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Uncertainty of Force Measurements

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Calibration Guide

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Purpose

This document has been produced to improve harmonisation in determination of uncertainties in force measurements. It provides information on measurement capabilities achieved by force calibration machines and gives guidance to calibration laboratories to establish a procedure for the expression of the overall uncertainty of calibration results of force transducers for calibrations performed according to ISO 376 and to other procedures. It also gives guidance on the estimation of the uncertainty of the forces subsequently measured by these transducers, either during the calibration of materials testing machines or in other industrial force measurement applications.

Authorship

The original document (EAL-G22, which was later re-branded EA-10/04) was developed by EAL Committee 2 (Calibration and Testing Activities), based on the draft produced by the EAL Expert Group on Mechanical Measurements. It is now amended and re-published by the EURAMET Technical Committee for Mass and Related Quantities (TC-M).

Official language

The English language version of this publication is the definitive version. The EURAMET Secretariat can give permission to translate this text into other languages, subject to certain conditions available on application.

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Guidance publications

This document represents preferred practice on how the relevant clauses of the accreditation standards might be applied in the context of the subject matter of this document. The approaches taken are not mandatory and are for the guidance of calibration laboratories. The document has been produced as a means of promoting a consistent approach to laboratory accreditation.

Further information

For further information about this publication, contact your National member of the EURAMET Technical Committee for Mass and Related Quantities (see www.euramet.org/index.php?id=tc-m).

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1 Introduction

In a wide range of industrial applications, there is the need to measure a tensile or compressive force. These applications range from materials testing to industrial weighing, and from engine thrust measurement to the proof loading of bridge bearings. In each application, there will be an uncertainty requirement on the force measurement – the equipment used to make the measurement must be traceable to a realisation of the SI unit of force (the newton) within this required uncertainty.

The situation may vary slightly from country to country, but this document is based on a country having one national metrology institute (NMI) realising the newton in a number of national force standard machines, and a number of calibration laboratories, generally accredited by their national accreditation body, using force calibration machines to calibrate force-measuring instruments. These instruments may then be used either to measure forces directly or to calibrate industrial force-generating equipment, such as tensile testing machines.

The force calibration machines will generally be traceable to the national force standard machines via comparisons using precision force transducers – and the accredited calibration and measurement capability (CMC) of the calibration laboratory will be based on the results of these comparisons.

Calibration of force-measuring instruments in the force calibration machines will generally be carried out in accordance with a documented procedure, such as ISO 376 [1], and the uncertainty of the calibration results will be dependent on the machine's CMC, as well as on the performance of the instrument during the calibration.

Similarly, the uncertainty of the calibration of the industrial force-generating equipment will be partly dependent on the uncertainty arising from the force-measuring instrument, and the uncertainty of any subsequent force measurements will depend in part on the uncertainty associated with the force-generating equipment.

It can be seen that the uncertainty of the final force measurement is dependent on all of the previous traceability stages, and this document aims to give guidance on how to estimate all of these contributions.

The above traceability situation strictly covers only static force measurement, whereas a significant number of industrial force measurement applications, such as fatigue and impact testing, are dynamic in nature – additional uncertainty considerations need to be made when dealing with such measurement areas.

2 Scope

The scope of this document is to give guidance on the estimation of force measurement uncertainty in a range of different areas, namely:

- uncertainty of forces generated by national force standard machines
- uncertainty of forces generated by force calibration machines (i.e. determination of CMC)
- uncertainty of forces measured by force-measuring instruments
- uncertainty of forces generated by industrial force-generating equipment

In each of these cases, the uncertainty determination is based on two major components – the uncertainty obtained during the calibration of the equipment and the uncertainty resulting from the equipment's subsequent use.

In addition, other uncertainty contributions that may need to be considered when dealing with dynamic force measurement applications are briefly discussed.

3 Symbols and abbreviations

Symbol	Description	Unit
a_{drift}	half-width of relative variation due to drift	-
b'	ISO 376 relative repeatability error	%
c	relative creep error	%
d	degree of equation	-
f_0	ISO 376 relative zero error	%
F	force	N
F_{min}	minimum calibration force	N
F_{nfsm}	force generated by national force standard machine	N
g	acceleration due to gravity	$\text{m}\cdot\text{s}^{-2}$
i_{30}	output 30 s after application or removal of maximum calibration force	$\text{mV}\cdot\text{V}^{-1}$
i_{300}	output 300 s after application or removal of maximum calibration force	$\text{mV}\cdot\text{V}^{-1}$
i_{f}	final indicator reading – i.e. after force application	$\text{mV}\cdot\text{V}^{-1}$
i_{o}	original indicator reading – i.e. before force application	$\text{mV}\cdot\text{V}^{-1}$
k	coverage factor	-
K	force instrument's temperature coefficient	$^{\circ}\text{C}^{-1}$
K_{ts}	calibration coefficient of transfer standard	$\text{N}\cdot(\text{mV}\cdot\text{V}^{-1})^{-1}$
m	mass	kg
r	resolution	N
w_{approx}	relative standard uncertainty due to approximation to interpolation equation	-
w_{c}	combined relative standard uncertainty	-
w_{cal}	relative standard uncertainty due to calibration of transfer standard	-
w_{corr}	relative standard uncertainty associated with correction value	-
$w(D)$	relative standard uncertainty due to drift	-
$w(d_{\text{fcm}})$	relative standard uncertainty associated with force generation in force calibration machine	-
w_{drift}	relative standard uncertainty due to drift of transfer standard	-
$w(F_{\text{nfsm}})$	relative standard uncertainty of force generated by national force standard machine	-
w_i	relative standard uncertainty associated with parameter i	-
$w(K_{\text{ts}})$	relative standard uncertainty of force value indicated by transfer standard	-
$w_{\text{ref\_instab}}$	relative standard uncertainty of reference force transducer's long-term instability	-
$w_{\text{ref\_tra}}$	relative standard uncertainty of calibration of reference force transducer	-
w_{rep}	relative standard uncertainty due to repeatability	-
w_{res}	relative standard uncertainty due to resolution	-
w_{rev}	relative standard uncertainty due to reversibility	-
w_{rv}	relative standard uncertainty of reference value	-
w_{std}	relative standard uncertainty due to transfer standard	-

w_{temp}	relative standard uncertainty due to temperature effects	-
$w(X)$	relative standard uncertainty of mean deflection	-
W	relative expanded uncertainty	-
W_{CMC}	relative expanded uncertainty of force generated by force calibration machine, equivalent to CMC (calibration and measurement capability)	-
W_{nfsm}	relative expanded uncertainty of force generated by national force standard machine	-
$W_{\mathrm{ref\_instab}}$	relative expanded uncertainty of reference force transducer’s long-term instability	-
$W_{\mathrm{ref\_tra}}$	relative expanded uncertainty of calibration of reference force transducer	-
W_{rv}	relative expanded uncertainty of reference value	-
W_{ts}	relative expanded uncertainty of force value indicated by transfer standard	-
X	mean deflection	$\mathrm{mV \cdot V^{-1}}$
X_{fcm}	mean deflection in force calibration machine	$\mathrm{mV \cdot V^{-1}}$
X_{fcm_i}	individual deflection in force calibration machine	$\mathrm{mV \cdot V^{-1}}$
X_i	individual deflection value in run i	$\mathrm{mV \cdot V^{-1}}$
X_{N}	deflection at maximum calibration force	$\mathrm{mV \cdot V^{-1}}$
$\bar{X}_{\mathrm{r}}$	mean deflection from ISO 376 runs 1, 3, and 5	$\mathrm{mV \cdot V^{-1}}$
δ_{r}	sum of squared deviations between mean deflection and calculated value	$(\mathrm{mV \cdot V^{-1}})^2$
Δd_{d}	decremental relative deviation between reference value and value obtained in force calibration machine	-
Δd_{i}	incremental relative deviation between reference value and value obtained in force calibration machine	-
Δd_{max}	absolute value of maximum relative deviation between reference value and value obtained in force calibration machine	-
ΔT	range of temperature during calibration	°C
ρ_{a}	density of air	$\mathrm{kg \cdot m^{-3}}$
ρ_{m}	density of weight	$\mathrm{kg \cdot m^{-3}}$
σ_{F}	standard deviation of force	N
σ_{g}	standard deviation of acceleration due to gravity	$\mathrm{m \cdot s^{-2}}$
σ_{m}	standard deviation of mass	kg
$\sigma_{\rho\mathrm{a}}$	standard deviation of density of air	$\mathrm{kg \cdot m^{-3}}$
$\sigma_{\rho\mathrm{m}}$	standard deviation of density of weight	$\mathrm{kg \cdot m^{-3}}$

4 National force standard machines

National force standard machines can be split into two categories – those where the generated force is calibrated against other force machines by the use of transfer standards and those where the generated force is calculated from a mathematical model of the force generation system. For the first category, the uncertainty of the force can be calculated following the guidance given in "5 Force calibration machines". This section deals purely with the second category which may include, but is not limited to, machines of the following types:

- deadweight
- hydraulic amplification
- lever amplification
- multiple transducer system

4.1 Deadweight force standard machines

The net downward vertical force (F, in N) generated by a weight (of mass m, in kg, and density ρ_m, in kg·m^{-3}) suspended in air (of density ρ_a, in kg·m^{-3}) in the Earth's gravitational field (of strength g, in m·s^{-2}) is given by:

$$F = mg\left(1 - \rho_\mathrm{a}/\rho_\mathrm{m}\right) \tag{1}$$

The uncertainties in the four variables on the right-hand side of this equation can be combined to determine the uncertainty in the calculated value of force (where σ_x is the standard deviation associated with variable x):

$$\left(\sigma_F/F\right)^2 = \left(\sigma_m/m\right)^2 + \left(\sigma_g/g\right)^2 + \left(\rho_\mathrm{a}/\rho_\mathrm{m}\right)^2 \times \left(\left(\sigma_{\rho_\mathrm{m}}/\rho_\mathrm{m}\right)^2 + \left(\sigma_{\rho_\mathrm{a}}/\rho_\mathrm{a}\right)^2\right) \tag{2}$$

The uncertainty associated with each of the variables should take into account its variation over time – air density and gravitational acceleration will vary throughout any given day, whereas the mass value is likely to be subject to longer-term drift, caused by wear, contamination, and surface stability.

In the case where the true mass value of the weight is not known, but its conventional mass value m_c is (i.e. the mass of a weight of density 8 000 kg·m^{-3} which will balance it in air of density 1.2 kg·m^{-3}) – the conventional mass is normally the value given on a mass calibration certificate – these two equations are amended as follows:

$$F = m_\mathrm{c}g\left(1 - \left(1.2/8\,000\right) + \left(\left(1.2 - \rho_\mathrm{a}\right)/\rho_\mathrm{m}\right)\right) \tag{3}$$

and

$$\left(\sigma_F/F\right)^2 = \left(\sigma_{m_\mathrm{c}}/m_\mathrm{c}\right)^2 + \left(\sigma_g/g\right)^2 + \left(\left(1.2 - \rho_\mathrm{a}\right)/\rho_\mathrm{m}\right)^2 \times \left(\left(\sigma_{\rho_\mathrm{m}}/\rho_\mathrm{m}\right)^2 + \left(\sigma_{\rho_\mathrm{a}}/\left(1.2 - \rho_\mathrm{a}\right)\right)^2\right) \tag{4}$$

The uncertainty budget for the machine also needs to consider possible force-generating mechanisms other than gravity and air buoyancy, including magnetic, electrostatic, and aerodynamic effects.

For machines in which the applied force is not a pure deadweight – where, for example, the weight of the loading frame is tared off with a lever and counterweight, or the scalepan is stabilised with a guidance system – the effect of any frictional or unbalanced forces needs to be additionally incorporated within the uncertainty budget, at each force within the machine's range.

The ability of the machine to hold the force transducer at the correct alignment – i.e. with its measuring axis vertical and concentric to the applied force – at each applied force will have an effect on the magnitude of the force vector applied to the transducer's measuring axis, and this should also be included in the uncertainty budget. Other machine-specific characteristics, such as compression platen stiffness and side force generation, may also affect transducer output (this will depend on the transducer's sensitivity to such effects) but do not contribute to the uncertainty of the applied force along the transducer's measuring axis – and this is the uncertainty to which an NMI's CMC value refers.

The uncertainty of measurement associated with the force scales realised at NMIs is ensured by means of international intercomparisons. The expanded relative uncertainty of measurement with which force values can be generated by deadweight force standard machines is stated by various NMIs as being as low as 1×10^{-5}. In practice, however, when different deadweight force standard machines are used to calibrate the same force transducer, the differences between the results may often be significantly greater, due to mechanical interaction effects. This became evident in BCR and WECC interlaboratory comparisons, based on force transducer calibrations carried out in 1987 and 1991 respectively [2, 3].

4.2 Hydraulic amplification force standard machines

In a hydraulic amplification machine, a deadweight force is amplified by the use of a hydraulic system with piston/cylinder assemblies of different effective areas, increasing the force by a factor approximately equal to the ratio of the two areas. Where the traceability of this larger force is directly derived from SI units, the uncertainty contributions that need to be considered will include, but are not limited to, the following:

- uncertainty of the deadweight force (see "4.1 Deadweight force standard machines" for details)
- uncertainty of both piston/cylinder assembly dimensional measurements
- uncertainty due to pressure differences throughout the hydraulic circuitry, caused by hydraulic fluid flow and vertical height
- uncertainty due to effect of temperature on area ratio (thermal expansion, at possibly different rates, of piston/cylinder assemblies) and pressure drops (temperature dependence of hydraulic fluid's viscosity)
- uncertainty due to effect of pressure on area ratio (elastic distortion of piston/cylinder assemblies)
- uncertainty due to instability of control system
- uncertainty due to friction/hysteresis within piston/cylinder assemblies or mechanical guidance systems
- uncertainty associated with setting the initial zero force point

Where possible, corrections should be made for the estimated effect of any of these components on the magnitude of the generated force. The standard uncertainties associated with these corrections, together with the standard uncertainties due to any effects that cannot be corrected for, should be combined in quadrature (if it can be demonstrated that the effects are not correlated) and then multiplied by a coverage factor to derive an expanded uncertainty for the generated force.

4.3 Lever amplification force standard machines

In a lever amplification machine, a deadweight force is amplified by the use of one or more mechanical lever systems, increasing the force by a factor approximately equal to the ratio of the lever arm lengths. Where the traceability of this larger force is directly derived from SI units, the uncertainty contributions that need to be considered will include, but are not limited to, the following:

- uncertainty of the deadweight force (see "4.1 Deadweight force standard machines" for details)
- uncertainty of the lever system dimensional measurements
- uncertainty due to friction within the lever systems
- uncertainty due to effect of temperature on lever arm ratio (thermal expansion, at possibly different rates, of lever systems)
- uncertainty due to effect of applied force magnitude on lever arm ratio (elastic distortion of lever systems)
- uncertainty due to instability of control system
- uncertainty due to alignment of generated force with transducer's measuring axis
- uncertainty due to positional reproducibility of moveable parts
- uncertainty due to wear/stability of knife-edges, if used

Where possible, corrections should be made for the estimated effect of any of these components on the magnitude of the generated force. The standard uncertainties associated with these corrections, together with the standard uncertainties due to any effects that cannot be corrected for, should be combined in quadrature (if it can be demonstrated that the effects are not correlated) and then multiplied by a coverage factor to derive an expanded uncertainty for the generated force.

4.4 Multiple transducer system force standard machines

These machines are based on a number of force transducers, individually calibrated in a force standard machine and then loaded in parallel. The generated force is calculated as the sum of the forces being measured by the individual transducers. For this type of machine, the uncertainty contributions that need to be considered will include, but are not limited to, the following:

- uncertainty of the calibrations of the individual transducers (for guidance, see section 6)
- uncertainty due to use of transducers subsequent to their calibration (for guidance, see section 7.1)
- uncertainty due to alignment of transducers with the measuring axis of the transducer under calibration
- uncertainty due to stability/performance of control system and data acquisition methodology

Where possible, corrections should be made for the estimated effect of any of these components on the magnitude of the generated force. The standard uncertainties associated with these corrections, together with the standard uncertainties due to any effects that cannot be corrected for, should be combined in quadrature (if it can be demonstrated that the effects are not correlated) and then multiplied by a coverage factor to derive an expanded uncertainty for the generated force.

5 Force calibration machines

5.1 Types of force calibration machine

The CMCs achieved by force calibration machines depend on the type of force generation - Table 5.1 shows typical values for different machine types. The uncertainty with which values of forces are realised by deadweight force calibration machines may be calculated in a way similar to that of a national force standard machine and may well be smaller than 5×10^{-5}. However, if traceability to national force standard machines is required or if the claimed CMC needs to be validated via a comparison with a national force standard machine, the demonstration of a CMC smaller than 5×10^{-5} may be either technically infeasible or simply too expensive. In most cases the requirements of the calibration laboratory are satisfied if a CMC of 1×10^{-4} can be achieved. This enables the calibration laboratory to calibrate force-measuring devices to the best classification specified within ISO 376.

In hydraulic and lever amplification machines, the lower values for the CMC can only be achieved by the correction of any systematic component of the amplification effect. For the determination of the CMC of the comparator type force calibration machine, the machine’s incorporated reference force transducer(s) should, if possible, first be calibrated in a force standard machine to determine relevant metrological characteristics – calibration of the force calibration machine should then be carried out using force transfer standards.

Table 5.1: Typical force calibration machine CMCs

Type of machine	Typical range of CMCs (expanded relative uncertainty)
Deadweight	5×10^{-5} to 1×10^{-4}
Hydraulic amplification	1×10^{-4} to 5×10^{-4}
Lever amplification	1×10^{-4} to 5×10^{-4}
Comparator with one or three reference force transducers	5×10^{-4} to 5×10^{-3}

It is clear that there are two distinct traceability paths for the forces generated by the force calibration machine, and the method for assessment of the associated uncertainties and CMC depend on the chosen method:

Traceability Path A: The force calibration machine derives its traceability directly from transfer standards calibrated in national force standard machines

The recommended method to determine the CMC for machines with this traceability path is given in section 5.2.

Traceability Path B: The force calibration machine has independent traceability to the base SI units of mass, length, and time

This traceability is derived from measurements of mass, gravity, lever length, piston areas etc. and the uncertainty associated with the generated force (and the laboratory's claimed CMC) is calculated, as for national force standard machines, from the uncertainties associated with these measurements, together with the other contributions detailed in section 4. It is necessary also to perform comparisons between the force calibration machine and an appropriate national force standard machine using high quality transfer standards – the procedure for this work may be as described in section 5.2 but the results need to be analysed in a different way, as it is a comparison exercise rather than a calibration. The analysis needs to demonstrate whether or not the results from the two machines are metrologically compatible – one method for assessing this is described in [4] and involves determining whether or not the E_n values calculated across the range of applied force exceed unity. If these values do exceed unity, it is not sufficient simply to increase the CMC to reduce the E_n value to an acceptable level, but the whole uncertainty budget associated with the force calibration machine (and with the comparison procedure) should be reviewed to the satisfaction of the national accreditation body.

5.2 Determination of the machine's CMC

To determine the machine's CMC, the following measurement plan should be applied:

- Selection of several force transducers as transfer standards to cover the whole force range of the force calibration machine. To minimise the influence of any interaction effects, the working range of each transfer standard should not normally begin at lower than 40 % of its maximum capacity. This will normally require the use of between three and five transfer standards - separate transfer standards for tension and compression may also be needed. It is assumed that high quality instrumentation will be used with the transfer standards, giving a resolution of better than 1 part in 200 000 at each calibration force – if this is the case, it might not be necessary to include a component due to resolution in the uncertainty calculations (this is the assumption made in the following analysis). If the magnitude of the resolution is significant with respect to the uncertainty of the applied force or the repeatability of the results, a resolution uncertainty component should be included.
- Calibration of these transfer standards in a national force standard machine. The measurements shall be carried out in at least three rotational positions and shall include hysteresis measurements – to determine repeatability, the measurements are to be repeated once in at least one of the rotational positions.
- Calibration of the transfer standards in the force calibration machine. The measurement procedure will be similar to the calibration of the transfer standard in the national force standard machine.
- Recalibration of the transfer standards in the national force standard machine to determine the overall reference values and the magnitude of any drift throughout the exercise.
- For each transfer standard at each nominal force level, determination of the relative deviation between the reference value and the value obtained in the force calibration machine.

The machine's CMC can now be determined following a five-step process

- Step 1 - Determination of the uncertainty of the force generated by the national force standard machine
- Step 2 - Determination of the calibration uncertainty of the transfer standard in the national force standard machine
- Step 3 - Determination of the uncertainty of the transfer standard's reference value
- Step 4 - Determination of the uncertainty of force generation in the calibration machine
- Step 5 - Determination of the calibration machine's CMC

Step 1 - Determination of the uncertainty of the force generated by the national force standard machine

The expanded relative uncertainty, W_{nfsm}, with which the unit of force is realised by a typical national force standard machine is calculated following the guidance in section 4 – typical values are given in Table 5.2.

Step 2 - Determination of the calibration uncertainty of the transfer standard in the national force standard machine

The quantity determined in the calibration of a force transducer used as a transfer standard for the selected force steps is its calibration coefficient K_{ts} which is the ratio of the applied force F_{nfsm} to the deflection X indicated by the force transducer.

$$K_{\mathrm{ts}} = \frac{F_{\mathrm{nfsm}}}{X} \tag{5}$$

To eliminate the influence of the rotation effect, the deflection X is the mean value of n rotational positions of the transducer uniformly spaced around its axis.

$$X = \frac{1}{n}\sum_{i=1}^{n} X_i \tag{6}$$

where X_i are the deflections indicated by the force transducer in the different rotational positions.

The relative variance of the mean deflection is

$$w^2(X) = \frac{1}{n(n-1)} \times \sum_{i=1}^{n} \left((X_i - X)/X\right)^2 \tag{7}$$

Alternatively, if the number of rotational positions is high enough ($n > 3$) and they are at equally distributed orientations, the relative variance of the mean deflection can be derived from the residuals of a sinusoidal fit of mean deflection against orientation.

The combined relative standard uncertainty of the value of force indicated by the transfer standard $w(K_{\mathrm{ts}})$ and its relative expanded uncertainty W_{ts} can be determined by the following equations:

$$w(K_{\mathrm{ts}}) = \sqrt{w^2(X) + w^2(F_{\mathrm{nfsm}})} \tag{8}$$

$$W_{\mathrm{ts}} = k \times w(K_{\mathrm{ts}}) \tag{9}$$

where k is the coverage factor required to give a confidence level of 95 % - this value will depend on the relative Type A and Type B uncertainty contributions, and can be calculated using the Welch-Satterthwaite equation.

Step 3 - Determination of the uncertainty of the transfer standard's reference value

As the transfer standard is used throughout a finite period of time, the influence of any drift D has to be taken into account by incorporating a further relative uncertainty contribution as follows:

$$w^2(D) = \frac{a_{\mathrm{drift}}^2}{3} \tag{10}$$

where its value is estimated by a rectangular probability distribution of half-width a_{drift} of relative variation of sensitivity. If it can be shown that the drift is time-dependent, the rectangular distribution may be replaced by a triangular one (using a divisor of 6 instead of 3). This replacement is only justified if the comparison measurements are made during a short period of time (typically about one month) and the calibration of the force calibration machine is performed approximately mid-way between the two calibrations in the national force standard machine.

The expanded relative uncertainty of the reference value is evaluated as follows:

$$W_{\mathrm{rv}} = k \times \sqrt{w^2(K_{\mathrm{ts}}) + w^2(D)} \tag{11}$$

Table 5.2 shows typical examples of the expanded relative uncertainty of reference values of four different qualities of force transfer standards in relation to some different types of force standard machines. The transfer standards with the lowest relative uncertainty achievable to date, as shown in column 2, are the force transducers for the range between 100 kN and 500 kN. For the range below 2 kN (column 3), it can be very difficult to find transfer standards of low relative uncertainty. If the force standard machines are not deadweight machines, the uncertainties of the transfer standards may be less important, as shown in columns 4 and 5. However, in the case of forces above 3 MN, investigations have to be carried out to select the proper transfer standards.

Table 5.2: Examples of expanded relative uncertainty of reference values

	National force standard machine type			
	Deadweight > 2 kN	**Deadweight < 2 kN**	**Lever amplification**	**Hydraulic amplification**
$w(F_{\text{nfsm}})$	1.0×10^{-5}	1.0×10^{-5}	5.0×10^{-5}	1.0×10^{-4}
$\boldsymbol{W_{\text{nfsm}}}$	$\mathbf{2.0 \times 10^{-5}}$	$\mathbf{2.0 \times 10^{-5}}$	$\mathbf{1.0 \times 10^{-4}}$	$\mathbf{2.0 \times 10^{-4}}$
$w(X)$	0.3×10^{-5}	0.5×10^{-5}	0.8×10^{-5}	1.7×10^{-5}
$\boldsymbol{W_{\text{ts}}}$	$\mathbf{2.1 \times 10^{-5}}$	$\mathbf{2.2 \times 10^{-5}}$	$\mathbf{1.0 \times 10^{-4}}$	$\mathbf{2.0 \times 10^{-4}}$
a_{drift}	3.0×10^{-5}	5.0×10^{-5}	5.0×10^{-5}	1.0×10^{-4}
$w(D)$	1.2×10^{-5}	2.0×10^{-5}	2.0×10^{-5}	4.1×10^{-5}
$\boldsymbol{W_{\text{rv}}}$	$\mathbf{3.2 \times 10^{-5}}$	$\mathbf{4.7 \times 10^{-5}}$	$\mathbf{1.1 \times 10^{-4}}$	$\mathbf{2.2 \times 10^{-4}}$

After the completion of the calibration of the force calibration machine, its calibration and measurement capability in relative terms may be determined using the following two steps. This calculation is based on the assumption that the force transducer to be calibrated will not introduce further significant components of uncertainty.

Step 4 - Determination of the uncertainty of force generation in the calibration machine

The output of the calibration of the force calibration machine will be, at each calibrated force, an incremental deviation from the reference value and a decremental deviation from the reference value, both with associated repeatability and reproducibility values. The machine can either be calibrated separately for incremental and decremental forces, in which case the following analysis should be applied only to the direction of interest, or it can be calibrated for both incremental and decremental forces, in which case all calibration results need to be taken into account.

It is highly likely that a force calibration machine will be calibrated using a range of transfer standards of different capacities. When this is the case, there should be common points at which the generated force is measured by two transfer standards. Any difference in the force measured by these two transfer standards is likely to be due to different interaction effects between the transfer standards and the machines, and should be carefully assessed prior to incorporation as a separate component in the uncertainty budget.

According to the GUM [5] (note to 6.3.1), corrections should be applied for all known significant systematic effects. If the measurements made in the force calibration machine demonstrate significant deviations between the generated force and the force generated in the national force standard machine, a correction should be made for this deviation, and it should also be borne in mind that the decremental deviation may well be a function of the maximum force applied – any uncertainty associated with these corrections should be incorporated in the uncertainty budget. As part of this process, the deviations at forces which were not applied during the calibration, but which are within the machine's range, will need to be estimated to enable correction values to be determined. Depending on the type of machine and the results obtained, a polynomial fit of deviation against force may be suitable – in such a case, the residuals from this fit will enable an estimate of uncertainty associated with the calculated corrections to be made. The relative standard uncertainty associated with the correction value at each calibration force is denoted w_{corr}.

If corrections for the measured deviations are not made, and it is strongly recommended that they are made, the deviations cannot simply be treated as uncertainty components because they are known systematic effects. In these cases, a worst-case estimate for the expanded uncertainty at each calibration force can be determined by adding the magnitude of the larger (incremental (Δd_i) or decremental (Δd_d)) relative deviation to the expanded uncertainty calculated from all other sources – the absolute value of this magnitude is denoted $\Delta d_{\max}$. Note that this approach is not that used in F.2.4.5 of the GUM, where a mean deviation across the range is calculated, and the expanded uncertainty incorporates contributions due to the variance of this mean deviation and to the mean variance associated with determining the individual deviation values – this results in an expanded uncertainty associated with the value obtained at each force when using a correction equal to the mean deviation.

The uncertainty contribution due to the lack of reproducibility of the force generated by the calibration machine is determined from the readings obtained from the transfer standard at a number of rotational positions equally spaced around the machine's measuring axis – this contribution is equal to the standard deviation of the calculated deflections expressed in relative terms and is added to the uncertainty associated with any correction to give the uncertainty associated with the force generation in the calibration machine:

$$w^2(d_{\mathrm{fcm}}) = \frac{1}{(n-1)} \sum_{i=1}^{n} \left(\left(X_{\mathrm{fcm}\_i} - X_{\mathrm{fcm}} \right) / X_{\mathrm{fcm}} \right)^2 + w_{\mathrm{corr}}^2 \qquad (12)$$

where X_{fcm_i} are the individual deflections obtained at n rotational positions and X_{fcm} is the mean deflection, at each calibration force. It should be noted that the standard deviation value used is that of the sample rather than the mean, as the uncertainty estimation needs to take account of how individual applications of force may vary, rather than the uncertainty associated with their mean value (in contrast to the case in equation (7) with the estimation of the uncertainty associated with the reference value).

Step 5 - Determination of the calibration machine's CMC

The calibration and measurement capability achieved by deadweight and lever or hydraulic amplification machines is calculated, at each calibrated force, from the following equation:

$$W_{\mathrm{CMC}} = k \times \sqrt{w_{\mathrm{rv}}^2 + w^2\left(d_{\mathrm{fcm}}\right)} + \Delta d_{\mathrm{max}} \qquad (13)$$

In the calculation for comparator type machines, two additional uncertainty components - the calibration uncertainty $w_{\mathrm{ref\_tra}}$ of the reference force transducer and its estimated long-term instability $w_{\mathrm{ref\_instab}}$ - must be considered and applied in the following equation:

$$W_{\mathrm{CMC}} = k \times \sqrt{w_{\mathrm{rv}}^2 + w^2\left(d_{\mathrm{fcm}}\right) + w_{\mathrm{ref\_tra}}^2 + w_{\mathrm{ref\_instab}}^2} + \Delta d_{\mathrm{max}} \qquad (14)$$

Table 5.3 finally shows the typical overall results of the calibration and measurement capability for different types of force calibration machines, assuming that corrections have not been made. The relative uncertainty of the reference force transducer can be calculated using the procedures given in sections 6 and 7. The long-term instability of the reference force transducer is to be determined from previous calibrations or by estimations.

Table 5.3: Examples of the calibration and measurement capability W_{CMC} for different force calibration machines

	Deadweight > 2 kN	Deadweight < 2 kN	Lever or hydraulic amplification	Comparator
$w_{\mathrm{ref\_tra}}$	—	—	—	3×10^{-4}
$w_{\mathrm{ref\_instab}}$	—	—	—	2×10^{-4}
w_{rv}	3.2×10^{-5}	4.7×10^{-5}	1.1×10^{-4}	2.2×10^{-4}
$w(d_{\mathrm{fcm}})$	3.3×10^{-6}	3.3×10^{-6}	8.3×10^{-6}	1.7×10^{-5}
Δd_{max}	5.0×10^{-5}	1.0×10^{-4}	3.0×10^{-4}	5.0×10^{-4}
W_{CMC}	8.3×10^{-5}	1.5×10^{-4}	4.1×10^{-4}	9.2×10^{-4}

6 Force transducers

This section deals with the uncertainty associated with the results of the calibration of a force transducer in a force calibration machine. Many force transducers are calibrated in accordance with ISO 376, as this is the force traceability route specified in ISO materials testing standards, such as ISO 7500-1 [6] (calibration of uniaxial testing machines) and ISO 6508-2 (calibration of Rockwell hardness testing machines) – Section 6.1

deals with ISO 376 calibrations. There are also other national and international standards covering the calibration of force transducers, such as ASTM E 74, BS 8422, and DKD-R 3-3 – some brief guidance on the uncertainty estimation approach to be used for these other calibration methods is given in Section 6.2, although much of the technical information given in Section 6.1 will also be applicable to these other methods.

6.1 Determination of the ISO 376 calibration uncertainty

The current issue of ISO 376 gives no guidance on the estimation of calibration uncertainty, although the next revision may do so – if it does and the guidance contradicts the approach followed here, this document will be revised and reissued. To be consistent with the rest of this document, the guidance given here will be based on a relative uncertainty approach, but it should be borne in mind that a force units approach is equally valid and may be simpler, both for this and for all other force uncertainty estimations in this document.

ISO 376 allows two different calibration methods – one calibrating the transducer for use only at specific forces and the other calibrating it to be used over a force range, with the applied force calculated as a function of the measured deflection using an interpolation equation. The definition of the calibration uncertainty is different for these two methods. For instruments classified for interpolation, the calibration uncertainty is the uncertainty associated with the mean increasing force applied in three runs (with the force-proving instrument rotated by 120° between runs and displaying the same deflection in each run) with the value of this mean force being calculated from the interpolation equation. For instruments classified for specific forces only, the calibration uncertainty is the uncertainty in the value of the mean increasing force applied in three runs (with the force-proving instrument rotated by 120° between runs) when the deflection in each run is equal to one of the mean deflections obtained during the calibration.

At each calibration force, a combined relative standard uncertainty w_c is calculated from the readings obtained during the calibration. These combined relative standard uncertainties are then plotted against force, and a least-squares fit to these values is calculated. This fit's coefficients are then multiplied by a coverage factor k (taken as being equal to 2) to give an expanded uncertainty value W for any force within the calibration range.

$$w_c = \sqrt{\sum_{i=1}^{8} w_i^2} \quad \text{and} \quad W = k \times w_c \tag{15}$$

where:

w_1 = relative standard uncertainty associated with applied calibration force

w_2 = relative standard uncertainty associated with reproducibility of calibration results

w_3 = relative standard uncertainty associated with repeatability of calibration results

w_4 = relative standard uncertainty associated with resolution of indicator

w_5 = relative standard uncertainty associated with creep of instrument

w_6 = relative standard uncertainty associated with drift in zero output

w_7 = relative standard uncertainty associated with temperature of instrument

w_8 = relative standard uncertainty associated with interpolation

Calibration force uncertainty, w_1

w_1 is the relative standard uncertainty associated with the forces applied by the calibration machine. This will generally be equal to the machine's CMC, expressed in relative terms, divided by the value of k specified in the machine's calibration certificate (likely to be equal to 2).

For machines for which the CMC is determined on the basis of corrections not being made (i.e. a non-zero value of $\Delta d_{\max}$ in equation (13) or (14)), this approach is not strictly correct, but the value determined should still be a reasonable estimate of the calibration force's standard uncertainty.

Reproducibility uncertainty, w_2

w_2 is, at each applied force level, the standard deviation of the mean incremental deflection obtained at equally-spaced orientations in the calibration, expressed as a relative value.

$$w_2 = \frac{1}{\left|\bar{X}_\mathrm{r}\right|} \times \sqrt{\frac{1}{6} \times \sum_{i=1,3,5} \left(X_i - \bar{X}_\mathrm{r}\right)^2} \tag{16}$$

where X_i are the deflections obtained in incremental series 1, 3, and 5, and $\bar{X}_\mathrm{r}$ is the mean of these three values.

Repeatability uncertainty, w_3

w_3 is, at each applied force level, the contribution due to the repeatability of the measured deflection at a single orientation, expressed as a relative value. It is calculated from:

$$w_3 = \frac{b'}{100 \times \sqrt{3}} \tag{17}$$

where b' is the instrument's relative repeatability error, defined in ISO 376 as follows:

$$b' = 100 \times \left| \frac{X_2 - X_1}{\left(X_1 + X_2\right)/2} \right| \tag{18}$$

where X_1 and X_2 are the deflections obtained at the given force level in series 1 and 2.

Resolution uncertainty, w_4

Each deflection value is calculated as the difference between two readings (the reading at zero force subtracted from the reading at an applied force). The resolution of the indicator therefore needs to be included twice as two rectangular distributions, each with a standard uncertainty of $r/(2\sqrt{3})$ where r is the resolution, expressed in units of force. This is equivalent to one triangular distribution with a standard uncertainty of $r/\sqrt{6}$, and needs to be expressed, at each force level, as a relative value:

$$w_4 = \frac{1}{\sqrt{6}} \times \frac{r}{F} \tag{19}$$

Creep uncertainty, w_5

This uncertainty component is due to the possibility that the instrument's deflection may be influenced by its previous short-term loading history. One measure of this influence is the change in output in the period from 30 s to 300 s after application or removal of the maximum calibration force. This change in output is not included in the reproducibility component because the same calibration machine is generally used for all runs and the time loading procedure will therefore be the same. The magnitude of this uncertainty component can be estimated as follows:

$$w_5 = \frac{c}{100 \times \sqrt{3}} \tag{20}$$

where c is the instrument's relative creep error, defined as follows:

$$c = 100 \times \left| \frac{i_{300} - i_{30}}{X_\mathrm{N}} \right| \tag{21}$$

where i_{30} and i_{300} are the instrument's output 30 s and 300 s respectively after application or removal of the maximum calibration force, and X_N is the deflection at maximum calibration force.

If the creep test is not performed during the calibration, this uncertainty contribution may be estimated as the contribution due to reversibility, given in equation (26), divided by a factor of three.

Zero drift uncertainty, w_6

This uncertainty component is due to the possibility that the instrument's zero output may vary between measurement runs - the subsequent measured deflections may therefore be a function of the time spent at zero force. This effect is not included in the reproducibility component because this time will generally be the same for all runs. One measure of this variation is the ISO 376 zero error f_0 so this effect can be estimated as follows:

$$w_6 = \frac{f_0}{100} \qquad (22)$$

where $f_0 = 100 \times \frac{i_\mathrm{f} - i_\mathrm{o}}{X_\mathrm{N}}$, i_o and i_f are the indicator readings before and after force application respectively, and X_N is the deflection at maximum calibration force.

Temperature uncertainty, w_7

This contribution is due to temperature variation throughout the calibration, together with the uncertainty in the measurement of this calibration temperature range. The sensitivity of the force-measuring instrument to temperature needs to be determined, either by tests or, more commonly, from the manufacturer's specifications. This component takes the same value at each force level and, expressed as a relative value, is equal to:

$$w_7 = K \times \frac{\Delta T}{2} \times \frac{1}{\sqrt{3}} \qquad (23)$$

where K is the instrument's temperature coefficient, in °C^{-1}, and ΔT is the calibration temperature range, allowing for the uncertainty in the measurement of the temperature. It is worth noting that, for temperature-compensated instruments, this component will generally be negligible (ΔT is unlikely to exceed 2 °C and a typical value for K is 0.000 05 °C^{-1}, giving w_7 = 0.003 %, less than the Class 00 calibration force uncertainty contribution).

Interpolation uncertainty, w_8

This uncertainty component is only taken into account for instruments classified for interpolation, as an interpolation equation is not applicable to instruments classified for specific forces only. It is the contribution due to the fitted line not passing exactly through all of the plotted 'applied force' against 'mean deflection' points, and may be calculated using either a residual or deviation method:

Residual method

This method estimates the component using statistical theory. If it is assumed that the calibration forces are evenly distributed, it can be calculated from the following equation:

$$w_8 = \frac{F_\mathrm{N}}{F \times X_\mathrm{N}} \sqrt{\frac{\delta_\mathrm{r}}{n - d - 1}} \qquad (24)$$

where F_N is the maximum calibration force, F is the applied force, X_N is the deflection at maximum calibration force, δ_r is the sum of squared deviations between the mean deflection and the value calculated from interpolation equation, n is the number of force calibration steps, and d is the degree of the equation.

Deviation method

This method estimates the component at each calibration force as the difference between the mean measured deflection, $\bar{X}_r$, and the value calculated from the interpolation equation, X_a, expressed as a relative value:

$$w_8 = \left| \frac{X_a - \bar{X}_r}{\bar{X}_r} \right| \tag{25}$$

Combined standard uncertainty and expanded uncertainty

At each calibration force, the combined standard uncertainty w_c is calculated from equation (15). A graph of w_c against force is plotted and the coefficients of a best-fit least-squares line through all of the data points are determined. The form of the fitted line (i.e. linear, polynomial, exponential) will depend on the calibration results. If this results in values that are significantly lower than the calculated values of w_c in any part of the calibration force range, a more conservative fit should be applied or a minimum value for the uncertainty needs to be specified for the relevant parts of the force range.

The expanded uncertainty W is then calculated from this best-fit line by multiplying its value at a given force by a factor of two – for any force within the calibration range, an expanded uncertainty can then be calculated, either as a relative value or in force units.

Table 6.1 gives the relative expanded uncertainty values for force-proving instruments which only just meet all of the classification criteria given in ISO 376, and so gives the worst-case incremental uncertainty limits for force-proving instruments classified for interpolation (although the temperature uncertainty term is taken as being insignificant, as a worst-case figure is hard to determine because the Standard does not limit the instrument's temperature sensitivity – and, in practice, it is likely to be negligible).

Table 6.1: Worst-case relative expanded uncertainties for instruments classified to ISO 376

Class	w_1	w_2	w_3	w_4	w_5	w_6	w_8	Relative expanded uncertainty
00	0.005 %	0.017 %	0.014 %	0.010 %	0.014 %	0.012 %	0.025 %	0.08 %
0.5	0.010 %	0.033 %	0.029 %	0.020 %	0.029 %	0.025 %	0.050 %	0.16 %
1	0.025 %	0.067 %	0.058 %	0.041 %	0.058 %	0.050 %	0.100 %	0.32 %
2	0.050 %	0.133 %	0.115 %	0.082 %	0.115 %	0.100 %	0.200 %	0.64 %

6.2 Determination of uncertainty of other calibration procedures

Many other procedures exist for the static or quasi-static calibration of force transducers. However, the method for estimating the uncertainty of the calibration results should be similar to that used in Section 6.1 – the principle which should be borne in mind is that the difference in calibration results from a transducer calibrated to the same procedure in different force calibration machines (within a short period of time) should not be large when compared with the combination of the two calibration uncertainties. In other words, the estimated uncertainties should incorporate all possible differences in the way a transducer can be calibrated but still be within the procedure's specified criteria – a corollary of this is that, in order to obtain a very low calibration uncertainty, the calibration procedure needs to be very tightly defined. An example of this is the very strictly controlled procedure used in CIPM and RMO Key Comparisons – this procedure has been specifically developed to minimise the various uncertainty contributions.

Possible uncertainty sources include, but are not limited to, the following:

- Calibration force
- Indicator resolution
- Reproducibility/repeatability of measured deflection
- Creep of transducer

- Effect of zero drift
- Effect of temperature
- How well the interpolation equation fits the data (if applicable)

NOTE: ASTM E 74 includes a mandatory method for calculating a value of uncertainty, which it defines as "a statistical estimate of error in forces computed from the calibration equation of a force-measuring instrument when the instrument is calibrated in accordance with this practice." This calculation of uncertainty only includes contributions due to reproducibility and deviation from the interpolation equation, although the value is increased to equal the resolution if the original value is calculated to be lower, and the uncertainty of the calibration force applied is also specified to be within certain limits. The method results in an uncertainty value, in units of force, which is applicable across the range of calibration forces and is used to determine the lower force limits for the two standard loading ranges (2 000 times the uncertainty for Class AA and 400 times the uncertainty for Class A). The uncertainty calculated by this method ignores some of the components included in Section 6.1 and, as such, is likely to result in different, and probably lower, values. The use of only the calculated uncertainty value associated with the calibration when developing an uncertainty budget for the subsequent use of the force-measuring instrument should be avoided – the contributions due to the other uncertainty components present during the calibration should also be included.

7 Industrial force measurements

7.1 Uncertainty contributions to be considered

When the force transducer is used subsequent to its calibration, the uncertainty in the force calculated from its displayed value will depend, in part, on its calibration uncertainty, but there are a number of other factors which also need to be considered. These uncertainty sources include, but are not limited to, the following:

- Resolution
- Contribution due to reversibility
- Drift in sensitivity since calibration
- Effect of being used at a different temperature
- Effect of being used with different end-loading conditions
- Effect of being used with different parasitic components
- Effect of being used with a different time-loading profile
- Effect of linear approximations to interpolation equation
- If applicable, effect of replacement indicator
- Dynamic nature of force being measured

If it can be assumed that none of these effects are correlated, their standard uncertainties can be summed in quadrature, together with the instrument's calibration uncertainty, to calculate a combined standard uncertainty at each force. This is based on the assumption that any known errors have been corrected for - for example, if the temperature sensitivity of the transducer is known, and so is the temperature difference (between calibration and subsequent use), either a correction should be made to the calculated force or the magnitude of the effect should be added to the combined expanded uncertainty linearly, rather than being combined in quadrature with the other uncertainty contributions.

Resolution uncertainty

The measured force is derived from new deflection values. Because of this, the resolution of the indicator needs to be included again in a similar way to that detailed in 6.1. If the readings fluctuate by more than the resolution of the indicator, the resolution is taken as half the range of fluctuation.

Calculation of contribution due to reversibility

The reversibility error defined in ISO 376 is not treated as a component of the calibration uncertainty. The way to take this contribution into account will depend on how the instrument is used after its calibration.

If the instrument is used to make only increasing measurements, no component due to reversibility needs to be included in the uncertainty of the measured force. However, if measurements of decreasing values of force are made, with no correction based on the calibration results, the uncertainty of the measured force needs to take the reversibility into account by including the following component:

$$w_{\text{rev}} = \frac{v}{100 \times \sqrt{3}} \tag{26}$$

where v is the relative reversibility error as defined in ISO 376.

This component is derived purely from the calibration results and may therefore be stated in the instrument's calibration certificate. If required, it can be also be added in quadrature to the calibration uncertainty components to obtain an expanded calibration uncertainty which includes the instrument's reversibility.

The reversibility characteristics of a specific force-proving instrument are generally fairly repeatable. Because of this, if the decremental measurements are being made after application of the maximum calibration force, it may be more effective to make corrections based on the calibration data, rather than to include the whole reversibility effect as an uncertainty contribution.

Drift in sensitivity since calibration

This contribution can be estimated from the history of the instrument's sensitivity, based on past calibration results. The exact uncertainty distribution (and possibly even an estimated error correction) will depend on the individual instrument, but a rectangular distribution with an expanded uncertainty of ± the largest previous change between two adjacent calibrations is suggested. If such information is not available, an estimate can be made based on the performance history of similar devices.

Temperature effect

The temperature effect on zero output can be ignored, as the calculation of deflection generally makes it insignificant (except in tests of long duration during which the ambient temperature is changing significantly), but the effect of temperature on sensitivity (or span) needs to be allowed for. If the actual temperature sensitivity of the instrument is known, a correction should ideally be made to the calculated force. If, as is more likely to be the case, the only information is the manufacturer's specification tolerance, an uncertainty component based on this figure and the difference in temperature between the instrument's calibration and its subsequent use should be used, with a recommended rectangular distribution. However, the coefficient (or the tolerance) is usually given for a stabilised temperature with no gradient - if the instrument is used in conditions in which it is subject to temperature gradients, an additional uncertainty contribution should be incorporated.

End-loading effect

The bearing pad test specified in ISO 376 gives an indication of the sensitivity of a compression force-proving instrument to specified variations in end-loading conditions. The results of this test, together with information as to the conditions in which the instruments will subsequently be used, should enable realistic uncertainty contributions for use in compression to be estimated. For instruments to be used in tension, it may be necessary to perform additional tests to determine sensitivity to possible variations in force introduction.

Parasitic components effect

The reproducibility component included in the calibration uncertainty is, as explained in 6.1, only valid for a mean of three measurements made on the calibration machine. Larger parasitic components than those applied during calibration are usually applied during the instrument's subsequent use.

It is recommended that the user, where possible, repeat the force measurement, rotating the instrument around the force axis between runs. A component related to any observed variation can then be taken into account.

If it is not possible to repeat measurements with rotation, the magnitude of any parasitic component should be estimated and the sensitivity of the instrument to such parasitic components evaluated or estimated. A component based on the product of the component's magnitude and the instrument's sensitivity should then be included in the uncertainty budget.

Time-loading profile

The force-proving instrument calibration method (as defined in ISO 376) and its subsequent use to verify a uniaxial testing machine (as defined in ISO 7500-1) specify different time-loading profiles (a wait of 30 s before taking a reading in ISO 376, whereas ISO 7500-1 allows calibration with a slowly increasing force). If the load cell is sensitive to time-loading effects, these different methodologies would lead to errors in the calculated force. The creep and zero drift uncertainty contributions in the calibration uncertainty budget will cover these effects, to some degree, but an additional uncertainty contribution may be needed, depending on the particular application.

Care must also be taken if no preload can be applied before the use of the transducer, particularly if it is to be used in both loading modes, i.e. from tension to compression or vice versa.

Effect of approximations to equation

If the calibration equation given in the certificate is not used, a component must be added based on the differences between the calibration equation and the equation that is used in practice.

Some indicators will allow a number of points from the calibration curve to be input, so that the display is in units of force, but will carry out linear interpolation between these points, rather than use the calibration equation. If this is the case, the effect of this linear approximation to the curve should be investigated and, if significant, an uncertainty contribution should be included.

Effect of replacement indicator

If the force transducer is subsequently used with a different indicator than that with which it was calibrated, the deviation between the two indicators must be determined (there are several methods, e.g. calibration of both indicators, use of a common bridge simulator) and the uncertainty of this deviation must be estimated (including factors such as calibration uncertainty of the indicator, stability of the common bridge simulator).

If corrections based on the measured deviation between the two indicators are made, the uncertainty of this deviation must be taken into account. If no corrections are made, both the deviation and its uncertainty must be considered.

Calibration uncertainty

This is half the value of the expanded uncertainty calculated in section 6 using the expanded uncertainty equation.

Effect of dynamic force

If the transducer is used under dynamic conditions, additional contributions have to be taken into account. For example the frequency responses of the force transducer and indicator, and the interaction with the mechanical structure, can strongly influence the measurement results. This requires a detailed analysis of dynamic measurement, which is not covered here.

7.2 *Calibration of testing machines to ISO 7500-1*

One of the main ISO standards that specifies the use of force-proving instruments calibrated in accordance with ISO 376 is ISO 7500-1 - this details a method to verify the forces generated by uniaxial materials testing machines. Annex D of this standard gives advice on uncertainty estimation, information that is summarised here.

ISO 7500-1 permits two ways of calibrating the machine – it is either set to display a nominal value and the transducer is used to measure the generated force (‘constant indicated forces’), or the force is increased until the value measured by the transducer is a specific value and the force displayed by the machine indicator is recorded (‘constant true forces’). The first method is recommended and will be discussed here – a similar analysis can be carried out for the second method.

The standard specifies that at least three series of measurements shall be taken with increasing force and, if required, one series shall also be taken with decreasing force. At each force value, the individual accuracy errors and the repeatability error are calculated, as is, if required, the reversibility error – together with the proving instrument classification, the zero error, and the machine resolution, these can be used to determine the machine’s classification.

The uncertainty associated with the machine calibration for incremental forces, as suggested in Annex D, is the uncertainty associated with the estimate of the relative accuracy error at each calibration force. This is based on, as a minimum, the repeatability of the results, the resolution of the machine indicator, and the contributions due to the transfer standard – these transfer standard contributions include its calibration uncertainty, its sensitivity to temperature, any drift since its calibration, and any effects due to approximations to the interpolation equation. These contributions are all covered in section 7.1 – the other items in that section should also be considered when estimating an uncertainty value for the machine calibration.

Annex D calculates the calibration uncertainty as follows:

$$W = k \times w_c = k \times \sqrt{w_{\mathrm{rep}}^2 + w_{\mathrm{res}}^2 + w_{\mathrm{std}}^2} \tag{27}$$

where:

w_{rep} is the standard deviation of the errors at a given force, expressed as a relative value

w_{res} is the contribution due to resolution (= relative resolution / $\sqrt{12}$)

w_{std} is the contribution due to the transfer standard, given by:

$$w_{\mathrm{std}} = \sqrt{w_{\mathrm{cal}}^2 + w_{\mathrm{temp}}^2 + w_{\mathrm{drift}}^2 + w_{\mathrm{approx}}^2} \tag{28}$$

where:

w_{cal} is the transfer standard's calibration uncertainty

w_{temp} is the uncertainty due to temperature effects

w_{drift} is the uncertainty due to drift of the standard's sensitivity

w_{approx} is the effect of approximating to the interpolation equation

7.3 *Other industrial force measurement applications*

In other industrial force measurement applications, similar uncertainty contributions will need to be considered. The basic philosophy is that the transducer will introduce a specific uncertainty based on its calibration results, and then there will be further uncertainty contributions due to the transducer being used at a different time and under different conditions to those experienced during its calibration – the magnitudes of these various contributions need to be estimated and, if it can be demonstrated that they are not correlated, then combined in quadrature to obtain a combined standard uncertainty for the measurement result. This standard uncertainty can then be multiplied by a coverage factor to give an expanded uncertainty at the required confidence level.

One of the major differences in conditions between calibration and use may be that the transducer has been calibrated under a fairly static force regime (probably due to the unavailability of dynamic standard facilities and/or calibration methods) but is used to make measurements of rapidly-changing, or dynamic, forces. Examples of such applications include the force measurement system in dynamic testing machines (such as fatigue machines), industrial presses, and road load data collection equipment. The uncertainty associated with the force measurement value will need to include components relating to such dynamic effects, but this is best done on a case-by-case basis – this major area of uncertainty analysis cannot be covered in full here, and readers are encouraged to consult the relevant references for further information.

8 References and further reading

8.1 *References*

1 EN ISO 376:2004. *Metallic materials. Calibration of force-proving instruments used for the verification of uniaxial testing machines*.

2 Sawla, A., Peters, M.: *EC – Intercomparison of Force Transducer Calibration*. Brussels, Commission of the European Communities, Bureau of Reference (1987), EUR 11324 EN.

3 Sawla, A., Peters, M.: *WECC Inter-laboratory Comparison F2 Force Transducer Calibration*. Braunschweig, PTB-Bericht PTB-MA-28, 1993.

4 Sawla, A.: Uncertainty scope of the force calibration machines. Proc. IMEKO World Congress. Vienna, Austria, 2000.

5 JCGM 100:2008 (GUM 1995 with minor corrections). *Evaluation of measurement data - Guide to the expression of uncertainty in measurement.*

6 EN ISO 7500-1:2004. *Metallic materials. Verification of static uniaxial testing machines. Tension/compression testing machines. Verification and calibration of the force-measuring system*.

8.2 Further reading

JCGM 200:2008. *International vocabulary of metrology — Basic and general concepts and associated terms (VIM).*

Sawla, A.: *Guidance for the determination of the best measurement capability of force calibration machines and uncertainty of calibration results of force measuring devices*. Braunschweig, PTB-Mitteilungen 104 4/94, 1994.

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