by helping companies improve their force and torque measurements. We have several other technical papers, guidance documents, and blogs that can add to your knowledge base. Visit www.mhforce.com for additional guidance on adapters, uncertainty, calibration techniques, and more.

References

[1] ISO 376:2011(en) *Metallic materials — Calibration of force-proving instruments used for the verification of uniaxial testing machines,* Annex A.4.1. https://www.iso.org/obp/ui/#iso:std:iso:376:ed-4:v1:en

[2] *International vocabulary of metrology - Basic and general concepts and associated terms (VIM),* (JCGM 200:2012, 3rd edition). https://jcgm.bipm.org/vim/en/2.39.html

[3] *International vocabulary of metrology - Basic and general concepts and associated terms (VIM),* (JCGM 200:2012, 3rd edition). https://jcgm.bipm.org/vim/en/2.44.html

[4] *OIML G 19:2017 The role of measurement uncertainty in conformity assessment decisions in legal metrology,* p.44. https://www.oiml.org/en/files/pdf_g/g019-e17.pdf

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Henry Zumbrun (hzumbrun@mhforce.com), Morehouse Instrument Company, Inc., York, PA 17403, USA.