Intercomparisons of the Measurement of Force among National Metrology Institutes

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Abstract

A description will be given of the ongoing Comité International des Poids et Mesures (CIPM) key comparison programs in force. The participation of the National Institute of Standards and Technology (NIST) in these programs to date will be discussed, including details of the preparation for the 4 MN force range comparison, for which NIST is the pilot institute. Various factors involved in force intercomparisons will be examined, such as transducer placement, load application timing, temperature, and adjustments of transducer responses for different nominal applied forces. The use of derived transducer calibration equations as a basis for comparison over a range of force will be discussed.

1. Introduction

As a provider of a force calibration service for force-measuring devices employing deadweight primary force standards[1-3] from 0.5 kN to 4.448 MN, the NIST Mass and Force Group has an ongoing keen interest, as well as a current requirement, in the agreement of its primary force standards with those of other laboratories having force measurement capabilities. An intercomparison among NIST and 27 other laboratories located in the United States was conducted[4] from 1975 to 1982. A bilateral effort was conducted in 1980 to compare the NIST 4.448 MN deadweight machine with hydraulic machines of 1 MN and 5 MN of the National Physical Laboratory (NPL) of the United Kingdom.

A bilateral force intercomparison between NIST and the Physikalisch-Technische Bundesanstalt (PTB) of Germany was performed[5,6] in 1989, in which the three larger NIST deadweight machines having capacities of 498 kN, 1.334 MN, and 4.448 MN were compared with two PTB machines having capacities of 1 MN and 15 MN. The PTB's 1 MN machine employed deadweights, and its 15 MN machine employed a hydraulic force multiplication system. A total of six force transducers were used as transfer standards in this comparison.

NIST has recently participated in a regional intercomparison, piloted by the Centro Nacional de Metrologia (CENAM) of Mexico, among countries from the Interamerican Metrology

System (SIM). This intercomparison, involving nine metrology laboratories in seven countries, was conducted in 1999 and 2000 using a 200 kN force transfer standard that was circulated by CENAM. NIST's 498 kN deadweight machine was employed for these measurements.

In 1999 a formal mutual recognition agreement, drawn up by the CIPM, was implemented among directors of the national metrology institutes of the Member States of the Metre Convention. This agreement provides a framework for the mutual recognition of national measurement standards and calibration certificates issued by national metrology institutes, based in part on results obtained through a set of key comparisons to be carried out by the Consultative Committees of the CIPM. The NIST Mass and Force Group is participating in each of the key comparisons that have been developed by the Consultative Committee for Mass and related quantities (CCM) Force Working Group.

2. CIPM Key Comparisons in Force

A program of key comparisons for force was outlined at a CCM Force Working Group meeting[7] held at CSIRO-NML in Sydney, Australia, in 1998. Four force ranges were chosen for these comparisons: 10 kN, 100 kN, 1 MN, and 4 MN. In order to keep the number of institutes participating in any intercomparison to a manageable number, specific institutes were chosen from four Regional Metrology Organizations (RMO): the Interamerican Metrology System (SIM), the European Collaboration on Measurement Standards (EUROMET), The Asia-Pacific Metrology Program (APMP), and the South African Development Cooperation Regional Metrology Organization (SADCMET). To best accommodate the varying force standard machine capacities of the participating institutes, the four force ranges were divided into two groups, such that one group (A) was assigned a capacity of 100 % of the force range and the other group (B) a capacity of 50 % of the range.

The institutes participating in the intercomparisons for the four force ranges are summarized in Tables 1-4:

Table 1. 10 kN Force Range (2000-2001); Pilot Institute -- MIKES (Finland)

Group A (10 kN)	
RMO	Participating Institutes
SIM	INMETRO (Brazil)
	CENAM (Mexico)
	NIST (USA)
EUROMET	MD (Belgium)
	MIKES (Finland)
	PTB (Germany)
	CNR-IMGC (Italy)
	VSL (Netherlands)
	CEM (Spain)
	UME (Turkey)
	NPL (UK)
APMP	NIM (China)
	NRLM (Japan)

Group B (5 kN)	
RMO	Participating Institutes
EUROMET	MD (Belgium)
	MIKES (Finland)
	BNM-LNE (France)
	CNR-IMGC (Italy)
	VSL (Netherlands)
APMP	NML (Australia)
	KRISS (Korea)
	PSB (Singapore)

Table 2. 100 kN Force Range (2001-2002); Pilot Institute -- NPL (UK)

Group A (100 kN)	
RMO	Participating Institutes
SIM	INMETRO (Brazil)
	CENAM (Mexico)
	NIST (USA)
EUROMET	MD (Belgium)
	MIKES (Finland)
	PTB (Germany)
	CNR-IMGC (Italy)
	SP (Sweden)
	UME (Turkey)
	NPL (UK)
APMP	NIM (China)
	NPL (India)
	KRISS (Korea)

Group B (50 kN)	
RMO	Participating Institutes
EUROMET	BNM-LNE (France)
	NPL (UK)
APMP	NRLM (Japan)
	KRISS (Korea)
	SIRIM (Malaysia)
SADCMET	NML (South Africa)

Table 3. 1 MN Force Range (2003-2004); Pilot Institute -- PTB (Germany)

Group A (1 MN)	
RMO	Participating Institutes
SIM	NIST (USA)
EUROMET	PTB (Germany)
	CNR-IMGC (Italy)
	VNIIM (Russia)
	NPL (UK)
APMP	NIM (China)

Group B (500 kN)	
RMO	Participating Institutes
SIM	NRC (Canada)
EUROMET	BNM-LNE (France)
	PTB (Germany)
	CNR-IMGC (Italy)
	GUM (Poland)
	CEM (Spain)
APMP	NML (Australia)
	NIM (China)
	NRLM (Japan)
	KRISS (Korea)

Table 4. 4 MN Force Range (2002-2003); Pilot Institute -- NIST (USA)

Group A (4 MN)	
RMO	Participating Institutes
SIM	NIST (USA)
EUROMET	BNM-LNE (France)
	PTB (Germany)
	NPL (UK)
APMP	NIM (China)
	NRLM (Japan)
	KRISS (Korea)
SADCMET	NML (South Africa)

Group B (2 MN)	
RMO	Participating Institutes
SIM	NIST (USA)
EUROMET	PTB (Germany)
	GUM (Poland)

Each key comparison, conducted at a specified nominal force, is designed to yield a quantitative measure of the deviation of each institute's national force standard from a key comparison reference value, which is derived from all of the comparison data using a protocol developed by the CIPM that includes averaging the results of the participants while still accounting for outliers. Uncertainties for the deviations are also determined.

Each force comparison is carried out with the use of transfer standards for which the combined standard uncertainty may be much larger than the standard uncertainty in the applied force at one or more of the national metrology institutes. The CCM Force Working Group has developed a set of hardware and procedural specifications designed to minimize the effects of the transfer standard characteristics.

The equipment to be provided by the pilot institute for circulation is listed as follows:

(1) two compression load cells of differing manufacture to be used as transfer standards for Group A, and another two for Group B;
(2) upper and lower fittings for supporting the load cell and applying the load;
(3) a specified electrical calibration device, to be circulated with the transfer standards, for calibrating the load cell voltage-ratio measuring instrument, or indicator, used by each institute.

Each participating institute is to provide its own load cell indicator, of a make and model specified by the working group, to be connected with the transfer standards; each indicator will be calibrated by the pilot institute's calibration device before and after each measurement set.

The same measurement sequence is to be conducted for each transfer standard by the participating institutes at a temperature of 20 °C ± 0.2 °C. The sequence is a series of identical preload or measurement cycles, with each cycle for the Group A comparison consisting of a zero-load step, 50 % step, 100 % step, and returning to zero in preparation for the next cycle. (The Group B comparison omits the 50 % step in each cycle.) The duration of each step is specified to be six minutes, to provide a long delay between the application of the load and the reading of the indicator. The sequence proceeds as follows:

(1) an initial set of four preload cycles and two measurement cycles at a transducer orientation of 0°;
(2) one preload cycle and one measurement cycle at each of six orientations spaced 60° apart;
(3) a repetition of the preload and measurement cycles at the same six orientations.

The entire sequence is to proceed without any interruption for the nine-hour time duration required to complete it.

The circulation among laboratories is to follow a "star" pattern, with the transfer standards returning to the pilot laboratory after each measurement set by a participating laboratory. The pilot laboratory conducts the same measurement set as the participating laboratories each time the devices are returned.

3. NIST Participation Details

NIST has already concluded its participation in the 10 kN key comparison force range, conducted during the week of June 5, 2000. These measurements were performed on two 10 kN force transfer standards circulated by the pilot institute of MIKES in Finland among the laboratories shown in Table 1. One transfer standard was a cylindrically shaped load cell and the other an S-shaped shear beam load cell fixtured to be loaded in compression. The measurements were performed in the NIST 27 kN deadweight machine. The nine-hour sequence, described in Sec. 2, was required to be performed once for each transducer, and was actually performed twice in order to assess NIST repeatability using this procedure. Thus the measurements spanned four days.

Each nine-hour procedure yielded a net mean transducer response for the 5 kN force step and for the 10 kN force step. The results of NIST's two repetitions of the sequence repeated within 0.0015 % of the 10 kN response for the cylindrical transducer, and within 0.0003 % for the shear beam transducer. The comparison of the results for the participating laboratories will be reported by the pilot institute, MIKES, after the conclusion of the circulation, which is to be completed later this year.

The measurement dates for NIST's participation in the 100 kN and 1 MN force range key comparisons, being piloted by NPL and PTB, respectively, have not yet been scheduled. The NIST 113 kN and 1.334 MN deadweight machines, respectively, will be used in these comparisons.

As shown in Table 4, NIST is the pilot institute for the 4 MN key comparison force range. NIST has the only facility with deadweights to that range; PTB has deadweights to 2 MN, for the Group B subrange. The NIST Mass and Force Group has purchased two precision force transfer standards, of capacities of 4 MN and 5 MN, to be circulated for this comparison. As of the end of March, 2001, one of these has been received. Because there are few participants for Group B, the CCM Force Working Group has directed that NIST need not purchase the two 2 MN capacity transducers; instead, the laboratories participating in Group B will receive the two Group A load cells and load them to 2 MN.

These transducers are from two different manufacturers, and have the best specifications available in this force range. The rated specifications for the two transducers include:

(a) a maximum repeatability error for different mounting positions of 0.005 % and 0.02 %, respectively;
(b) a maximum temperature sensitivity of 0.001 %/°C and 0.005 %/°C, respectively;
(c) a maximum creep error over a 15 min period of 0.008 % and 0.04 %, respectively.

A circulation schedule beginning January, 2002, and ending December, 2003, is possible for incorporating all of the institutes shown in Table 4 if the time of possession at each facility is limited to one month and the time for each shipment is limited to two weeks.

Preliminary work is underway to characterize each transducer prior to circulation, with respect to the following: the repeatability for different mounting orientations within the NIST machine, any long term drift that is detectable over the first few months, the thermal sensitivity, the creep response, and the transducer calibration equation.

4. Uncertainty Factors

An objective of the key comparison in force is to obtain the relative differences among participating institutes in the apparent applied forces for a specified nominal force applied with each institute's national force standard. A difficulty in this endeavor is an uncertainty associated with the use of a force transfer standard that may be many times greater than the uncertainty in an institute's applied force.

The NIST Mass and Force Group estimates the standard uncertainty in the forces applied by its deadweight force standards to be 0.0005 % of the applied force. The factors contributing to this uncertainty, which are associated with the determination of the deadweight mass, the gravitational acceleration, and the air density, have been described previously[1]. The use of the term *standard uncertainty* is in accordance with NIST guidelines for the expression of uncertainty[8], and here represents the estimated standard deviation in the applied force.

The uncertainties associated with the use of a force transducer as a transfer standard in an intercomparison include the effects of transducer placement, thermal sensitivity, load application timing, and adjustments for different nominal forces. These are described in the following sections.

4.1. Transducer Placement

The variation in a force transducer's response with mounting alignment and orientation within a particular force application machine (and thus relative to mounting in different machines) is often a large source of uncertainty. The CIPM key comparison in force seeks to minimize this source of uncertainty by (a) recommending the purchase of transducers with good specifications over mounting positions, (b) specifying that the transducers be purchased with matching upper and lower fittings to facilitate alignment and reduce the effect of interaction with different machines, and (c) incorporating six orientational positions in the loading sequence.

The rated values for the maximum repeatability error for different mounting positions are 0.005 % and 0.02 % for the two transfer standards purchased by NIST for the 4 MN range. The use of six mounting orientations in the intercomparison may reduce the associated uncertainties to the neighborhood of 0.002 % and 0.009 %, respectively (i.e., the above values for repeatability times the factor $(n\text{-}1)^{-1/2}$, where n is the number of mounting orientations).

4.2 Thermal Sensitivity

The effect of the variation of the transducer response with temperature is to be controlled through the purchase of transfer standards with low thermal sensitivity, and by specifying a narrow window of ±0.2 °C for the participating institutes to meet. For the NIST 4 MN range transfer standards, the resulting uncertainty associated with temperature variations among the participants should be limited to 0.0002 % to 0.001 %.

It is possible to make corrections for this effect if the actual transducer sensitivities are known, and if the temperatures at the times of measurement are accurately measured. The NIST Mass and Force Group intends to provide for this with initial and final characterizations of the transducer temperature sensitivities, and (as was also done by MIKES for the 10 kN range) by supplying monitoring sensors to accompany the transfer standards for automatically recording the temperature during the circulation schedule.

4.3 Load Application Timing

The response of a transducer to an applied force is dependent upon the magnitude, timing, and loading direction of the forces that have immediately preceded the force being applied. The key comparison procedure minimizes the uncertainty associated with this effect by excluding any descending sequence of forces, by specifying a sequence and timing of force application to be followed uniformly by all participants, by setting a long delay of six minutes before reading the indicator after each force application, and by recommending the purchase of transfer standards that have low creep.

For the 4 MN force range intercomparison, a difference in the loading characteristics may remain between the NIST 4.448 MN deadweight machine and the machines of other institutes. The NIST machine makes the zero-to-2 MN transition by adding nine equal weights successively at uniform time intervals, reaching 2 MN after 162 s. The 2 MN-to-4 MN transition is similar. For machines with hydraulic force application, these transitions may be accomplished as single step functions. Since 198 s of delay before reading the indicator still remain after reaching the target force at NIST, the effect of interlaboratory differences is probably small.

A larger difference may pertain to the 4 MN-to-zero transition. This transition, as shown in Figure 1, requires 390 s to complete in the NIST machine. Thus the duration for this step will need to be extended beyond six minutes. The zero reading at the end of this transition is used to calculate the deflections of subsequent steps. Thus attempts may be needed to characterize the effect due to these loading differences, possibly through supplementary measurements at the other laboratories.

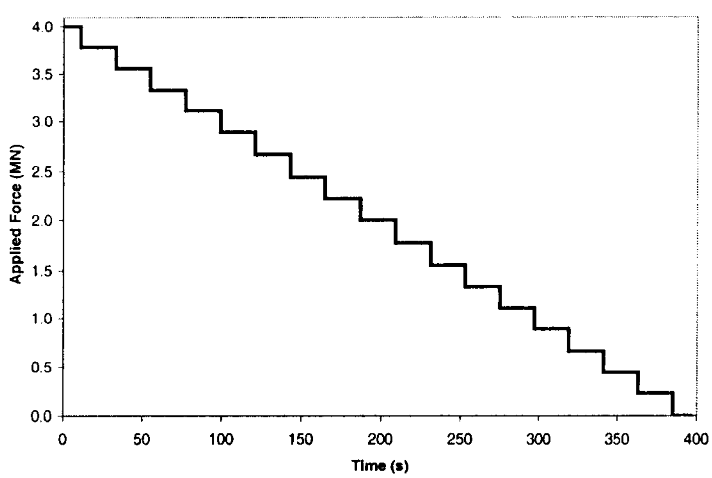

Figure 1. Actual applied force vs. time for the 4 MN-to-zero transition in the NIST 4.448 MN deadweight machine.

4.4 Adjustments for Different Nominal Forces

Comparing the national force standards of several institutes for specific nominal applied forces cannot always be directly implemented because the weight sets of some machines may not be able to attain the exact target values. The NIST 4.448 MN deadweight machine actually applies 2.0017 MN and 4.0034 MN for the two steps of the 4 MN force range, a deviation of 0.085 %. For the 1 MN force range, the NIST applied forces will deviate from the target forces by 6.8 %.

An intercomparison among laboratories can be carried out only if such deviations are numerically adjusted. This can be accomplished in a precise manner for small adjustments if the transducer calibration equation has been determined, as described below in Sec. 5. Such calibration measurements are being carried out prior to circulation on the two transfer standards NIST is preparing for the 4 MN range.

5. Comparison using Transducer Calibration Equations

The CIPM key comparison procedure compares institutes' national force standards at one or two specific force values for a given range. For a deadweight force standard machine, this procedure may bring only a particular subset of that machine's weights into comparison with other institutes' standards. In addition, the key comparison target force may differ significantly from the force values achievable with a particular weight set, requiring a large adjustment with a possibly significant error.

When it is desirable to compare force standard machines over an extended range of forces, the above considerations may be addressed by comparing the transducer response curves derived from calibration measurements in each machine for the transfer standard employed. The NIST deadweight machines are primarily used for the calibration of force transducers, usually in accordance with ASTM E 74-00, *Standard Practice of Calibration of Force-Measuring Instruments for Verifying the Force Indication of Testing Machines*[9]. A comparison of the calibration equations for the same transducer determined from two or more force standard machines directly compares the end-use operational output of the machines.

The calibration data acquired for a force sensor consists of the values of the forces applied to the sensor and the associated readings of the indicating system. The applied forces span the working range of the sensor and incorporate several orientations of the sensor in the force machine. The readings at finite applied loads are corrected for readings at no applied force to obtain the net responses, or deflections. A calibration equation is derived by fitting a polynomial equation to the force and net response values using the method of least squares, yielding the form

$$R = A_0 + \sum A_i F^i \ , \qquad (1)$$

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

Figure 2 shows an example of a comparison between two laboratories of the transducer response determined by each laboratory. The smooth curve is the difference between two smooth transducer response curves, each having the form of Eq. (1), derived for the same force transducer from least-squares fits to data from the NIST 498 kN deadweight machine and from a deadweight machine in another laboratory (not to be identified at this point; the purpose of this section is only to describe the comparison technique). The difference is expressed in percent relative to the response at maximum load. The smooth curve in Figure 2 can be considered to be an estimate of the difference between the applied forces of the two laboratories, for any nominal force value in the range covered by this curve. Superimposed on this plot are the differences between the mean deflections obtained at each laboratory for the individual load points used in the comparison.

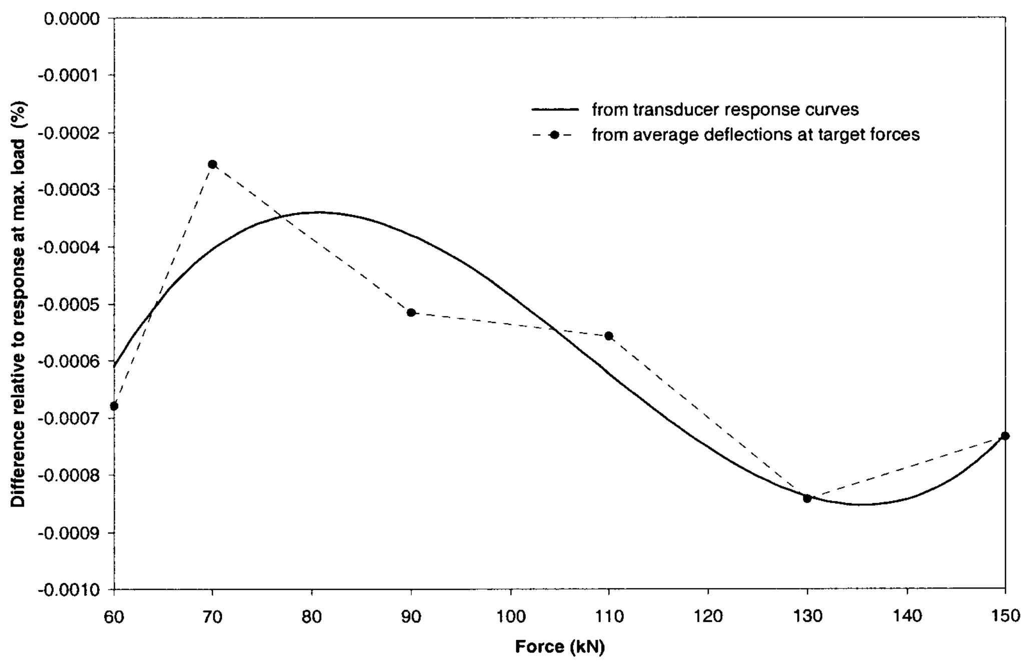

Figure 2. The difference between the deflections obtained at NIST and another laboratory for the same force transducer.

The expanded uncertainty *U*, calculated for the transducer response curve derived for the NIST data in the above comparison, is 0.0027 % relative to the response at maximum load. (The expanded uncertainty is defined for a coverage factor of 2, giving a confidence level of about 95 %, in accordance with NIST guidelines for the expression of uncertainty[8].) The corresponding expanded uncertainty for the other laboratory calculated from the data is comparable to the NIST value.

As a part of its quality assurance program, the NIST Mass and Force Group periodically conducts intercomparisons of its own deadweight machines, using a set of precision force transducers as transfer standards among the machines. While it is recognized that the uncertainty in the response of each force transducer is greater than the uncertainty in the applied force, this process is useful in maintaining assurance that detectable faults have not crept into one or more of the measurement systems.

Since the NIST deadweight machines are housed in separate laboratory rooms with separate climate controls, and each machine has its own voltage-ratio excitation supply and measuring instrument, the quality assurance process provides a check on each entire system, rather than focusing solely on the deadweight force standards.

Figure 3 shows a typical intercomparison involving four NIST deadweight machines (the 498 kN, 113 kN, 27 kN, and 2.2 kN machines) and their associated instruments. The intercomparison was done by performing an independent ASTM E 74 calibration measurement[7] on the same load cell in each machine, without any attempts to match weights across machines. The capacity of the transfer standard was 44.48 kN. For the purpose of comparison, the 113 kN machine was chosen as a reference, being the most closely "matched" to the capacity of the load cell.

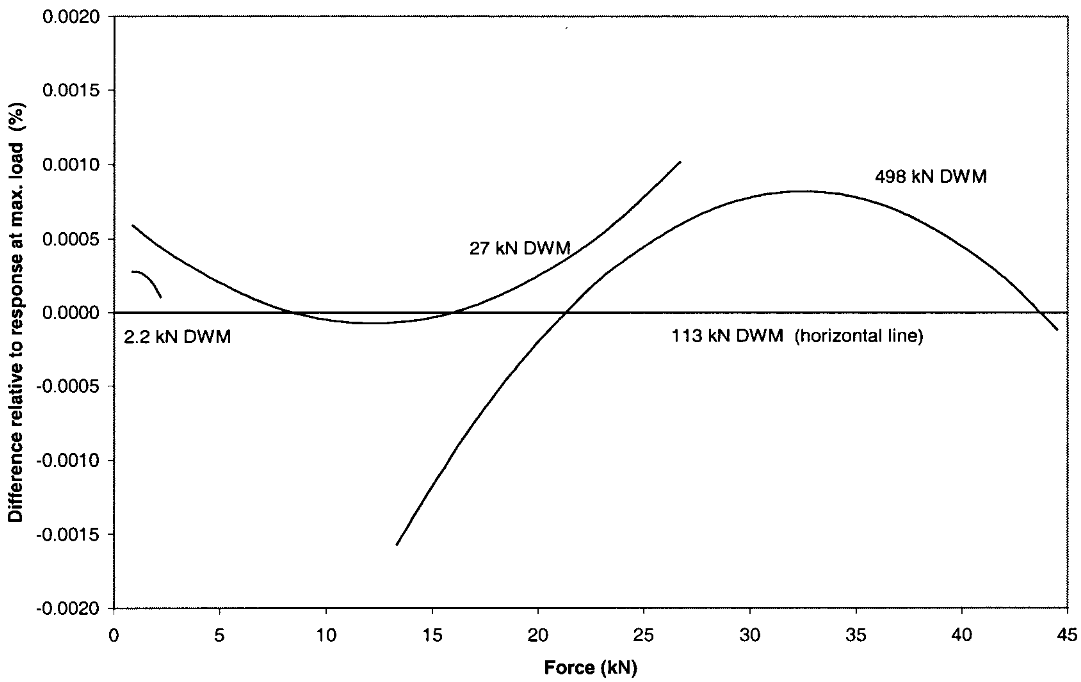

Figure 3. Intercomparison of four NIST deadweight machines (DWMs), shown as the difference between the 113 kN machine and the other three.

The horizontal reference line at 0 % represents the 113 kN machine, and the three curves shown represent the other three machines, each curve giving the difference between the calibration equation from that machine and the calibration equation from the 113 kN machine. The three difference curves are plotted in percent relative to the response at the load cell capacity of 44.48 kN. The length of each curve represents the common force range that the calibration measurement in that machine and in the 113 kN machine can cover for the load cell employed.

The 2.2 kN machine, having a capacity that is small relative to that of the load cell, is depicted by a very short curve on the plot. It is best characterized by means of a smaller load cell; however, it is included here to show that machines of considerably different ranges still demonstrate comparable force values when acting upon the same device.

The expanded uncertainty for the force equation derived from the 113 kN machine, incorporating all significant sources of error, is about 0.0023 % relative to the response at the load cell capacity; this uncertainty is slightly less for the other machines. As the difference curves all range from -0.0015 % to +0.0010 %, the intercomparison is regarded as satisfactory.

6. Conclusion

The intercomparison of national force standards among metrology institutes serves to promote confidence in these standards, foster collaboration among institutes to improve measurement methods, and to support current mutual recognition agreements in the area of force. While measurement uncertainties in the use of force transducers as intercomparison transfer standards may be limited by certain transducer characteristics, appropriate measurement and analysis protocols can allow laboratory differences of less than 0.005 % to be distinguished. The NIST Mass and Force group is anticipating a comparable level of comparison in the 4 MN force range key comparison being piloted by NIST.

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