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Force Calibration Guidance for Beginners

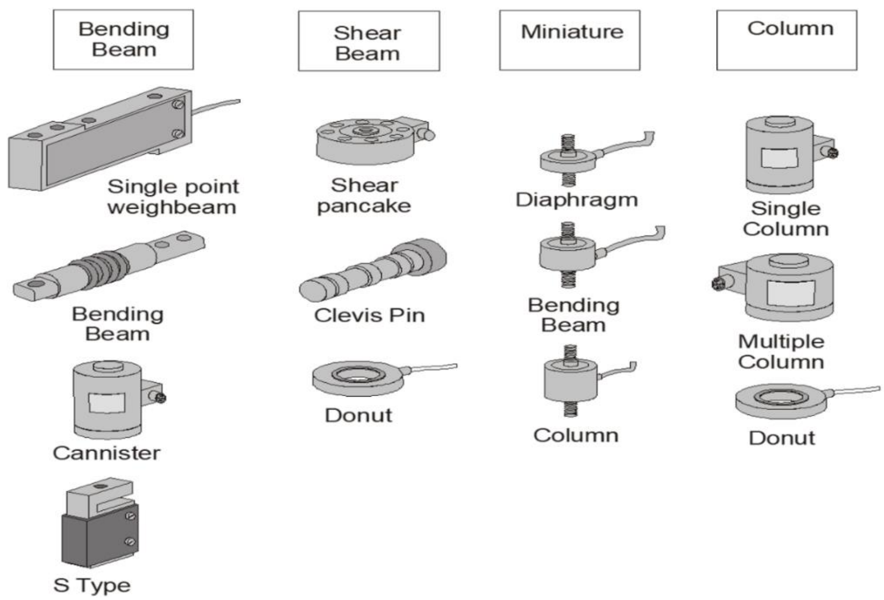

Table of Contents

Introduction

Morehouse Instrument Company has shared tremendous 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.

The information can be overwhelming when someone is new to calibration or metrology. There is so much to digest that people can quickly become overwhelmed. Some have joked that an introduction to metrology is like drinking through a fire hose.

Morehouse created this guidance document to simplify things and help anyone new to force. Even seasoned metrologists or technicians with years of experience may learn something new, or maybe this document can be a refresher for more advanced people. In either case, the knowledge gained will ultimately help you become better.

Figure 1: Force Calibration Basics

1. 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, the same force will be required to break the egg in my hand. It will 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 the illustration below, force is derived 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 1N as the force required to accelerate 1 kg to 1 meter per second squared in a vacuum.

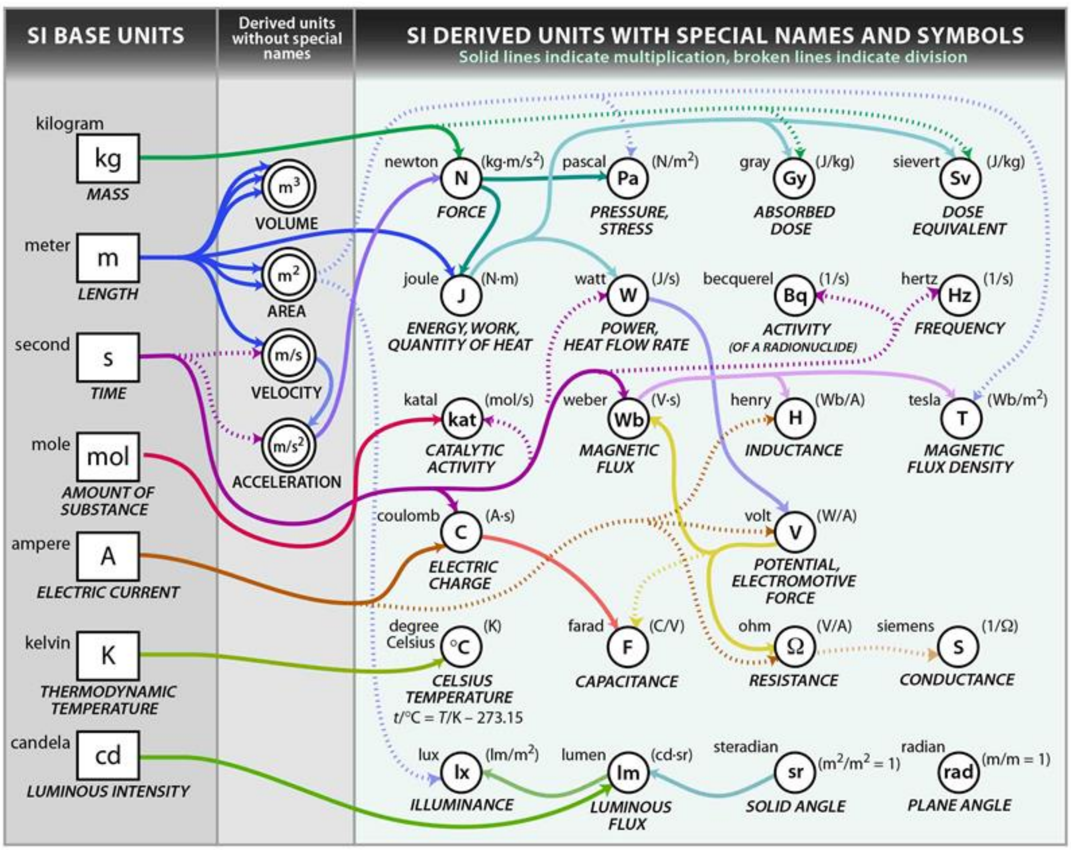

Figure 2: SI Units courtesy of NIST [1]

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.) 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, correcting the concrete strength measurement is essential. Ensuring the steel is tested, and the cables are appropriately checked for prestress, or post-tension is essential. Bad things happen when these measurements are incorrectly done, as shown below.

Figure 3: 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 nationwide, the harder ones will last longer and ripen during shipment. In contrast, the softer ones might be distributed locally.

Figure 4: Testing Apple Ripeness

The example on page 6 shows the fishing line being tested. I am sure any fisherman would not want the line to break as they haul in their prized fish.

Figure 5: Testing Fishing Line

In general, force measurement is performed so frequently that we take it for granted. However, almost every material item is tested using some form of traceable force measurement. Testing may vary from sample testing on manufactured lots, including anything from the materials used to build your house to the cardboard on that toilet paper roll.

2. How a Transducer Measures Force

What is a Transducer?

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

Figure 6: A Battery is a Transducer

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.

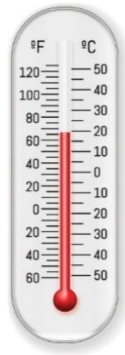

Figure 7: A Thermometer is Transducer

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.

Figure 8: A Load Cell is a Transducer

3. A load cell is a transducer 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.

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 placed on the material inside the load cell.

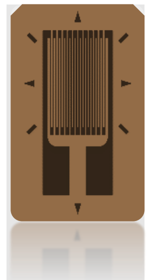

Figure 9: Strain Gauge

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, the placement of the gages, and the number of gages.

A meter or indicator displays the force measurement value when hooked up to a load cell. 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

3. Compression and Tension Force Calibration

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

What is a Compression Calibration?

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

Compression calibration can be thought of as compressing or pushing

Figure 10: Compression Calibration Examples

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

The key to this type of calibration is ensuring everything is aligned and 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.

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.

Tension calibration can be thought of as pulling or stretching the material

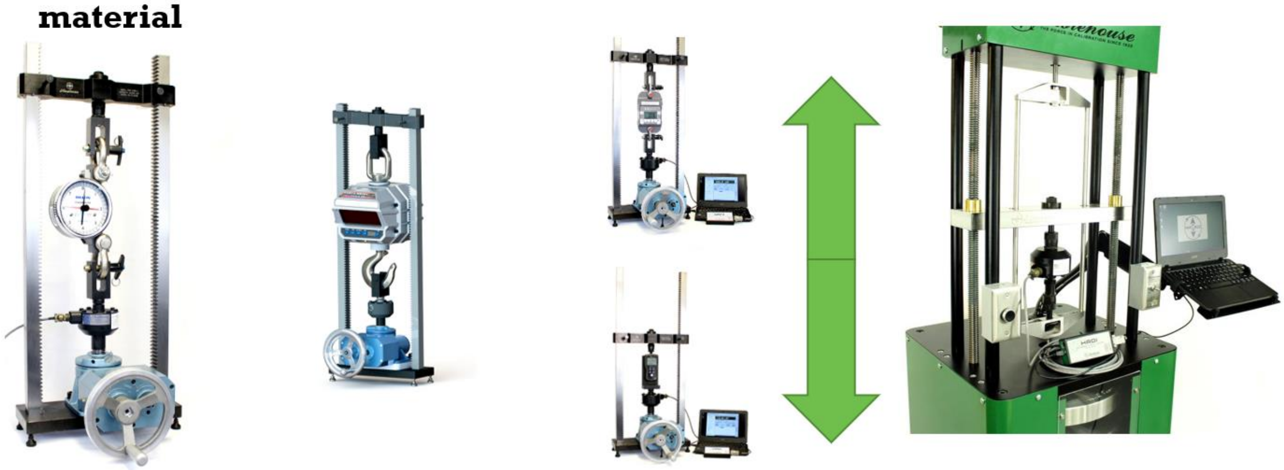

Figure 11: Tension Calibration Examples

Above are multiple examples of tension setups in calibrating machines. The machine on the left is the Morehouse 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 instruments, from crane scales to hand-held force gauges. The picture on the right shows a load cell fixtured for tension calibration in a Morehouse 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 so 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, two intermediate rings. In contrast, compressive force transducers should be fitted with one or two compression pads."2 Morehouse follows the ISO 376 standard for several of our products. We also design adapters to help technicians and end-users replicate and reproduce calibration results.

4. 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. My favorite definitions are below:

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 ensure drift and other characteristics are controlled. Thus, in simple terms, calibration can be thought of as validation.

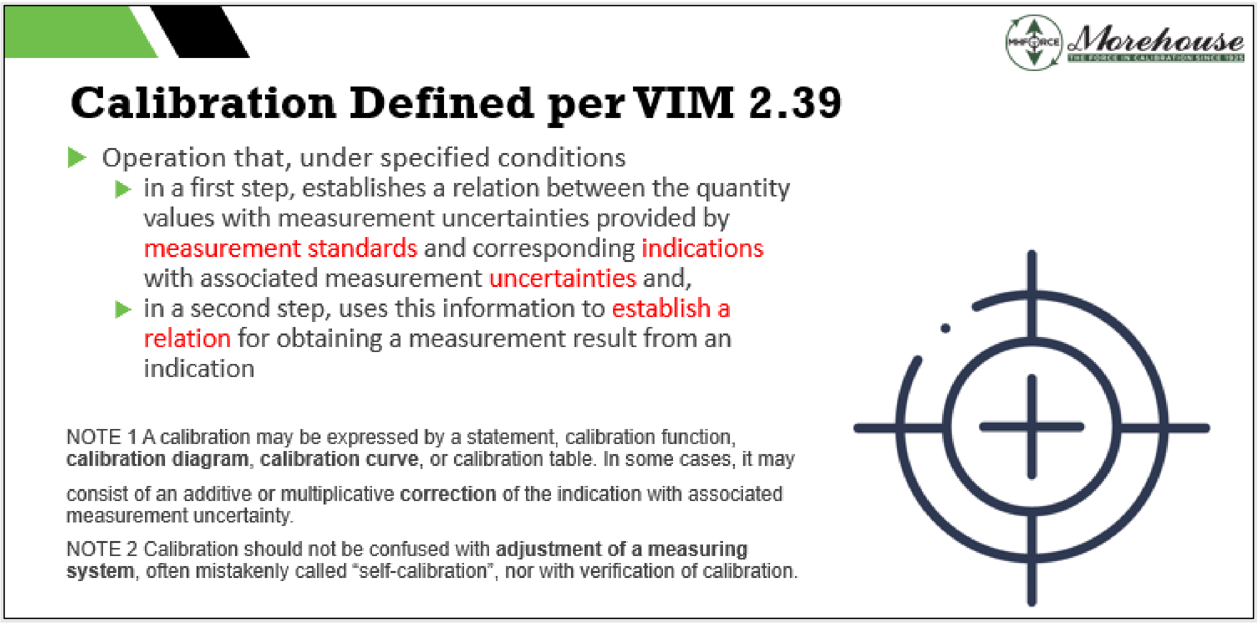

Figure 12: Calibration Definition

The definition from the International Vocabulary of Metrology (VIM) in section 2.39 is interesting because many assume calibration is also an adjustment. It is not. The VIM is clear in Note 2: "Calibration should not be confused with a measuring system, often mistakenly called "self-calibration," nor with verification of calibration." Think about it this way: when you send most instruments to a National Metrology Institute, such as NIST, they only report the device's value 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 be better than 0.002 % of applied force, and the end-user later uses this device, 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 providing objective evidence that a given item fulfills specified requirements. Then, the VIM goes on to list several additional examples:

- Example 1: Confirmation that a given reference material, as claimed, is homogeneous for the quantity value and measurement procedure concerned, down to a measurement portion having a mass of 10 mg.
- Example 2: Confirmation that performance properties or legal requirements of a measuring system are achieved.
- Example 3: Confirmation that a target measurement uncertainty can be met.

Note 1: When applicable, measurement uncertainty should be taken into consideration.
Note 2: The item may be, e.g., a process, measurement procedure, material, compound, or measuring system.
Note 3: The specified requirements may be, e.g., that a manufacturer's specifications are met.
Note 4: Verification in legal metrology, as defined in VIML [53], and in conformity assessment in general, pertains to the examination and marking and/or issuing of a verification certificate for a measuring.
Note 5: Verification should not be confused with calibration. Not every verification is a validation.
Note 6: In chemistry, verification of the identity of the entity involved or of activity 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, is submitted to Morehouse, and found to be within ± 5 lbf, per the customer's required tolerance of 0.05 % of full scale.

Figure 13: 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, 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 measurement uncertainties must be reported to ensure measurement traceability. **You should not calibrate with a verification statement without reporting the measurement uncertainty. That uncertainty should be considered when making a statement of conformance to a specification.**

Therefore, these definitions and examples show how calibration and verification differ.

5. Measurement Uncertainty

What is Measurement Uncertainty?

What measurement uncertainty is not is an error. Understanding these two terms' differences is imperative, as they are often confused. Error is the difference between the measured value and the device's actual value or artifact being measured. We often try to correct the known errors by applying corrections sometimes from the calibration certificate. These corrections can be a curve, a diagram, a table, and all items found in note 1 of the calibration definition from the VIM..

Uncertainty, often called 'doubt,' is the quantification of 'doubt' about the measurement result. The

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VIM in section 2.26 defines uncertainty as a non-negative parameter characterizing the dispersion of the quantity values attributed to a measurement based on the information used. The VIM goes into further detail with several notes about the 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 defines 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." 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://measurementuncertainty.info/

Why is Measurement Uncertainty Important?

The uncertainty of the measurement must 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 wants you to make a statement of conformance on whether the device or artifact is in tolerance. 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, defined in Vim as the 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.

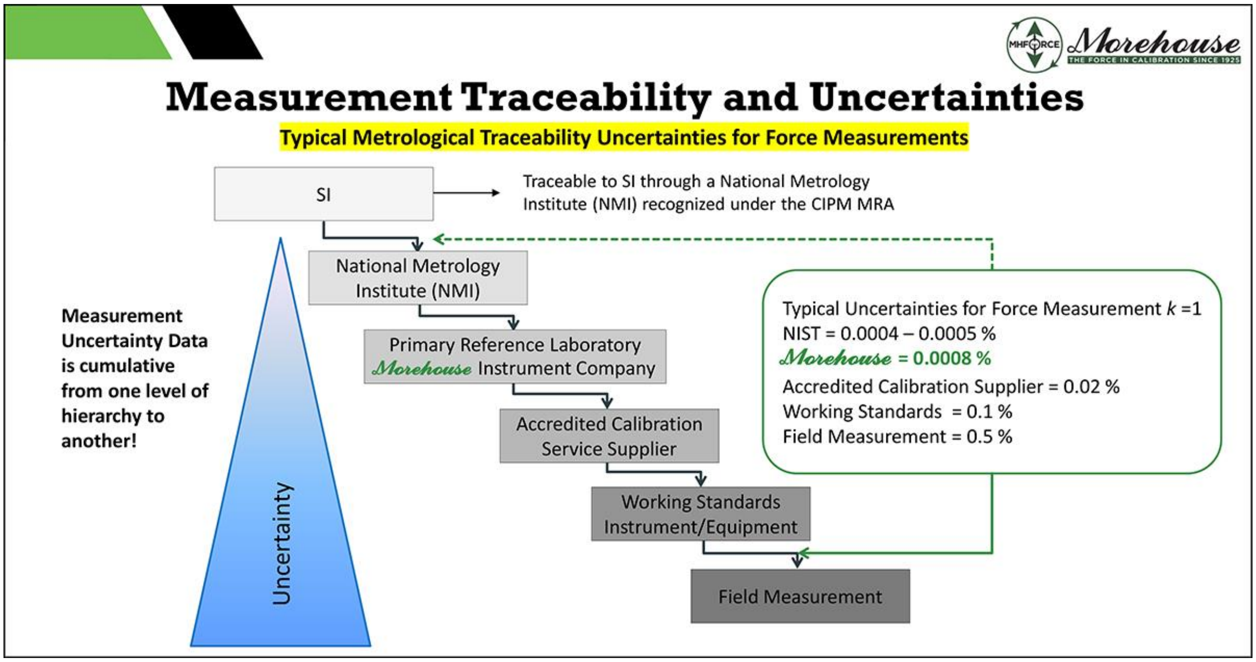

Figure 14: An Example of Measurement Traceability for Force

In In simplistic terms, the measurement uncertainty is crucial because you want to know that the laboratory calibrating 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 right calibration lab to calibrate or verify your device or artifact.

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

Your Measurement Uncertainty is directly affected by the standards used to perform the calibration. Morehouse offers the lowest uncertainties for a commercial calibration laboratory. We work with customers to help lower their measurement risk. We have been successful in helping our customers make better measurements for over a century.

6. Load Cell Terminology

Non-Linearity, Non-Repeatability, Hysteresis, and Static Error Band are common load cell terminology typically found on a load cell specification sheet. There are several more terms regarding the characteristics and performance of load cells. However, I chose these four because they are the most common specifications found on calibration certificates.

When broken out individually, these terms can help you select the suitable load cell for an application. Some of these terms may not be as important today as they were years ago because better meters that overcome inadequate specifications are available. One example is Non-Linearity. An indicator capable of multiple span points can significantly reduce the impact of a load cell's non-linear behavior.

The meanings for these terms are described in detail below.

Specifications	Model - Capacity (lbf / kN)					
	300-2K / 1-10	5K-10K / 20-50	25K-50K /100-250	60K / 300	100K / 500	200K / 900
Accuracy						
Static Error Band, % R.O.	±0.02	± 0.03	± 0.03	± 0.03	± 0.05	± 0.05
Non-Linearity, % R.O.	±0.02	± 0.03	± 0.03	± 0.03	± 0.05	± 0.05
Hysteresis, % R.O.	± 0.02	± 0.04	± 0.04	± 0.04	± 0.05	± 0.05
Non-Repeatability, % R.O.	± 0.005	± 0.005	± 0.005	± 0.005	± 0.005	± 0.005
Creep, % Rdg / 20 Min.	± 0.015	± 0.015	± 0.015	± 0.015	± 0.015	± 0.015
Off-Center Load Sensitivity, %/in	±0.1	± 0.1	± 0.1	± 0.1	± 0.1	± 0.1
Side Load Sensitivity, %	± 0.1	± 0.1	± 0.1	± 0.1	± 0.1	± 0.1
Zero Balance, % R.O.	± 1.0	± 1.0	± 1.0	± 1.0	± 1.0	± 1.0

Figure 15: Morehouse Load Cell Specification Sheet

Non-Linearity: The quality of a function that expresses a relationship that is not one of direct proportion. For force measurements, Non-Linearity is the algebraic difference between the output at a specific load and the corresponding point on the straight line drawn between the outputs at minimum and maximum load. It is usually expressed in units of % of full scale. It is usually calculated between 40 – 60 % of the full scale.

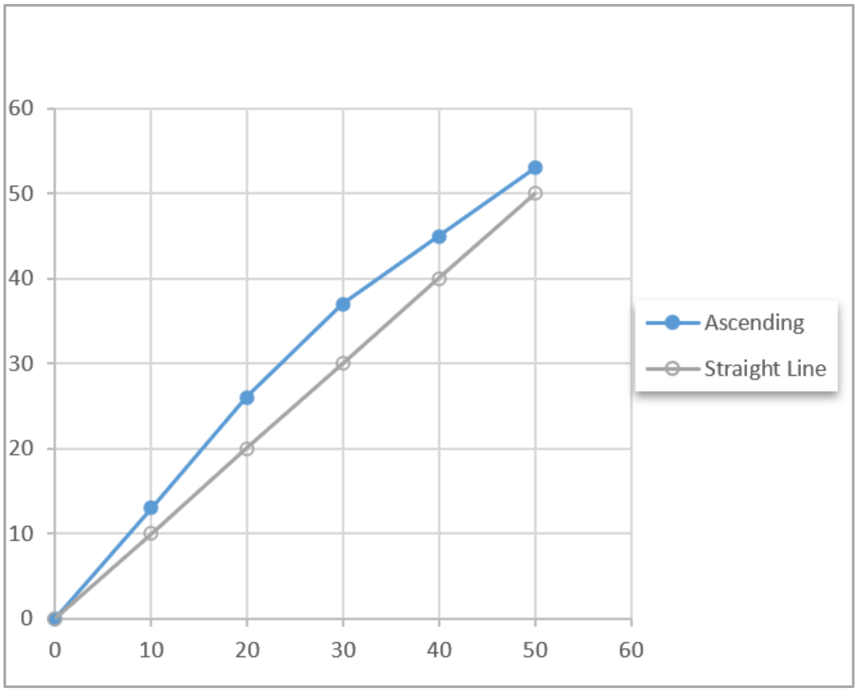

Figure 16: Non-Linearity Expressed Graphically

Non-Linearity is one of the specifications that would be particularly important if the indicating device or meter used with the load cell only has a two-point span, such as capturing values at zero and capacity or close to capacity. The specification gives the end-user an idea of the anticipated error or deviation from the best fit straight line. However, suppose the end-user has an indicator capable of multiple span points and uses coefficients from an ISO 376 or ASTM E74 type calibration. In that case, the non-linear behavior can be corrected, and the error significantly reduced.

One way to calculate Non-Linearity is to use the slope formula or manually perform the calibration by using the load cell output at full scale minus zero and dividing it by force applied at full scale and 0. For example, a load cell reads 0 at 0 and 2.00010 mV/V at 1000 lbf. The formula would be (2.00010-0)/ (1000-0) = 0.002.

This formula gives you the slope of the line, assuming a straight-line relationship. Some manufacturers take a less conservative approach and use higher-order quadratic equations.

Plot the Non-Linearity baseline as shown below using the force applied * slope + Intercept or y = mx +b formula. If we look at the 50 lbf point, this becomes 50 * 0.0020001 +0 = 0.100005. Thus at 50 lbf, the Non-Linearity baseline is 0.100005.

To find the Non-Linearity percentage, take the mV/V value at 50 lbf minus the calculated value and divide by the full-scale output multiplied by 100 to convert to a percentage. Thus, the numbers become ((0.10008-0.100005)/2.00010) *100) = 0.004 %.

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Non-Linearity Calculations Ignoring Ending Zero though Running it through the formula						
Force Appied (lbf)	Run 1 Adjusted	Non-Linearity Base line	Non-Linearity (%FS)		Non-linearity Line	
0	0.00000	0	0.000		Slope=	0.0020001
50	0.10008	0.1000050	0.004		Intercept=	0
100	0.20001	0.2000100	0.000			
200	0.40002	0.4000200	0.000			
300	0.60001	0.6000300	0.001		Non-linearity=	0.004
400	0.80002	0.8000400	0.001		(%FS)	
500	1.00005	1.0000500	0.000			
600	1.20002	1.2000600	0.002			
700	1.40003	1.4000700	0.002			
800	1.60004	1.6000800	0.002			
900	1.80006	1.8000900	0.001			
1000	2.00010	2.0001000	0.000			
0	0.00000	0				

Figure 17: Non-Linearity Baseline

Non-Linearity Calculations Reducing Ending Zero						
Force Appied (lbf)	Run 1 Adjusted	Non-Linearity Base line	Non-Linearity (%FS)		Non-linearity Line	
0		=(E7*$K$7+$K$8)	=ROUND(ABS(F7-G7)/$F$18*100,3)		Slope=	=(F18-F7)/(E18-E7)
50	0.10008	=(E8*$K$7+$K$8)	=ROUND(ABS(F8-G8)/$F$18*100,3)		Intercept=	0
100	0.20001	=(E9*$K$7+$K$8)	=ROUND(ABS(F9-G9)/$F$18*100,3)			
200	0.40002	=(E10*$K$7+$K$8)	=ROUND(ABS(F10-G10)/$F$18*100,3)			
300	0.60001	=(E11*$K$7+$K$8)	=ROUND(ABS(F11-G11)/$F$18*100,3)		Non-linearity=	
400	0.800015	=(E12*$K$7+$K$8)	=ROUND(ABS(F12-G12)/$F$18*100,3)		(%FS)	=MAX(H7:H19)
500	1.00005	=(E13*$K$7+$K$8)	=ROUND(ABS(F13-G13)/$F$18*100,3)			
600	1.200015	=(E14*$K$7+$K$8)	=ROUND(ABS(F14-G14)/$F$18*100,3)			
700	1.400025	=(E15*$K$7+$K$8)	=ROUND(ABS(F15-G15)/$F$18*100,3)			
800	1.60004	=(E16*$K$7+$K$8)	=ROUND(ABS(F16-G16)/$F$18*100,3)			
900	1.80006	=(E17*$K$7+$K$8)	=ROUND(ABS(F17-G17)/$F$18*100,3)			
1000	2.0001	=(E18*$K$7+$K$8)	=ROUND(ABS(F18-G18)/$F$18*100,3)			
0		=(E19*$K$7+$K$8)				

Figure 18: Non-Linearity Calculations

Hysteresis: The phenomenon in which the value of a physical property lags changes in the effect causing it. An example is when magnetic induction lags the magnetizing force. For force measurements, Hysteresis is often defined as the algebraic difference between output at a given load descending from the maximum load and output at the same load ascending from the minimum load.

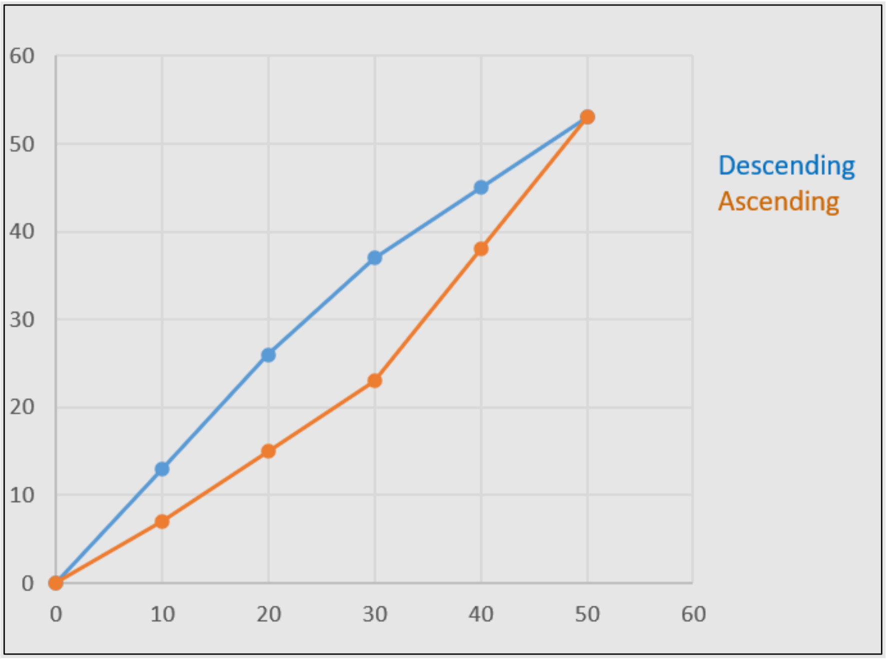

Figure 19: Hysteresis Example

Hysteresis is normally expressed in units of % full scale. It is normally calculated between 40 - 60 % of full scale. The graph above shows a typical Hysteresis curve where the descending measurements have a slightly higher output than the ascending curve.

If the end-user uses the load cell to make descending measurements, they may want to consider the effect of Hysteresis. Errors from hysteresis can be high enough that if a load cell is used to make descending measurements, it must be calibrated with a descending range. The difference in output on an ascending curve versus a descending curve can be significant. For example, an exceptionally good Morehouse 100K precision shear-web load cell had an output of -2.03040 on the ascending curve and -2.03126 on the descending curve.

At Morehouse, our calibration lab sampled several instruments and recorded the following differences.

Load Cell Manufacturer (names removed)	1	2	3	4	5	5	3	4
Ascending Output 50 % Force Point	1.49906	1.20891	-2.0304	24990	-5.18046	-2.49899	-2.0886	-2.15449
Descending Output 50 % Force Point	1.49947	1.21022	-2.03126	25020	-5.18265	-2.50103	-2.08846	-2.15579
Difference	0.027%	0.108%	0.042%	0.120%	0.042%	0.082%	0.007%	0.060%

Figure 20: Errors From Hysteresis

Load cells from five manufacturers were sampled, and the results were recorded. The differences between the ascending and descending points varied from 0.007 % (shear web type cell) to 0.120 % on a column type cell. On average, the difference was approximately 0.06 %. Six of the seven tests were performed using deadweight primary standards, which is accurate within 0.0016 % of the applied force.

Non-Repeatability: The maximum difference between output readings for repeated loadings under identical and environmental conditions. Usually, this is expressed in units as a % of rated output (RO). Non-repeatability tells the user a lot about the performance of the load cell. It is important to note that non-repeatability does not tell the user about the load cell's reproducibility or how it will perform under different loading conditions (randomizing the loading conditions). At Morehouse, we have observed numerous load cells with good non-repeatability specifications that perform poorly when the loading conditions are randomized or the load cell is rotated 120 degrees as required by ISO 376 and ASTM E74.

The calculation of non-repeatability is straightforward. First, compare each observed force point's output and run a difference between those points. The formula would look like this: Non-Repeatability = ABS(Run1-Run2)/AVERAGE (Run1, Run2, Run3) *100. Do this for each combination or run, then take the maximum of the three calculations.

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non-repeatability calclulations		
Run 1	Run 2	Run 3
4.0261	4.02576	4.02559
Difference b/w 1 & 2 (%FS)	Difference b/w 1 & 3 (%FS)	Difference b/w 2 & 3 (%FS)
0.0084	0.0127	0.0042
Non-Repeatability (%FS)=		0.013

Figure 21: Non-Repeatability Numbers

non-repeatability calclulations		
Run 1	Run 2	Run 3
4.0261	4.02576	4.02559
Difference b/w 1 & 2 (%FS)	Difference b/w 1 & 3 (%FS)	Difference b/w 2 & 3 (%FS)
=ABS(U4-V4)/AVERAGE($U$4:$W$4)*100	=ABS(U4-W4)/AVERAGE($U$4:$W$4)*100	=ABS(W4-V4)/AVERAGE($U$4:$W$4)*100
Non-Repeatability (%FS)=		=MAX(U9:W9)

Figure 22: Non-Repeatability Calculations

Static Error Band: The band of maximum deviations of the ascending and descending calibration points from a best-fit line through zero output. It includes the effects of Non-Linearity, Hysteresis, and non-return to minimum load. It is usually expressed in units of % of full scale.

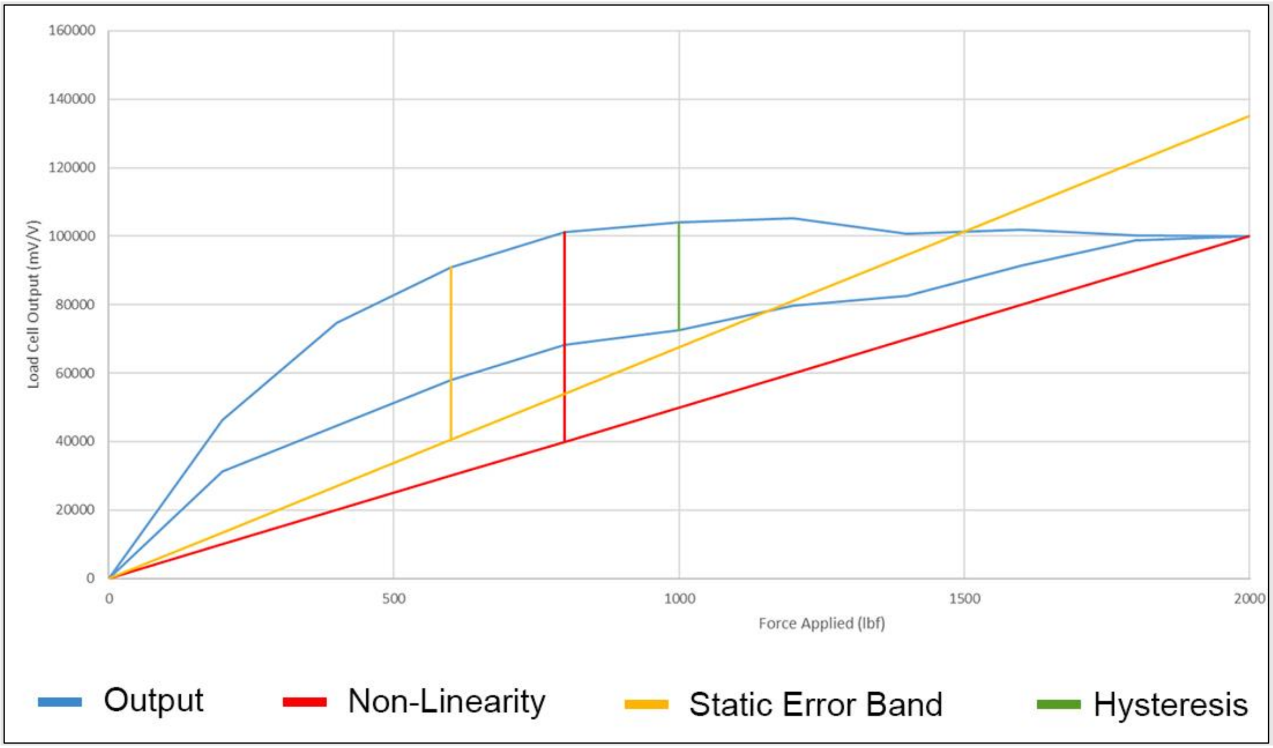

Figure 23: Static Error Band and Other Specifications Displayed Visually

Because of what it captures, the Static error band might be the most exciting term. If the load cell is always used to make ascending and descending measurements, this term best describes the load cell's actual error from the straight line drawn between the ascending and descending curves. Earlier, I noted that the end-user might want to consider the effects of Hysteresis unless they use the load cell described above because a static error band would be the better specification. The end-user could likely ignore Non-Linearity and Hysteresis and focus on static error band and non-repeatability.

However, we find that many calibration laboratories primarily operate using ascending measurements and, on occasion, may have a request for descending data. When that is the case, the user may want to evaluate Non-Linearity and Hysteresis separately. When developing an uncertainty budget, use different budgets for each type of measurement, i.e., ascending and descending.

What needs to be avoided is a situation where a load cell is calibrated following a standard such as ASTM E74 or ISO 376 and additional uncertainty contributors for Non-Linearity and Hysteresis are added. ASTM E74 has a procedure and calculations that, when followed, use a method of least squares to fit a polynomial function to the data points. The standard uses a specific term called the Lower Limit Factor (LLF), which is a statistical estimate of the error in forces computed from a force-measuring instrument's calibration equation when the instrument is calibrated following the ASTM E74 practice.

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To learn more about load cell creep, check out our blog.

7. Types of Load Cells

It is essential to understand the common types of load cells used in force measurement and choose your application's suitable load cell.

The four types of load cells typically used in force measurement are bending beam, shear beam, miniature, and column. We will describe the common types used as reference and field standards below. Many other load cells are shown in commercial applications, such as scales used at supermarket checkouts, weight-sensing devices, and weighing scales.

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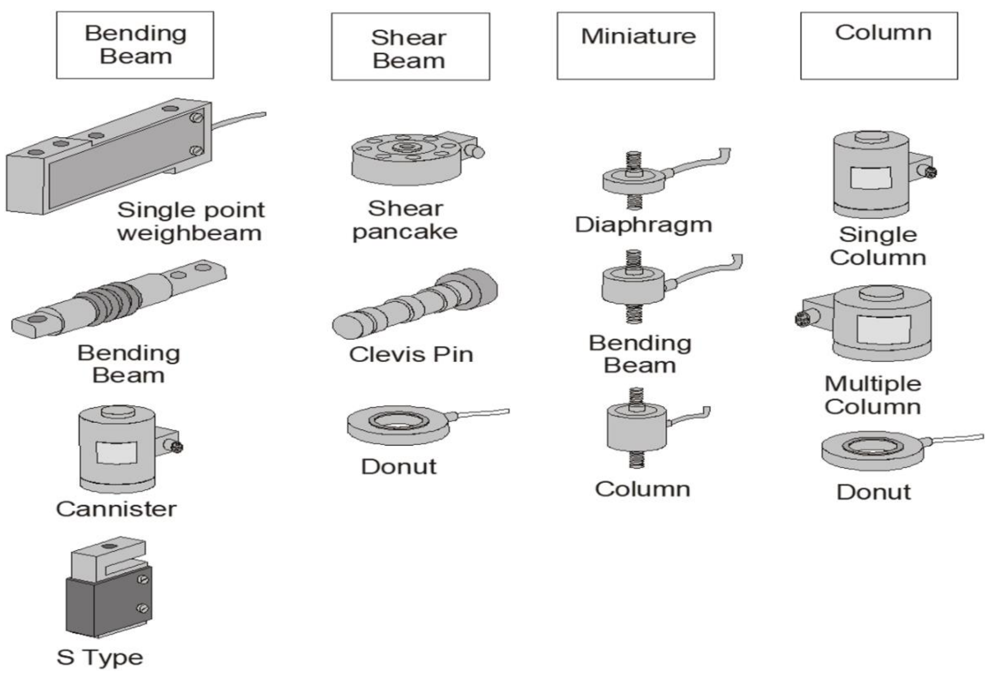


Figure 24: Types of Load Cells

S-beam (S-type)
The S-beam is a bending beam load cell typically used in weighing applications under 50 lbf. These load cells work by placing a weight or generating a force on the load cell's metal spring element, which causes elastic deformation. The strain gauges in the load cell measure the fractional change in length of the deformation. There are generally four strain gauges mounted in the load cell.

Figure 25: S-beam Load Cell

Advantages

- In general, linearity will be enhanced by minimizing the deflection ratio at the rated load to the length of the sensing beam, thus minimizing the change in the element's shape
- Ideal for measuring small forces (under 50 lbf) when physical weights cannot be used.
- It is suited for scales or tension applications.

Disadvantages

- The load cell is susceptible to off-axis loading.
- Compression output will differ if the load cell is loaded through the threads versus flat against each base.
- Typically, it is not the right choice for force applications requiring calibration to the following standards: ASTM E74, ASTM E4, ISO 376, and ISO 7500.

Watch this video demonstrating the misalignment due to off-axis loading.

Shear Web

The shear web is a shear beam load cell that is ideal as a calibration reference standard up to 100,000 lbf. Morehouse shear web load cells are typically the most accurate when installed on a tapered base with an integral threaded rod installed.

Figure 26: Morehouse Ultra-Precision Shear Web Load Cells

Advantages

- Typically have very low creep and are not as sensitive to off-axis loading as the other load cells.
- Recommended choice for force applications from 100 lbf through 100,000 lbf.

Disadvantages

- After 100,000 lbf, the cell's weight makes it exceedingly difficult to use as a reference standard in the field. A 100,000 lbf shear web load cell weighs approximately 57 lbs. A 200,000 lbf shear web load cell weighs over 120 lbs.

Watch this video showing a Morehouse load cell with only 0.0022 % off-axis error. If this load cell is used without a base or an integral top adapter, there may be significant errors associated with various loading conditions.

Button Load Cell

The button is a miniature load cell typically used with limited space. It is a compact strain gauge-based sensor with a spherical radius often used in weighing applications.

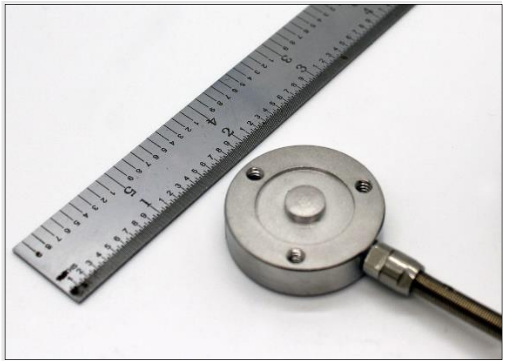


Figure 27: Button Load Cells

Advantages

- Suitable for applications where there is minimal room to perform a test.

Disadvantages

- High sensitivity to off-axis or side loading. The load cell will produce high errors from any misalignment. For example, a 0.1 % misalignment can produce a significant cosine error. Some have errors anywhere from 1 % - 10 % of rated output.
- Does not repeat well in the rotation.

Figure 28: Button and Washer Load Cell Adapters

Morehouse has developed custom adapters for button, washer, and donut load cells that improve repeatability. In our testing, we achieved a 525 % improvement using the above adapters. If your laboratory calibrates these load cells and observes the same repeatability problems, please contact Morehouse, as the above adapters will improve the calibration results.

Morehouse has developed custom adapters for button, washer, and donut load cells that improve repeatability. In our testing, we achieved a 525 % improvement using the above adapters. If your laboratory calibrates these types of load cells and observes the same repeatability problems, please contact Morehouse as the above adapters will improve the calibration results.

Single-Column or High-Stress Load Cells

The single column is a column load cell good for general testing. The spring element is intended for axial loading and typically has a minimum of four strain gauges, with two in the longitudinal direction. Two are oriented transversely to sense the Poisson strain. The Morehouse single-column load cell is economical and lightweight.

Figure 29: Morehouse Single Column Load Cell

Advantages

- Physical size and weight: It is common to have a 1,000,000 lbf column cell weigh less than 100 lbs.

Disadvantages

- Reputation for inherent Non-Linearity. This deviation from linear behavior is commonly ascribed to the change in the column's cross-sectional area (due to Poisson's ratio), which occurs with deformation under load.
- Sensitivity to off-center loading can be high.
- Larger creep characteristics than other load cells and often do not return to zero as well as other load cells. (ASTM Method A typically yields larger LLF.)
- Different thread engagement can change the output.
- The design of this load cell requires a top adapter to be purchased with it. Varying the hardness of the top adapter will change the output.

Multi-Column Load Cells

The multi-column is a column load cell that is good from 100,000 lbf through 1,000,000 plus lbf. Four or more small columns carry the load in this design, each complementing strain gauges. The corresponding columns' gauges are connected in a series in the appropriate bridge arms. The

Morehouse multi-column 600K load cell weighs 27 lbs and has an accuracy of better than 0.02 % of full scale.

Figure 30: Morehouse Light Weight 600k (26 lbs) Multi-Column Load Cell

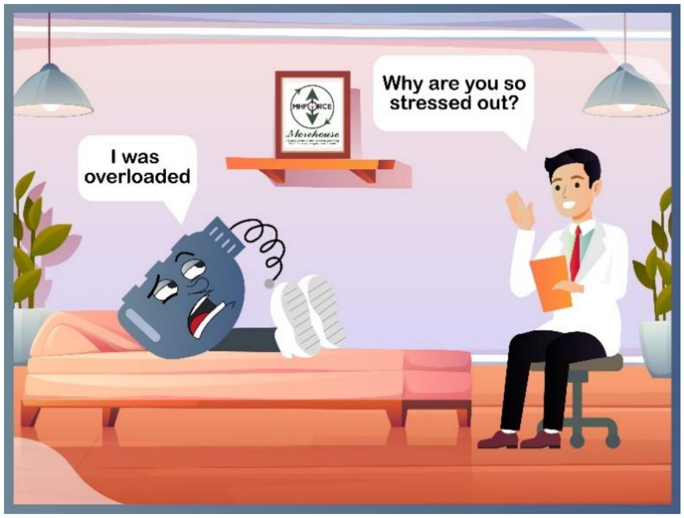
Advantages

- It can be more compact than single-column cells.
- Improved discrimination against the effects of off-axis load components.
- Typically have less creep and better zero returns than single-column cells.
- In many cases, a properly designed shear-web spring element can offer greater output, better linearity, lower hysteresis, and faster response.

Disadvantages

- The design of this load cell requires a top adapter to be purchased with it. Varying the hardness of the top adapter will change the output.

Several more types of load cells have various advantages and disadvantages. If the type of load cells you commonly use is not covered, contact us, and we will be happy to discuss the advantages and disadvantages based on our experience.



8. Load Cell Troubleshooting

Have you ever wasted hours troubleshooting a nonworking load cell to diagnose the problem? If you deal with load cells, you know how much of a time suck they can be when they are not working correctly. This section is designed to save you or your technicians valuable time by following an easy seven-step troubleshooting guide. The time saved can be beneficial to getting more calibrations done or getting the measurements correct by using the proper setups and adapters and understanding how to replicate how the end-user uses the device.

7-Step Process for Troubleshooting a Load Cell

Morehouse technicians have seen many different load cell issues and have lots of experience identifying and fixing the problems. With this experience, we developed a 7 Step Process for Troubleshooting a Load Cell to shorten our calibration lead time (most calibrations are performed in 5-7 business days) and provide better customer service.

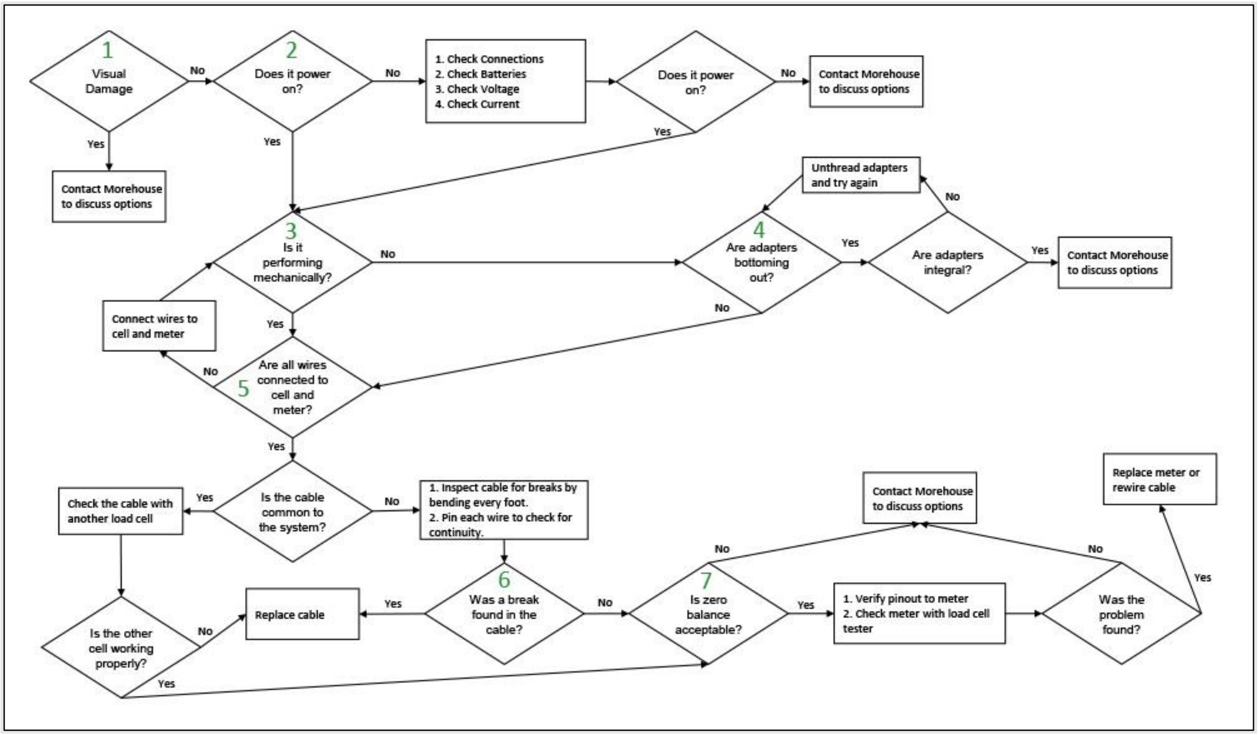


Figure 31: Load Cell Troubleshooting Process

This 7-step process outlined above and explained below can save you countless hours trying to diagnose the problem with your load cell.

1. Visually inspect the load cell for noticeable damage. If it is damaged, contact Morehouse to discuss options.

Figure 32: Overloaded Load Cell

2. Power on the system. Make sure all connections are made and verify batteries are installed and have enough voltage. Check the voltage and current on the power supply. If it still does not power on, then replace the meter. An inexpensive multimeter like the one pictured below can be used for **Steps 2, 6, and 7.**

Figure 33: Multimeter

3. If everything appears to be working, the output does not make sense, check for mechanical issues. For example, some load cells have internal stops that may cause the output to plateau. Do not disassemble the load cell, as it will void the manufacturer's warranty and calibration. The best example of this error is that the load cell is linear to 90 % capacity. Then, either the indicator stops reading or the output becomes severely diminished. The data will show poor linearity when using 100 % of the range and incredibly good linearity when only using the data set to 90 % of the range. Morehouse can likely fix this error and should be contacted for more information.
4. Ensure any adapters threaded into the transducer are not bottoming out. If an adapter is bottoming out and integral, contact Morehouse to discuss options.
5. Ensure the leads (all wires) are correctly connected to the load cell and meter. If the cable is common to the system, check another load cell and verify that the other cell works correctly. If the other load cell is not working, contact Morehouse to discuss options.
6. Inspect the cable for breaks. With everything hooked up, test the cable, making a physical bend every foot. Pin each connection to check for the continuity of the cable.
7. Use a load cell tester or another meter to check the load cell's zero balance. You can check the bridge resistance with an ordinary multimeter if you do not have a load cell tester. A typical Morehouse shear web load cell pins (A & D) and (B & C) should read about 350 OHMS ± 3.5. If one set reads high and another low (ex. (A & D) reads 349 and (B & C) reads 354), then there is a good chance that the load cell was overloaded.

Note: Different load cells use different strain gauges and have different resistance values. It is essential to check with the manufacturer on what they should read and the tolerance.

Figure 34: inside an overloaded shear web load cell showing a clear break of the web element.

Diagnose with a load cell tester.
A Morehouse load cell tester can be used to test for the following:

- Input and Output Resistance
- Resistance difference between sense and excitation leads.
- Signal Output
- Shield to Bridge
- Body to Bridge
- Shield to Body
- Linearity

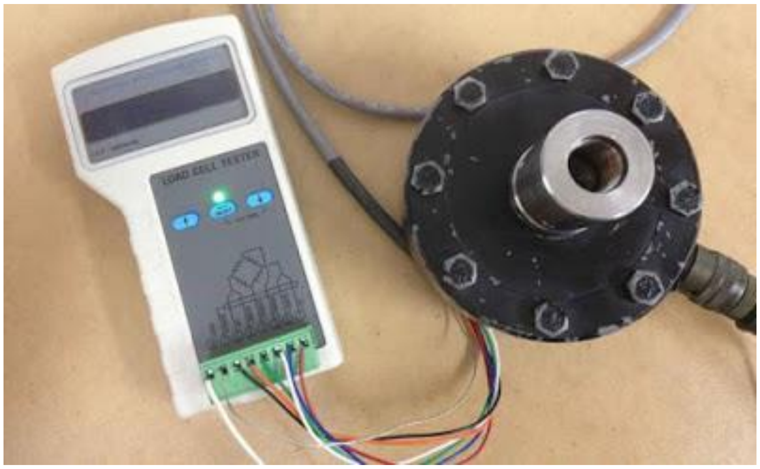


Figure 35: Morehouse Load Cell Tester

Watch this video showing how the load cell tester works.

Overloaded load cell

It is important to note that if a load cell has been overloaded, mechanical damage has been done that is not repairable. Overloading causes permanent deformation within the flexural element and gauges, which destroys the carefully balanced processing. While it is possible to electrically re-zero a load cell following overload, it is not recommended because this does nothing to restore the affected performance parameters or the degradation of structural integrity..

Morehouse stocks common capacity load cells, and most equipment is available in 1 week, with calibration performed using deadweight primary standards. Shorter lead times are available upon request, and Morehouse always aims to provide superior customer support. Visit mhforce.com/load-cells/ for more information on our wide selection of load cells

9. Indicator Basics

Figure 36: Morehouse High Accuracy Digital Indicator (HADI)

When force is exerted on a load cell, the mechanical energy is converted into equivalent electrical signals. The load cell signal is converted to a visual or numeric value by a "digital indicator." When there is no load on the cell, the two signal lines are at equal voltage. As a load is applied to the cell, the voltage on one signal line increases slightly, and the voltage on the other line decreases very slightly.

The indicator reads the difference in voltage between the two signals that may be converted to engineering or force units. Several indicators are available, and they have different advantages and disadvantages. The decision for which indicator to use should be based on what meets your needs and has the best Non-Linearity and stability specifications.

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Figure 37: Morehouse 4215 High Stability Indicator

Non-linearity and uncertainty specifications

The specification that most users look for in an indicator is the Non-Linearity. The better the Non-Linearity is, the less the indicator will contribute to the system uncertainty.

Some indicators on the market may specify accuracies in terms of percentage of reading. Although these may include specifications such as 0.005 % of reading, they can cause negative impacts on the system's uncertainty. The problem is that the resolution or number of digits may be such that the specification will not be maintained. Morehouse has a high stability 4215 indicator pictured above with 0.002 % Non-Linearity specification. The Morehouse 4215 meter will display up to 5 decimals in mV/V, equating to a resolution of 200,000 to 400,000 counts on the most common load cells. In other cases, the indicator may require adjustment at various span points to achieve Non-Linearity between span points, substituting an overall accuracy specification. The purpose of multi-spanning the range in an indicator is to divide the sensor output range into smaller segments and reduce Non-Linearity errors. However, accuracy claims can be questionable. Ensure the accuracy specification includes stability over time, repeatability, Non-Linearity, temperature characteristics, and consideration of the resolution or avoid this type of indicator.

Non-linearity errors in a load system can be drastically reduced by:

- Employing the right calibration and measurement process.
- Pairing a highly stable indicator to the load cell.
- Having the system calibrated to highly accurate standards such as Primary Deadweight Standards.
- Using ASTM E74 or ISO 376 calibration coefficients to convert load cell output values into force units.

Better linearity can be achieved using a Morehouse HADI or 4215 indicators in conjunction with the Morehouse calibration software, which is included with the indicator. When comparing Non-Linearity, the HADI is better than 0.002 % of full scale, the 4215 is better than 0.005 % of full scale, and the PSD is better than 0.005 % of full scale.

Stability and drift

This characteristic is often more difficult to quantify on non-high-end multimeters. Some indicators will specify thermal drift, long-term stability of zero, and some actual stability per range. Often over $10,000, the indicators will fall into specifying drift at different intervals, such as 90 days (about 3 months) and one year. Most indicators under $2,500 will not specifically address 90 days or 1-year stability. Stability can be monitored and maintained by a load cell simulator. However, a user can live with the entire system drift of the load cell and indicator combined.

The $10,000 plus indicators from Agilent, Keysight, and Fluke win in this category, but these are not portable and are often overkill for general application force systems. The Morehouse HADI, with long-term stability of zero at 0.0005 %/year at room temperature, is an excellent choice for under $1,000.00.

Resolution

If you use the indicator as a field system, a stable resolution of greater than 50,000 counts over the load cell's output range will allow higher-order fits. It is also desirable for ASTM E74 calibrations because a higher order fit generally yields a Lower Limit Factor (LLF) and better Class AA and Class A loading ranges. The Morehouse HADI is an excellent indicator to pair with your reference standard to calibrate other load cells, as it can display 4.50000 mV/V stable to within 0.00001 mV/V on a good load cell. The Morehouse 4215 is the next best choice as it is typically stable to within 0.00002 mV/V.

Number of span points

This assumes you require the actual display to read in engineering units and are not okay with 4.00001 mV/V representing 10,000.0 force units such as lbf or kN. If you want the indicator to read 10,000.0 when 10,000.00 is applied and do not want to use a computer for the physical display, then the Morehouse 4215 with multiple span points and store coefficient files is an excellent choice.

Figure 38: Morehouse Gauge Buster 2 Indicator

Another excellent option is the Morehouse/Admet Gauge Buster with a High Stability option. The indicator comes standard with more than 10-point linearization. However, any system's downfall for direct reading is that it cannot be maintained. As the system drifts, so will the readings. Therefore, 10,000.0 today may equate to 10,000.9 in a year. Consequently, we highly recommend reading the output in mV/V and converting it via software or internally. The Morehouse 4215 Plus can use calibration coefficients, or the Morehouse 4215 and HADI with the software are the best options if one wants drift corrected during calibration.

Environmental conditions

Specifications such as temperature effect on zero and temperature effect on span indicate the environmental effects. The Morehouse HADI is excellent in this category, with a typical one ppm per degree Kelvin and a max of 2 ppm.

Four or six wire sensing

Cable resistance is a function of temperature and length. A 4-wire system will have additional errors from temperature changes and from using different length cables. In fact, in most cases changing a cable will require calibration, while a 6-wire system will run sense lines separate from excitation and eliminate the effects due to these variations. The Morehouse 4215 and HADI are both 6-wire systems.

To learn more about the difference between a 4-wire and 6-wire system, read this blog.

Required load cell output.

Some indicators cannot handle load cell output above 2.5 mV/V, creating problems with 3 mV/V and 4 mV/V load cells. Morehouse indicators such as the PSD, HADI, and 4215 handle load cells with output up to 4.5 mV/V.

Figure 39: Morehouse PSD Indicator

Ease of use

This is a preference-based consideration. Some ease-of-use examples are eliminating the need for a computer or power supply. Or not having to use load tables and merely pushing the spacebar for the computer to grab readings. If you want something simple that does not need a power cord, the PSD is the winner. The HADI is the winner if you want a portable system that can run on laptop power and capture readings

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Figure 40: Morehouse PD6100 Indicator

If one can use a power cord and wants a bit more in terms of span points, less cost, and less portability, we have a PD6100 indicator that provides a simple solution for one compression and tension-type load cell. Multiple span points for each channel can be programmed to get closer to the nominal value. This meter is a direct replacement and upgrade over other meters on the market.

Ruggedness

The Morehouse HADI, PD6100, and PSD are enclosed and more durable than the 4215. The PSD, Admet, and PD6100 would be the hardest to break physically and the best choice for a very rugged environment where a computer cannot go.

Number of load cell channels required.

If you want to use several load cells on the system, the Morehouse 4215 or HADI can be used. If the requirement is to set each channel up to multiple span points, then the 4215 or the Morehouse/Admet Indicator would win.

Excitation voltage

Some users may need to change the excitation voltage or have a specific requirement for a 10V dc excitation to be applied to the sensor. In this scenario, the Morehouse 4215 is the only choice.

Choosing the right indicator is often a matter of personal preferences. The HADI indicator comes first for several selection criteria, but these may not be the criteria that matter for your individual needs. Choose the indicator that meets your needs with the best Non-Linearity and stability specifications. A PSD is an excellent choice if you need a rugged, battery-powered indicator with at least 50,000 resolution counts. The HADI may make the most sense if you need a stable system and can carry a laptop. Finally, if you need a system where you must have a live display, use a computer, and need a 10V excitation source, 4215 would be a great option.

The topics covered in this section cover the basics of selecting the right equipment and knowing the proper terminology; the next section will cover more advanced applications.

10. Force Calibration System Accuracy

At Morehouse, we are frequently asked about Accuracy, with questions such as "What is the accuracy of this system you offer for sale?" At first glance, it should be an easy question to answer, and, indeed, we could give a glib answer of "Our system is accurate to 0.005 % of full scale." However, there are so many variables to consider that giving this throwaway answer sets the wrong expectations. Morehouse recommends systems based on an understood requirement and where the end-user can control certain conditions. We must understand the application and know the customer's expectations. When we know these parameters, we can only provide a complete system with the right indicator and appropriate adapters. To further clarify, below is a detailed explanation based on these basic premises and ground rules:

1. The definition of Accuracy per the VIM.
2. You cannot have a more accurate system than the reference standard used to calibrate it.
3. Agreement on the calibration method for portability of the data.
4. Other manufacturers may overpromise and underdeliver.

1. The definition of Accuracy per the VIM

The current draft of the International Vocabulary of Metrology (VIM) defines Measurement Accuracy as "the closeness of agreement between a measured value and a reference value of a measurand."The VIM then states that Accuracy can be interpreted as the combination of measurement trueness and measurement precision.

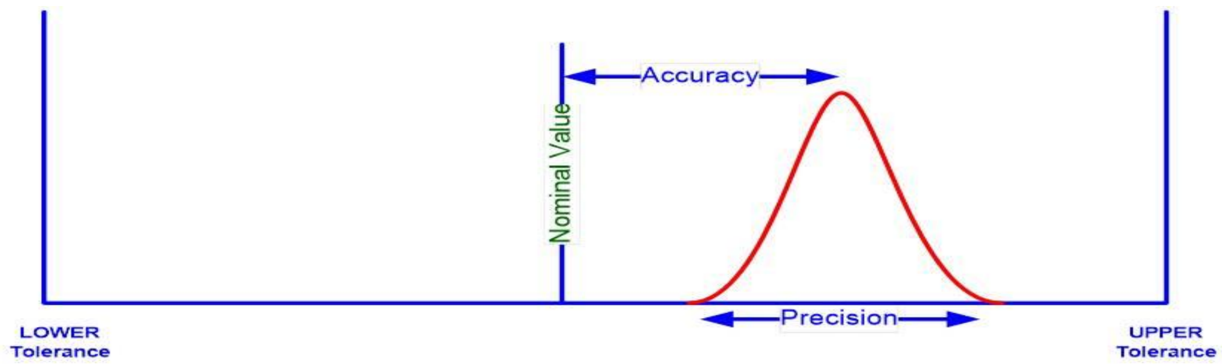

Figure 41: Measurement Accuracy Expressed Graphically

Accuracy is how close the system is to the nominal value (measurement trueness) and how well the system repeats (measurement precision). The above graph gives a graphical representation of this explanation. For example, suppose we had a 10,000 lbf load cell and the accuracy specification was ± 0.05 % of full scale. In that case, we should expect the system to read 10,000 ± 5 lbf when used under the same calibration conditions, and that specification should be repeatable

Repeatability, or how well it repeats, is defined in the VIM as "it repeats when the same procedure, operators, system, operating conditions, location, and force machine are used."1 This definition is what makes defining Accuracy difficult. Force is mechanical, and the interactions of different equipment and loading conditions can significantly affect the output and Accuracy of the force-measuring system. Therefore, we must understand the application, know the expectations, and provide the complete system with the appropriate indicators and adapters..

2. **You cannot have a system that is more accurate than the reference standard used to calibrate it.**

Common sense says that the reference standard must be more accurate and repeatable than the system used to calibrate. Many international standards document these calibration procedures and calculations, which subsequently allow the portability of test data, along with laboratory accreditation groups that keep everyone honest.

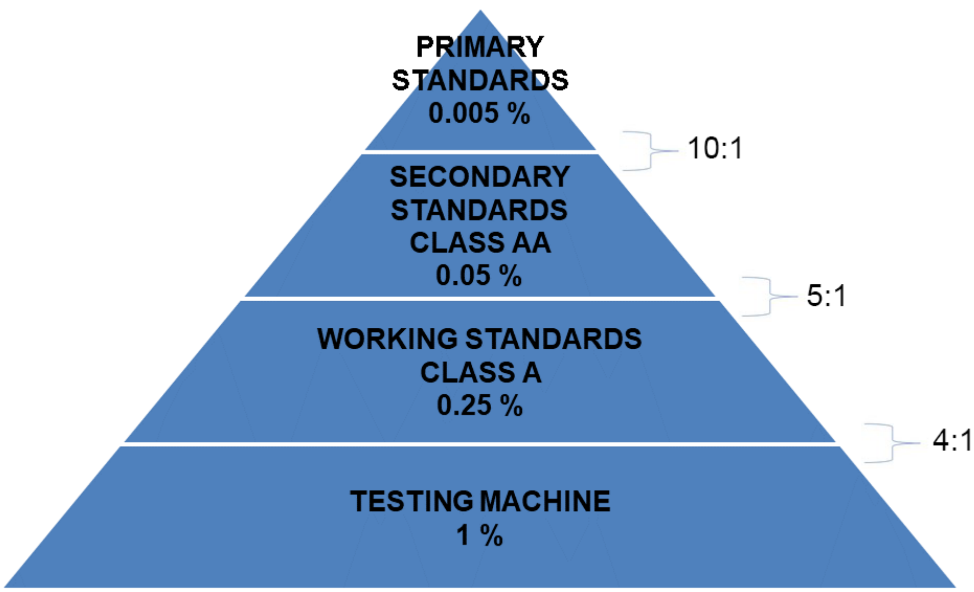

Figure 42: ASTM E74 Pyramid of Ratios

International calibration standards agree on the factors and levels of accuracy, which are depicted here. Any accredited calibration laboratory should have a scope, and their measurement capability should be listed using the abovementioned classifications.

However, things are not always what they appear to be, and you need to know what to look for in these certs and promises. For example, let us look at three labs:

1. The way it should be - using an actual calibration laboratory as an example.
2. Barely acceptable - using a hypothetical laboratory.
3. Disaster - using a hypothetical laboratory.

In these examples, we will demonstrate measurement risk as far as capability is concerned. Here are three examples of what happens at various levels of Accuracy: Morehouse at 0.0016 %, Calibrations "R" Us at 0.04 %, and Malarky Calibration at 0.1 %.

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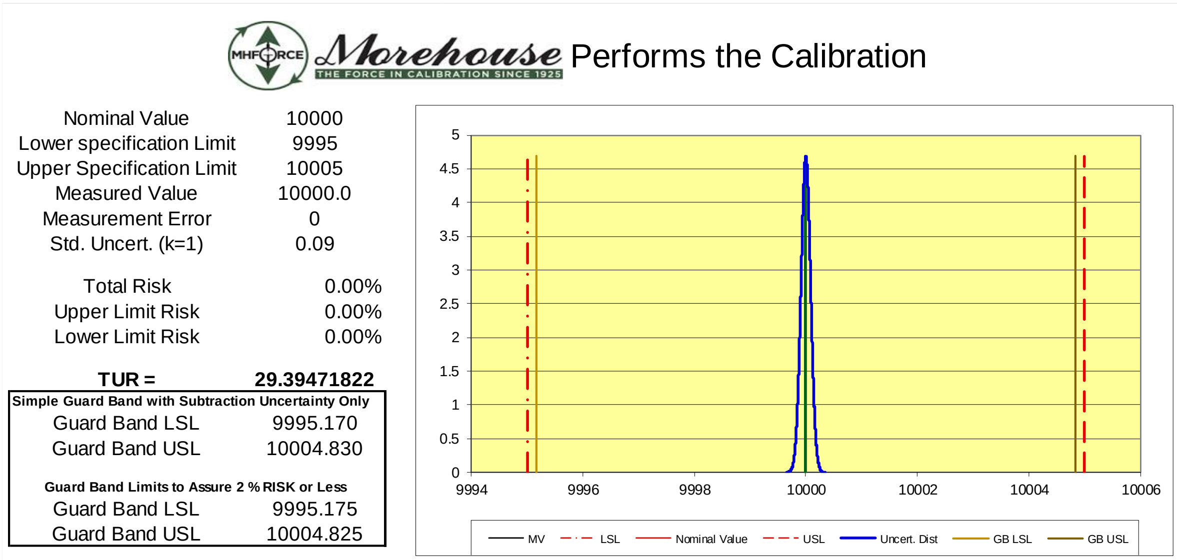

Figure 43: Morehouse Does the Calibration with Primary Standards

When a 10,000 lbf force-measuring system has a specification of ± 5 lbf or 0.05 % of full scale, applying generally accepted compliance decisions, Morehouse can "pass" the instrument if the reading is between 9,995.170 and 10,004.825. This is a significantly larger window to say an instrument is good compared to other calibration laboratories that use secondary standards. They use standards that are typically 10-20 times less accurate.

The second laboratory with the 0.04 % capability can only "pass" the instrument when it reads almost perfect between 9,999.108 and 10,000.892.

Calibration "R" US Performs the Calibration

Nominal Value	10000
Lower specification Limit	9995
Upper Specification Limit	10005
Measured Value	10000.0
Measurement Error	0
Std. Uncert. (k=1)	2.00
Total Risk	1.24%
Upper Limit Risk	0.62%
Lower Limit Risk	0.62%
TUR =	**1.249869804**
Simple Guard Band with Subtraction Uncertainty Only	
Guard Band LSL	9999.000
Guard Band USL	10001.000
Guard Band Limits to Assure 2 % RISK or Less	
Guard Band LSL	9999.108
Guard Band USL	10000.892

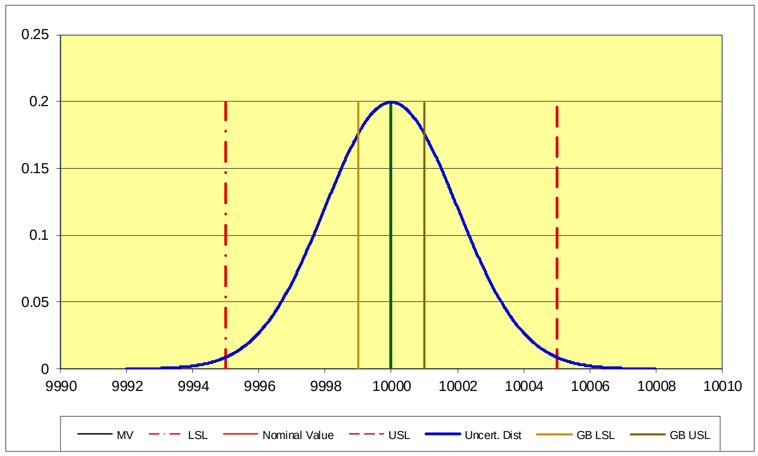

Figure 44: A Lab Using Load Cells as Standards Does the Calibration

Lastly, we have a disaster when a device is submitted to a laboratory that does not have the capability. They “calibrate” the device where the expectation is ± 5 lbf, but the best they can do is ± 10 lbf. Their graph shows that 31.73 % of the curve will be outside the specification limit in the absolute best case. This means the customer must accept an absurd amount of risk. The risk to the end-user of this equipment is high, as is the likelihood of future lawsuits, mass recalls, enormous amounts of rework or scrap, and worse still, a seriously tarnished reputation for quality.

Malarky Calibration Performs the Calibration

Nominal Value	10000
Lower specification Limit	9995
Upper Specification Limit	10005
Measured Value	10000.0
Measurement Error	0
Std. Uncert. (k=1)	5.00
Total Risk	31.73%
Upper Limit Risk	15.87%
Lower Limit Risk	15.87%
TUR =	**0.499991666**
Simple Guard Band with Subtraction Uncertainty Only	
Guard Band LSL	10005.000
Guard Band USL	9995.000
Guard Band Limits to Assure 2 % RISK or Less	
Guard Band LSL	10005.269
Guard Band USL	9994.731

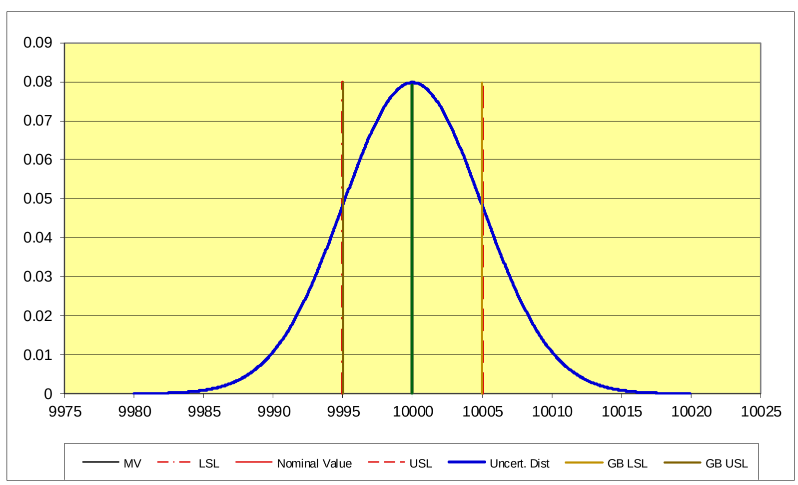

Figure 45: A Lab Using Load Cells as Standards Calibrated by Other Load Cells Does the Calibration

3. Agreement on the calibration method for portability of the data

We will keep this simple by limiting our analysis to the two most common types of calibration:

a. Calibration following ASTM (American Society for Testing & Materials) E74.
b. Commercial type of calibration consisting of a 5 to 10 pt. calibration, known as the non-ASTM method.

a. Morehouse Load Cells and Accuracy with ASTM E74 Calibration
The specifications of our Ultra-Precision Load Cell state that they are accurate to 0.005 % of full scale, meaning that the ASTM LLF (lower limit factor, which is the expected performance of the load cell) is better than 0.005 % of full scale. However, this is only one component to the much larger Calibration and Measurement Capability Uncertainty parameter (sometimes referred to as CMC). When the load cell is under the same conditions that Morehouse used for calibration (same adapters, application with a machine that is just as plumb, level, square, rigid, has low torsion, and other repeatability conditions), it is expected to perform better than 0.005 % of full scale.

On a 10,000 lbf load cell, the expected performance is better than 0.5 lbf (10,000 * 0.005 %). Therefore, at the time of calibration, the load cell's expected performance will be better than 0.005 % or 50 parts per million.

b. Morehouse Load Cells and Accuracy with Non-ASTM Calibration

We know from the accreditation requirements that when we test a good force-measuring system in our machine, it will repeat. We have done countless tests and incorporated these into our CMC uncertainty parameter. When we perform calibrations, we report the measurement uncertainty and take it into account.

Thus, when we set the specification, it includes our measurement uncertainty at the calibration time. That uncertainty captures the repeatability conditions well. The uncertainty is also quite low in almost all cases below 120,000 lbf of Force. The uncertainty is 0.002 % of applied Force or better because Morehouse Deadweight Primary Standards are the most accurate force machines.

4. **Other manufactures may overpromise and underdeliver.**

Figure 46: Averages Hide the Extremes

Morehouse will not overpromise and underdeliver a solution. However, other manufacturers have different methods to test their devices. Some are conservative, others not so much. Morehouse has been around long enough to hear and witness countless customer stories. Often, it is too late because the end-user has bought a device and been promised an accuracy that no other calibration laboratory can meet. These overpromising suppliers do not understand metrology and consequently promote terrible, often impossible, measurement practices. Some notable examples include:

1. Averages are used to specify a tolerance. Figure 5 on page 44 shows a plane being weighed. Not all the values are within the target weight, but based on the average (30,000 lbf), all is good since the target has not been breached.
2. The simple, more economical way is easier than doing things correctly. It is easy to say you can do things, apply some force, and report results without knowing its use. This is an exploitation of the customer.
3. The resolution is equal to Accuracy. This is a large, complex issue with respect to conformity assessment and uncertainty. We have many published guidance documents and whitepapers on Measurement Risk and TUR (Test Uncertainty Ratio) are available for download from our website.
4. Using a specification of non-linearity for Accuracy. The problem is that this does not include critical factors such as the meter, reference standard, adapters, and everything that impacts the measurement results.
5. Not considering the location of the measurement when making conformity assessment a “pass” or a “fail.”

11. Glossary of Terms

This section contains a glossary of common terms in force measurement. It is important to have these for reference because most of these terms are used when speaking about characteristics of load cells, discussions on measurement uncertainty, and calibration standards.

ASTM E74 – Standard Practices for Calibration and Verification for Force-Measuring Instruments: ASTM E74 is a practice that specifies procedures for the calibration of force-measuring instruments.
Best existing force-measuring instrument (ILAC P14): The term "best existing force-measuring instrument" is understood as a force-measuring instrument to be calibrated that is commercially or otherwise available for customers, even if it has a special performance (stability) or has a long history of calibration. For force calibrations, this is often a very stable force transducer (load cell) and indicator with enough resolution to observe differences in repeatability conditions.
Calibration and Measurement Capability (ILAC-P14): A CMC is a Calibration and Measurement Capability available to customers under normal conditions:

a) as described in the laboratory's scope of accreditation granted by a signatory to the ILAC Arrangement; or
b) as published in the BIPM key comparison database (KCDB) of the CIPM MRA.
The scope of accreditation of an accredited calibration laboratory shall include the Calibration and Measurement Capability (CMC) expressed in terms of:
a) measurand or reference material;
b) calibration/measurement method/procedure and/or type of instrument/material to be calibrated/measured;
c) measurement range and additional parameters where applicable, e.g., frequency of applied voltage;
d) uncertainty of measurement

Note: The scope of calibration is where one will find the best capability a company can achieve. It is important to check this when deciding on who to use for a calibration laboratory. If the scope says the best a company can do is 0.02 % from 1,000 lbf through 100,000 lbf, you cannot have uncertainty or accuracy better than that. Also, the best a company can do is usually what is reported on the certificate, though that does not mean that your equipment will be put in the same equipment as used for the CMC. It is imperative to ask the calibration provider about their measurement capability. Morehouse can calibrate equipment up to 120,000 lbf known to within 0.0016 % of applied force. However, if someone sends in an instrument that is 36 inches long, we cannot fit it in that machine, and therefore, the best we can do is 0.01 % of applied in our elongated Universal Calibrating Machine.

Environmental Factors: Environmental conditions, such as temperature, influence the force transducer output. The most common specification is the temperature effect found on the force-measuring instrument's specification sheet. It is important to note that any deviation in environmental conditions from the temperature that the force-measuring instrument was calibrated at must be accounted for in the measurement uncertainty, using the user's force transducer measurements. For example, the laboratory calibrated a force-measuring instrument at 23°C. The force-measuring instrument is then used from 13-33°C or ±10°C from the calibration. Based on the manufacturer's specification, this temperature variation could cause an additional change on the force output by 0.015 % reading per °C, or 0.15 % reading for ±10°C. This number is typically found on the force transducer's specification sheet as Temperature: Effect on Sensitivity, % Reading/100 °C or °F. The value will vary depending on the force transducer used. The example uses a common specification found for most shear-web type force transducers.

Force Units: A force unit can be any unit representing a force. Common force units are N, kgf, lbf. The SI unit for force is N (Newton).

Hysteresis: The phenomenon in which the value of a physical property lags changes in the effect causing it, as for instance when magnetic induction lags the magnetizing force. For force measurements hysteresis is often defined as the algebraic difference between output at a given load descending from the maximum load and output at the same load ascending from the minimum load. Normally it is expressed in units of % full scale. It is normally calculated between 40 - 60 % of full scale.

ISO 376 - Calibration of force proving instruments used for the verification of uniaxial testing machines: ISO 376 is an International Standard that specifies a method for the calibration of force-proving instruments used for the static verification of uniaxial testing machines (e.g., tension/compression testing machines) and describes a procedure for the classification of these instruments.

Lower limit factor (LLF): This is an ASTM specific term. The ASTM E74 standard uses a method of least squares to fit a polynomial function to the data points. The standard deviation of all the deviations from the predicted values by the fit function versus the observed values is found by taking the square root of the sum of all the squared deviations divided by the number of samples minus the degree of polynomial fit used minus one. This number is then multiplied by a coverage factor (k) of 2.4 and then multiplied by the average ratio of force to deflection from the calibration data. The LLF is a statistical estimate of the error in forces computed from the calibration equation of a force-measuring instrument when the instrument is calibrated in accordance with this practice.

Metrological traceability (JCGM 200:2012, 2.41): Property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.

Non-Linearity: The quality of a function that expresses a relationship that is not one of direct proportion. For force measurements, Non-Linearity is defined as the algebraic difference between the output at a specific load and the corresponding point on the straight line drawn between the outputs at minimum load and maximum load. Normally it is expressed in units of % of full scale. It is normally calculated between 40 - 60 % of full scale.

Non-Repeatability (per force transducer specification and not JCGM 200:2012): The maximum difference between output readings for repeated loadings under identical loading and environmental conditions. Normally expressed in units as a % of rated output (RO).

Other Force Measurement Errors: Most force-measuring instruments are susceptible to errors from misalignment, not exercising the force-measuring instrument to full capacity, and improper adapter use. There will be additional errors in almost all cases if the end user fails to have the force-measuring instrument calibrated with the same adapters being used in their application. Other errors may include temperature change under no-load conditions. Errors from loading equipment not being level, square and rigid can have significant contributions.

Primary Standard: Per ASTM E74, a deadweight force is applied directly without intervening mechanisms such as levers, hydraulic multipliers, or the like whose mass has been determined by comparison with reference standards traceable to the International System of Units (SI) of mass. NOTE: Weights used for force measurement require the correction for the effects of local gravity and air buoyancy and must be adjusted to within 0.005 % of nominal force value. The uncertainty budget for primary standards also needs to consider possible force-generating mechanisms other than gravity and air buoyancy, including magnetic, electrostatic, and aerodynamic effects.

Rated Output or RO: The output corresponding to capacity, equal to the algebraic difference between the signal at "(minimal load + capacity)" and the signal at minimum load.

Reference Standard(s) Calibration Uncertainty: This is usually the measurement uncertainty in the calibration of the reference standard(s) used to calibrate the force-measuring instrument.

Reference Standard(s) Stability: The change in the output of the reference standard(s) from one calibration to another. This number is found by comparing multiple calibrations against one another over time. If the instrument is new, the suggestion is to contact the manufacturer for stability estimation on similar instruments.

Repeatability condition of measurement, repeatability condition (JCGM 200:2012, 2.20): The condition of measurement, out of a set of conditions that includes the same measurement procedure, same operators, same measuring system, same operating conditions, and same location, and replicate measurements on the same or similar objects over a short period of time.

Measurement repeatability, Repeatability (JCGM 200:2012, VIM 2.21): Measurement precision under a set of repeatability conditions of measurement.

Repeatability can be calculated by taking the sample standard deviation of a series of at least two measurements at the same test point (three or more are recommended). The overall repeatability of more than one group of data is calculated by taking the square root of the average of variances, which is also known as pooled standard deviation. The purpose of this test is to determine the uncertainty of force generation in a force calibrating machine or test frame. For laboratories testing multiple ranges, it is recommended that the measurement sequence takes a point for every 10% of the ranges they calibrate.

Example: A laboratory performing calibrations from 10 N through 10,000 N. The ranges calibrated may be 10 N - 100 N, 100 N - 1,000 N, and 1,000 N – 10,000 N. Recommended practice would be to take test points at 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1,000, 2,000, 3,000, 4,000, 5,000, 6,000, 7,000, 8,000, 9,000, and 10,000 N.

For this application, zero should never be considered as a first test point. A force-measuring instrument should not be used to calibrate other force-measuring instruments outside the range it was calibrated over. A force-measuring instrument calibrated from 10 % through 100 % of its range may not be capable of calibrating force-measuring instruments outside of this range.

Resolution (JCGM 200:2012, VIM 4.14): The smallest change in a quantity being measured that causes a perceptible change in the corresponding indication.

Resolution of a Displaying Device (JCGM 200:2012, VIM 4.15): The smallest difference between displayed indications that can be meaningfully distinguished.

Reproducibility condition of measurement, reproducibility condition (JCGM 200:2012, VIM 2.24): The condition of measurement, out of a set of conditions that includes different locations, operators, measuring systems, and replicate measurements on the same or similar objects.

Measurement reproducibility, Reproducibility (JCGM 200:2012, VIM 2.25): Measurement precision under reproducibility conditions of measurement.

Reproducibility calculations between technicians can be found by taking the standard deviation of the averages of the same test point taken multiple times (multiple groups). There are other acceptable methods for determining reproducibility, and it is up to the end user to evaluate their process and determine if the method presented makes sense for them. For guidance on Repeatability and Reproducibility, the user should consult ISO 5725 Parts 1 - 6.

Secondary force standard (ASTM E74): An instrument or mechanism, the calibration of which has been established by comparison with primary force standards.

Static Error Band: The band of maximum deviations of the ascending and descending calibration points from a best fit line through zero OUTPUT. It includes the effects of NON-LINEARITY, HYSTERESIS, and non-return to MINIMUM LOAD. Normally expressed in units of %FS.

12. Additional Information

Visit www.mhforce.com for additional guidance on adapters, uncertainty, calibration techniques, and more.

Your time is valuable. Morehouse, thanks you for taking the time to read this document. We wish you the absolute best and are always here to help!

About Morehouse Instrument Company

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. To learn more and stay up to date on future documents and training, subscribe to our newsletter and follow us on social media.

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13. References

[1] Reprinted courtesy of the National Institute of Standards and Technology, U.S. Department of Commerce. Not copyrightable in the United States.
[2] ISO 376, Annex A.4.1 https://www.iso.org/obp/ui/#iso:std:iso:376:ed-4:v1:en