

Guide to the Uncertainty of Force Measurement

Liam Maybank, Andy Knott, and David Elkington

**Centre for Mechanical and Acoustical Metrology
National Physical Laboratory
Queens Road
Teddington
Middlesex
TW11 0LW**

Abstract

This guide discusses the estimation of uncertainty in force measurement, including interpretation of relevant national and international standards.

An introduction to uncertainty is provided, together with its application to deadweight force standard machines, force transducers, secondary force standard machines, and materials testing machines. There then follows a recommendation on good practice in the treatment of the uncertainty of measurement as applied to force transducers. An appendix provides a more detailed introduction to the characteristics of force transducers.

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National Physical Laboratory
Teddington, Middlesex TW11 0LW

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Approved on behalf of the Managing Director, NPL,
by G R Torr, Head, Centre for Mechanical and Acoustical Metrology

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1. Introduction

There are increasing demands on metrologists to estimate the uncertainties associated with the measurements that they make. Taking information from a variety of sources, this guide aims to lead users through the estimation of their own uncertainties in the measurement of static force.

The measurement of static force is long established and modern deadweight machines achieve uncertainties in applied force as low as 1 part in 200 000. Related documents include ISO/TAG 4/WG 3 ‘Guide to the expression of uncertainty in measurement’ (GUM)¹ and the EA-4/15 guidance document². The BSI committee ISE/NFE/4/-/3 covers issues relating to the ‘Uncertainty of measurement in the mechanical testing of metals’.

2. Force - basic concepts

The manufacture of nearly all industrial products requires the controlled application of forces. In many industries, these forces need to be measured to ensure that the manufactured items will perform correctly. The precision of force measurement varies from ‘a few per cent to a few parts per million’³. Although the requirements vary, good practice needs to be followed.

2.1 Units of force

The International System of Units (SI) is widely used for trade, science, and engineering. The SI unit of force is the newton (N). The base units relevant to force are:

- the metre, unit of length, symbol m,
- the kilogram, unit of mass, symbol kg,
- the second, unit of time, symbol s.

Force is defined as the rate of change of momentum. For an unchanging mass, this is equivalent to mass $\times$ acceleration.

Thus $1 \text{ N} = 1 \text{ kg} \cdot \text{m} \cdot \text{s}^{-2}$

Table 1: Summary of SI prefixes

Multiplying Factor	SI prefix	Scientific Notation
1 000 000 000 000	tera (T)	10^{12}
1 000 000 000	giga (G)	10^9
1 000 000	mega (M)	10^6
1 000	kilo (k)	10^3
0.001	milli (m)	10^{-3}
0.000 001	micro (μ)	10^{-6}
0.000 000 001	nano (n)	10^{-9}
0.000 000 000 001	pico (p)	10^{-12}

The use of abbreviated forms for large and small numbers is encouraged by the SI system. Reducing ninety five million four hundred thousand newtons to 95.4 MN greatly simplifies the reporting of data. SI prefixes represent multiples of 10^3 or 10^{-3} as in Table 1. There is an exception to the system

caused by adoption of the kilogram as the base unit for mass rather than the gram. The effect of this is that prefixes above ‘kilo’ are not used for mass. The tonne is 10^3 kg.

2.1.1 Other units of force

Historically there have been a variety of units of force, and some approximate conversion factors to older units are given in Table 2.

Table 2: Some conversion factors from non-SI units

Unit	Symbol	Is approximately equal to
pound-force	lbf	4.448 N
ton-force	tonf	9.964 kN
kilogram-force (or kilopond)	kgf (kp)	9.807 N

2.2 Other related quantities

2.2.1 Mass

The term mass is used to measure the amount of material in an object, and can be deduced from the number and type of atoms present. Mass is a constant of a body and can only be changed by adding or removing matter (neglecting any relativistic effects of high velocity which are not relevant here).

2.2.2 Weight

Weight is a term that must be used with care. In everyday life it is often confused with mass. In this guide, the term weight will only be used to describe a calibrated mass.

2.2.3 Load

In this guide, load is defined as the force acting on a body.

3. Generation of force

This section describes the common types of machine used for generating forces.

The machines offering the lowest uncertainty use deadweights. They are known as primary machines because they are traceable to base units. Deadweight machines capable of generating large forces are expensive, and it is unusual to find deadweight machines with capacities above a few hundred kilonewtons outside national standards laboratories. There are very few deadweight machines in the world with capacities much above 1 MN.

Larger forces are usually generated using hydraulic or lever machines. These are known as secondary force standard machines because they have indirect traceability to the measurement standards of mass, length, and time.

3.1 Deadweight force standard machines

3.1.1 Description

A deadweight machine has a series of weights that can be applied to a device. The masses of the weights are known, together with g , the local acceleration due to gravity. After a correction for the buoyancy force acting upwards on the weights, the forces generated by the weights can be calculated.

3.1.2 Theory

The resultant downward force experienced by a weight in air in the Earth's gravitational field is given by

$$F = m_c g \left(1 - \frac{1.2}{8000} + \frac{(1.2 - \rho_a)}{\rho_w} \right)$$

Equation 1

where m_c is the conventional mass of the weight, ρ_a is the air density, and ρ_w is the density of the weight.

3.2 Hydraulic amplification force standard machines

Hydraulic amplification machines use a deadweight stack to apply forces to a small piston-cylinder assembly connected hydraulically to a much larger piston-cylinder assembly. The larger piston cylinder is mounted in a testing-machine frame.

An example of this design is the NPL 5 MN machine (Figure 1). A 22 kN deadweight stack is connected to a 5 MN frame that can operate in both compression and tension. Neither of the piston-cylinder assemblies has a mechanical seal; instead, there is a continual leakage of oil between piston and cylinder to minimise frictional losses. The cylinder of the small assembly is rotated about the piston to reduce the friction further. A servo-valve controls the hydraulic pressure so that the scalepan and selected weights of the 22 kN machine are maintained at a datum position.

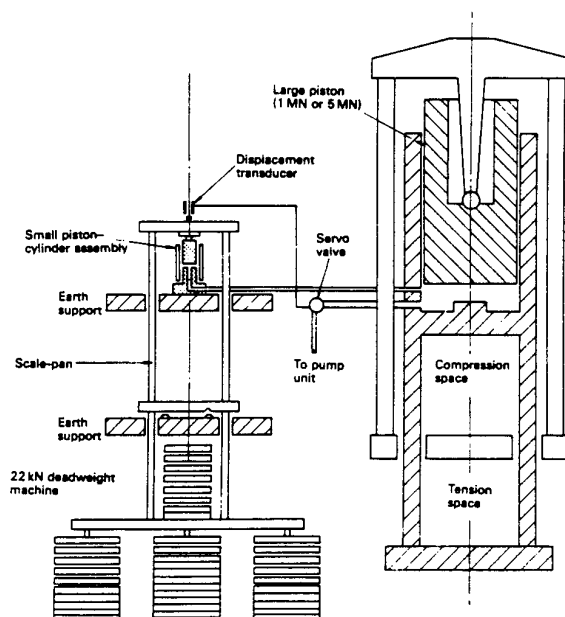


Figure 1: NPL's 5 MN hydraulic amplification machine

3.3 Transducer-based hydraulic force standard machines

The application of large forces is usually achieved using a conventional hydraulic press. The force can be monitored using a pressure transducer in the hydraulic system. An alternative method is to strain gauge the columns of the machine.

NPL has 12 MN and 30 MN (Figure 2) hydraulic machines. Each consists of a base casting, incorporating an up-stroking hydraulic ram with a mechanical seal, and an upper casting incorporating a spherically-seated platen. The two castings are separated by four columns. Metal-foil strain gauges have been bonded to each of the four columns.

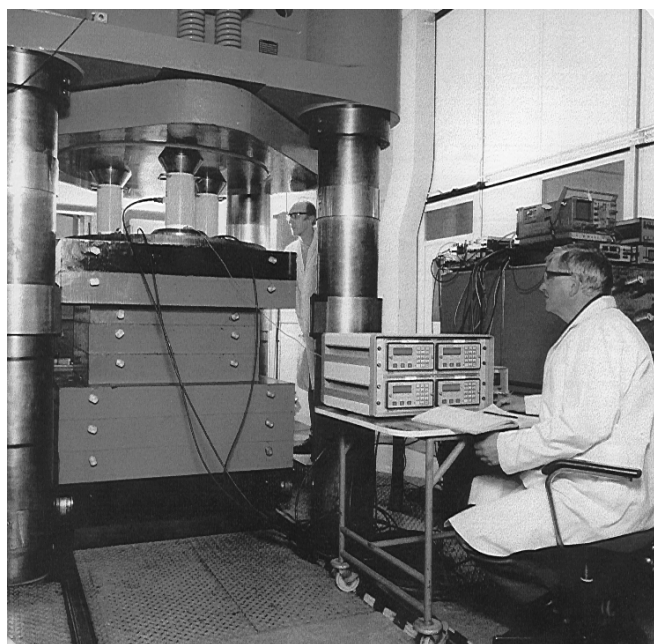


Figure 2: NPL's 30 MN hydraulic machine

The outputs of the complete bridge circuits on the four columns of the machine are summed by a microprocessor-based indicator. Both the sensitivity and linearity of the indicator can be adjusted so that the force applied is displayed directly in units of kilonewtons.

Each machine is calibrated, and then adjusted, by measuring the applied force using three compression load cells arranged in parallel. This ‘build-up’ technique starts with three 1.2 MN load cells calibrated in the NPL 1.2 MN deadweight machine and proceeds, stage by stage, to three 10 MN load cells calibrating the 30 MN machine.

3.4 Lever amplification force machines

A lever amplification force machine normally comprises a series of weights with an arrangement of levers to generate larger forces. Although there may be an arrangement of more than one lever, the amplification of the force is given by the overall lever ratio. These machines have some of the advantages of a deadweight machine without the expense of large weights.

4. Measurement of force

4.1 Introduction to force transducers

A transducer is a device that transforms energy from one type to another. The transducer most commonly used for force measurement converts mechanical energy into electrical energy. These devices can be installed where the force is to be measured but the display can be positioned at the convenience of the operator. Such devices are commonly referred to as load cells.

A variety of measurement techniques are used, the alternatives include capacitive, piezoelectric, inductive, and resistive. Piezoelectric elements are well suited to compact devices where the self-energising output is useful. Capacitive and inductive sensors tend to be used where a special aspect of the application requires them⁴. The standard sensor for force transducers is the bonded metallic resistance strain gauge.

Mechanical force transducers are still used in many areas. The most common of these is the proving ring which consists of a ring of metal with a dial gauge across the inside. As the ring is deformed the reading of the dial gauge will change.

4.2 Characteristics of force transducers

The performance of force transducers is limited by a number of factors. They are characterised in terms of their repeatability, non-linearity, creep, hysteresis, temperature sensitivity, end loading sensitivity, sensitivity to moments and side forces, and their long-term stability. In addition, the resolution and stability of the instrumentation used with the force transducer must be considered together with the interpolation error.

Details of the characteristics of force transducers, and their application for high-accuracy measurement, are given in Appendix 0.

5. Introduction to uncertainty

5.1 Concepts

If it is to be complete, the expression of a result of a measurement must have a statement of the associated uncertainty. This uncertainty is a measure of the range of values that could reasonably be attributed to the quantity measured (measurand). The uncertainty is stated as a range of values within which the measurand is expected to lie, to a stated level of confidence. For example, if a force is quoted as (100 ± 1) N with a confidence of 95 %, it means that there is a 95 % probability that the true force lies between 99 N and 101 N.

The terms ‘error’ and ‘uncertainty’ are not synonymous. Error is the measurement result minus the *true* value of the measurand. While the *true* value cannot be known exactly, corrections should be made whenever possible to remove the estimated error from the measurement result. As the corrections will be approximate there will be some residual error remaining, the uncertainty of which contributes to the overall uncertainty of the measurement result.

5.2 Range of possible error

Uncertainty can be thought of as the range about zero in which the error is thought to lie. The probability distribution of the error characterises the uncertainty, linking the confidence that the error lies within the stated range to the size of the range itself. The distribution itself may be deduced from the random spread of results, prior knowledge of the system, or in some other way. The standard deviation is a measure of the spread of the distribution, but this does not complete the result, as a confidence level must be stated, giving the probability that a measurement of the measurand will lie within a stated range (levels most commonly used are 95 % or 99 %).

5.3 Type A and B standard uncertainties

GUM separates uncertainties into two kinds: Type A and Type B, both being variances. Type A uncertainties have a statistical origin arising from multiple measurements of a measurand. Type B uncertainties are ‘evaluated using available knowledge’, and are ‘often based on a pool of comparatively reliable information’. The two types are treated differently in uncertainty calculations and it is important to distinguish between them.

5.4 Standard deviation

When a series of measurements are made of what is nominally the same thing, there will usually be more than one result. If the resolution is sufficiently high, almost every time a measurement is made it will be different. The spread of these results about the mean is expressed using the standard deviation. The standard deviation is simply the root mean square deviation from the mean. The greater the standard deviation the larger the ‘spread’ of measurements is around the mean.

A Type A standard uncertainty is the population standard deviation of the mean result, as shown in Equation 2

$$u_A = \frac{1}{\sqrt{n}} \sqrt{\frac{1}{(n-1)} \sum_{i=1}^n (x_i - \bar{x})^2}$$

Equation 2

5.5 Types of uncertainty distribution

The distribution of a set of measurements about the mean is not always the same. A classic distribution of results would be a normal distribution which has a bell shape and is typical of results with a well defined mean and no fixed upper and lower limits, Figure 3.

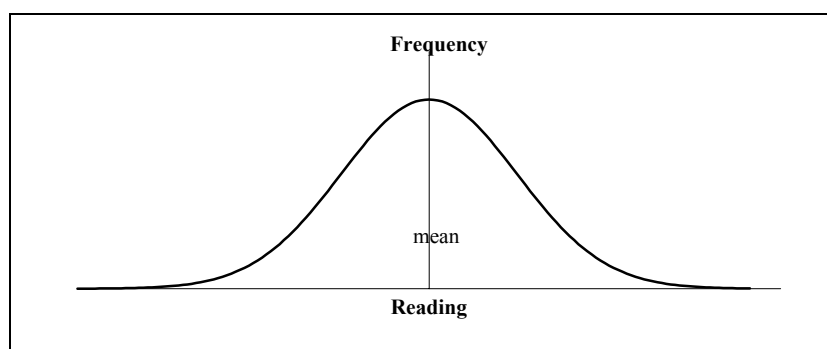


Figure 3 : Normal distribution

The last digit of a digital indicator has fixed upper and lower limits with no well defined mean, this is best modelled with a rectangular distribution, Figure 4.

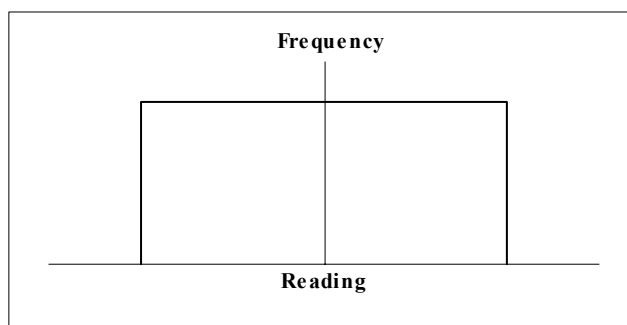


Figure 4 : Rectangular distribution

Distributions with a well defined mean and upper and lower limits may be modelled with a triangular distribution, Figure 5.

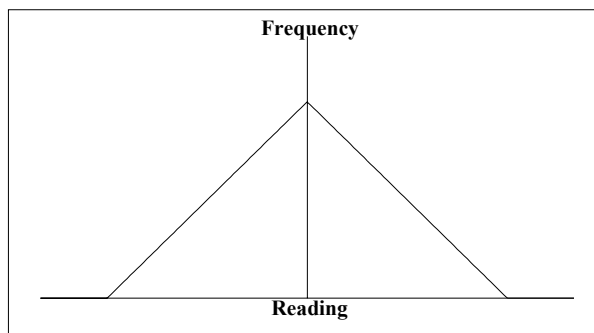


Figure 5 : Triangular distribution

Distributions with upper and lower limits where the reading is most likely to be found are best represented with a U-shaped distribution, Figure 6.

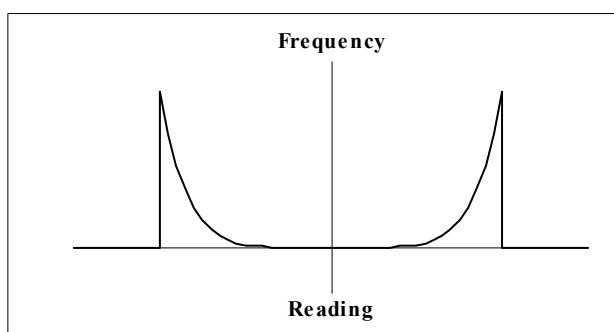


Figure 6 : U-shaped distribution

The differing shapes of these distributions result in different characteristic coverage factors, the number of standard deviations from the mean that includes 95 % of the readings. This will be used later in example calculations of uncertainties. The coverage factor is also known as the divisor when combining uncertainties.

Table 3 : Distributions and their coverage factors

Distribution	Coverage Factor
Normal	2
Rectangular	$\sqrt{3}$
Triangular	$\sqrt{6}$
U-shaped	$\sqrt{2}$

6. Introduction to calibration

6.1 Traceability and the national measurement system

Traceability is the ability to link a measurement back through the calibration chain to base SI units. The national measurement system for force is illustrated below. It shows the traceability of measurements back from the materials testing laboratory to the NPL.

The starting point in Figure 7 is in the top left hand corner. The base units for time, length and mass are realised at NPL with uncertainties of approximately 1 part in 10^{13} for the second, 3 parts in 10^{11} for the metre, and 2 parts in 10^8 for the kilogram. NPL's deadweight machines, maximum capacity 1.2 MN, have been calibrated directly against standards for these base units with an uncertainty of 1 part in 200 000. Furthermore, NPL's deadweight machines have been intercompared with deadweight machines at several other national standards laboratories, using portable force transfer standards, thereby ensuring agreement with other national standards for force. Portable force transfer standards are also used to calibrate NPL's high-capacity hydraulic machines with an uncertainty of 1 part in 2 000 at 5 MN and 1 part in 1 000 at 30 MN. Portable force transfer standards, calibrated in the various NPL machines, are then used to calibrate deadweight and hydraulic machines at UKAS-accredited laboratories. These UKAS machines are then used to calibrate force proving devices which are in turn used to calibrate machines in industry. The classes of proving device are according to BS EN 10002 - 2, 1992.

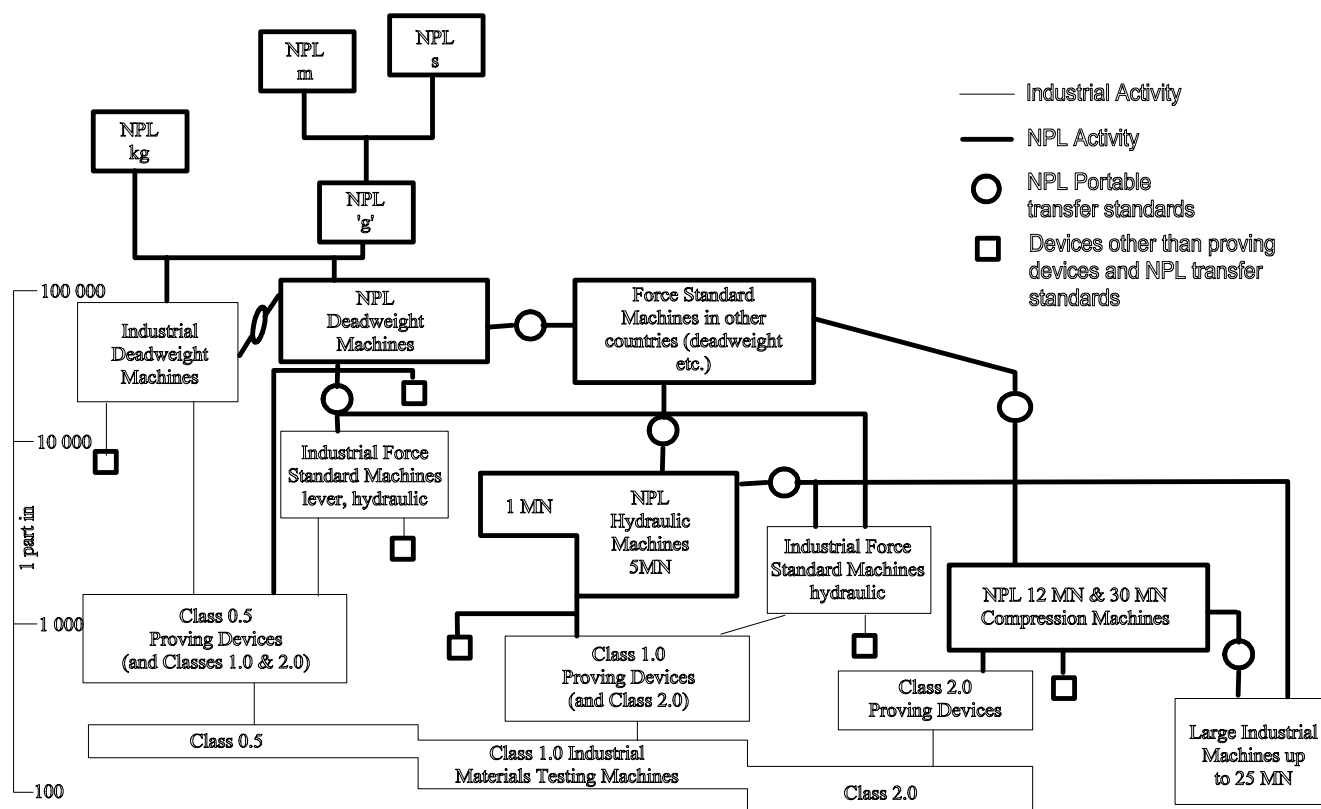


Figure 7: Traceability to national standards

There is a rapid increase in uncertainty, indicated by the scale on the left hand side of the diagram, as the number of steps from the base units increases. Provided that appropriately certified force transfer standards have been used, and the relevant standards have been strictly adhered to, traceability to the base SI units can be claimed.

6.2 Calibration

Calibration can be defined as ‘The process of determining experimentally the absolute values corresponding to the graduations on an arbitrary or inaccurate scale of measurement’. There are four types of calibration relevant to force metrology.

- Calibration of a primary force standard machine
- Calibration of a secondary force standard machine
- Calibration of a force transducer
- Calibration of a materials testing machine

7. Calibration of a primary force standard machine

Primary force standard machines are calibrated without a measurement of force. A primary deadweight machine is calibrated by measuring the mass of a weight and the acceleration due to gravity, and determining the buoyancy correction.

7.1 Uncertainty of deadweight machines

The mass of a weight can be measured with a low uncertainty. The local value of g can also be measured and the air density monitored. Combining the uncertainties gives an overall uncertainty of applied force as low as 1 part in 200 000. Because they can have such a low uncertainty, deadweight machines form the foundation for force measurement throughout the world.

7.1.1 Fundamental sources of uncertainty

To calculate the uncertainty associated with the generated force, it is necessary to determine the contribution of the individual terms to the total standard deviation. An example calculation, for the NPL 1.2 MN deadweight force standard machine, is given in section 7.2.

7.1.2 Stability of earth platens, side forces, bending moments

In all force machines, side forces may be introduced due to interaction between the load cell and the loading surfaces of the machine. While deadweight machines will only apply vertical forces, due to gravity, non-horizontal load surfaces can offset the load cell, thereby introducing side forces.

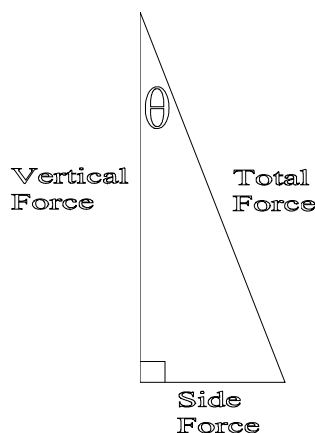


Figure 8: Non-vertical force components

Figure 8 shows a non-vertical force separated into vertical and horizontal components. The system is static so the system is in equilibrium and the forces complete a triangle as shown. At an angle θ , the error in the vertical force is given in Equation 3.

$$\text{error}(\%) = (1 - \cos(\theta)) \times 100$$

Equation 3

An angle of 1° will introduce an error of 0.015 %. In practice, the errors due to side forces may be reduced to insignificant levels (<0.1 ppm) by accurate construction of the machine's loading

surfaces. The effect on the performance of a load cell will be much greater than the cosine term. This is discussed in more detail in section 0 of the appendix.

7.1.3 Agreement between machines, and the ‘interaction effect’

The loading surface geometry and composition of loading surfaces in different deadweight machines will behave differently under load. A softer/harder material or a different shape platen can lead to a slightly different position of the load cell under load. Devices that are sensitive to these differences will exhibit a different calibration profile in different machines. For this reason results from two different machines are unlikely to match exactly.

7.2 Example ‘Uncertainty of NPL’s 1.2 MN deadweight force standard machine’

The machine incorporates a two-part stainless steel scalepan and a set of 55 stainless steel weights which are used individually or in combination to generate the required forces. In order to apply the correct force, it was essential to know what mass was required to generate the desired force in newtons. The weight could then be machined down to this mass value.

The machine is housed in an air-conditioned, dust-free enclosure which controls the temperature to $17-23^{\circ}\text{C} \pm 1^{\circ}\text{C}$ and the humidity to between 40 % and 70 % RH.

The force experienced by a weight in air in the Earth’s gravitational field can be represented by (see Equation 1)

$$F = m_c g \left(1 - \frac{1.2}{8000} + \frac{(1.2 - \rho_a)}{\rho_w} \right)$$

where m_c is the conventional mass of the weight, g is the local gravitational acceleration, ρ_a is the air density, and ρ_w is the density of the weight.

The accuracy of the force generated by the deadweight machine is dependent upon the accuracy to which these terms can be measured and controlled.

Taking variances in the equation above it is possible to say:

$$\left(\frac{\sigma_F}{F} \right)^2 = \left(\frac{\sigma_{m_c}}{m_c} \right)^2 + \left(\frac{1.2 - \rho_a}{\rho_w} \right)^2 \left(\frac{\sigma_{\rho_w}}{\rho_w} \right)^2 + \left(\frac{\sigma_{\rho_a}}{\rho_w} \right)^2$$

Equation 4

where σ^2 is the variance of an individual term.

In order to calculate the uncertainty associated with the generated force, it is necessary to determine the contribution of the individual terms to the total standard deviation.

7.3 Standard deviations of the individual terms for NPL's 1.2 MN deadweight force standard machine

7.3.1 Mass, m

Adjustment of the weights for the machine was a two stage process⁵. The initial adjustment took place during the weight manufacture, where the mass was machined to be approximately 0.1% overweight and its centre of gravity was adjusted to within 1 mm of its geometric centre. The final adjustment of the weights was carried out using the 2.7 tonne mass comparator at NPL. This allowed a comparison between the unknown mass and a standard mass, comprising of a number of weights of smaller capacity, each weighed on the NPL 300 kg equal-arm balance. The unknown mass was adjusted to equal its required value, with the final mass value having a standard deviation of 1.0 ppm.

Previous experience with austenitic stainless steel masses of similar surface area to mass ratios has indicated that the mass is likely to be stable to better than 0.2 ppm over a period of 10 years. Together with an estimated allowance of 1.0 ppm for change of mass due to wear, this combines to give a total standard deviation of 1.2 ppm for the mass.

7.3.2 Gravitational acceleration, g

The value of g is not constant, as it varies with altitude and over the surface of the Earth. This is due to three effects: the Earth is not a perfect sphere; the centripetal acceleration varies with latitude; and the Earth is not homogeneous. The value of g also varies with time because of the gravitational attractions of the Sun and Moon.

It is possible to measure the value of g at a particular point to a high degree of accuracy, and then to measure the change in g to a nearby site with the use of a gravity meter. This gravity transfer can keep the uncertainty associated with the value of g at the second site to less than 0.1 ppm. This value will change with time by less than 0.2 ppm. It is necessary to allow for the height at which this second reading is taken, as the value of g varies appreciably in a vertical direction. For example, the value of g changes by 2.5 ppm over the height of the 8 m stack of weights in the new deadweight machine. It is therefore necessary to determine a value of g for each of the weights in the machine. The standard deviation of each g value is estimated to be $1.1 \times 10^{-6} \text{ m s}^{-2}$.

7.3.3 Density of the weight, ρ_w

Density measurements have been made on samples from a number of the weights. These measurements indicate that the mean density of the weights is $7\,907 \text{ kg m}^{-3}$ with a standard deviation of 4.1 kg m^{-3} .

A change in temperature of 1°C will change the density of the mass by approximately 0.4 kg m^{-3} . This does not therefore significantly affect the overall standard deviation of this term.

7.3.4 Air density, ρ_a

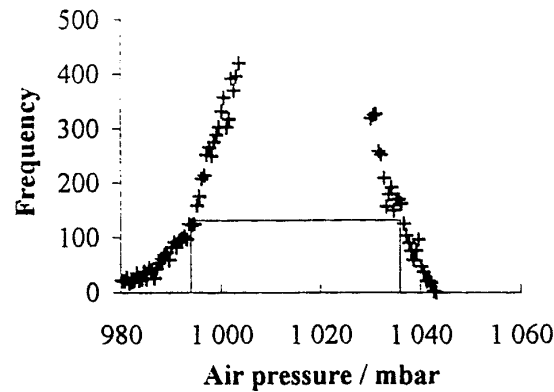


Figure 9: Pressure distribution at Heathrow airport

In common with the distributions of many meteorological elements, the statistical characteristics of air pressure variation show a slight negative skewness⁶. In temperate regions, the standard deviation is much greater (generally about twice as great) in winter than in summer, consequently the effect of combining readings for the whole year is to produce a distribution which is leptokurtic as well as skew.

In order to calculate the uncertainty associated with the air density term, it was necessary to determine how the atmospheric air pressure varied at the site of interest, i.e. Teddington. The UK Meteorological Office provided data describing the air pressure variation for the period from January 1982 to December 1987 at Heathrow, only four miles from Teddington (Figure 9). By analysing this data, it was possible to determine an interval of pressure in which 95 % of the readings lay. This interval was from 994 mbar to 1 036 mbar. The midpoint of this interval (1 015 mbar) is the best estimate for the air pressure from which to calculate ρ_a as it minimises the maximum possible error, at a 95 % confidence level.

If the variation of temperature and humidity throughout their control intervals is taken into account, the overall standard deviation associated with the mean value of 1.2015 kg m^{-3} is 0.013 kg m^{-3} .

7.3.5 Uncertainty of the applied force, F

If we now substitute the standard deviations obtained in the previous section into (Equation 4) and set ρ_a to be 1.138 kg m^{-3} (as a ‘worst case’, corresponding to an air pressure of 961.6 mbar, the lowest recorded in the six year period), we have, for a 10 kN weight:

$$1.96 \frac{\sigma_F}{F} = 4.0 \times 10^{-6} = 4.0 \text{ ppm}$$

Equation 5

These calculations show that the gravitational and air buoyancy force generated by any of the weights is accurate to 4.0 ppm, at a 95% level of confidence. This corresponds to an accuracy of 1 part in 250 000.

7.3.6 Other factors

The previous sections relate only to the gravitational and air buoyancy forces on the weights. There are, however, other factors which may affect the vertical force applied to the device under test. These include:

- Aerodynamic forces
- Magnetic forces
- Electrostatic forces

7.3.6.1 Aerodynamic

Consider the force caused by a 0.1 m/s airflow around the bottom 1.0 kN weight, as illustrated in Figure 10. An airflow of this magnitude could easily arise in practice in a normal air-conditioned room.

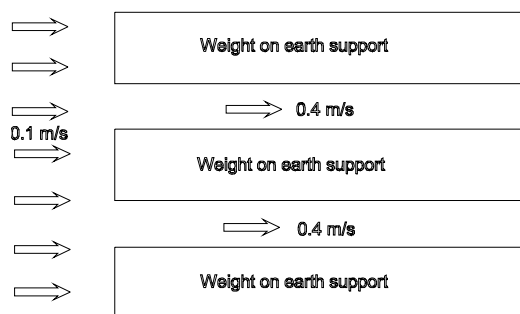


Figure 10 Aerodynamic effect on a 10 kN weight

If it is assumed that all of the air which impinges between the centre lines of the weights then travels between the weights, the velocity in the gap would be 0.4 m/s. This calculation is based on a weight thickness of 52 mm and a gap between weights of 18 mm. In practice, losses due to friction and turbulence would considerably reduce this velocity.

The pressure drop across the weight caused by this velocity difference can be calculated by Bernoulli's equation to be 85 mPa. Over a plate area of 2.6 m², this results in a force of 0.22 N which is equivalent to 22 ppm!

It is apparent, from the above example, that significant forces can be caused by airflow across weights and that design of air-conditioning and enclosures to avoid such effects is therefore of great importance.

The weightstacks of the 1.2 MN machine are screened from draughts and the air conditioning ducts were designed in such a way so as to avoid airflow across the weights. No change in load cell output has been observed at different weight gap settings and it is therefore assumed that these measures have been successful in preventing such effects, as changing the plate separation would otherwise change the velocity in the gap leading to a different resultant pressure.

Further work, such as a full airflow analysis, would improve understanding of the situation. For the present, an estimated uncertainty of 2 ppm due to airflow across the weights is assumed.

7.3.6.2 Magnetic

The weights of the 1.2 MN machine are of large areas and are separated by small gaps. It is therefore important that the possibility of magnetic forces between the weights was examined and overcome at the design stage.

This has been achieved by manufacturing the weights from austenitic stainless steel, which has very low magnetic relative permeability. The surfaces of the weights were also left in the ‘as-rolled’ condition, rather than being machined, as the plastic deformation during machining leads to increased permeability. The plates were surveyed after machining and the magnetic relative permeability was found not to exceed 1.03.

Without a full magnetic survey, it is not possible to determine the magnitude of the magnetic forces associated with these permeability levels: however, the load cell output has not been observed to change with the gap between plates. It has therefore been assumed that the effect of magnetic forces between weights, and between weights and the supporting structure, does not exceed 2 ppm.

7.3.6.3 Electrostatic

In the 1.2 MN machine, the weights applied to the scalepan are held at a voltage of +15 V. The weights at rest on the sideplates are effectively earthed, and so there is a maximum voltage difference of 15 V between the two. The force resulting from this voltage difference is negligible and electrostatic effects can therefore be ignored.

7.4 Discussion

The total vertical force, F_T applied by the scalepan and weights to the device under test is given by:

$$F_T = F_G + F_A + F_M$$

Equation 6

where F_G is the force due to gravity and air buoyancy, F_A is the aerodynamic force, and F_M is the force due to magnetic effects. Taking variances, we have:

$$\sigma_{F_T}^2 = \sigma_{F_G}^2 + \sigma_{F_A}^2 + \sigma_{F_M}^2$$

Equation 7

which gives a 95% uncertainty for the force applied of 4.9 ppm, or 1 part in 200 000.

If greater accuracy is required for specific calibrations, it is possible to measure separately the air pressure, temperature, and humidity, and hence to calculate the air density. This removes one of the major areas of uncertainty and the overall uncertainty is reduced to less than 3.6 ppm.

7.5 Conclusions

While measurements have indicated that the aerodynamic forces are small, calculations indicate that these forces can be very significant and that poor design of the airflow within the enclosure could have resulted in uncertainties which are large in comparison with the contributions from other sources.

The equation determining the force applied by a suspended mass has been carefully studied, in connection with the NPL 1.2 MN deadweight force standard machine. Values of the terms in this relationship have been determined, along with their related uncertainties. From these calculations, it is possible to say that the magnitude of the vertical force vector applied to a device by the machine is accurate to better than 5 ppm, or 1 part in 200 000, at a 95 % confidence level.

8. Calibration and classification of a secondary force standard machine

This is the calibration of a force standard machine using one or more calibrated force transducers. The differences between the forces indicated by the machine and those indicated by the force transducer are determined. Hydraulic and lever force machines are usually calibrated using a calibrated load cell or load cells. There are standards for the calibration of materials testing machines and these are described in a later section. There are no internationally agreed standards for the calibration of force standard machines. Some laboratories have deadweight force standard machines which need to be traceable to primary standards. There are two routes that this traceability can take; the first being through transfer of standards from a national standards laboratory such as NPL to the laboratory, the second being through mass and gravity measurement in the same way that NPL's deadweight force machines are traceable to primary standards. The second method can provide lower uncertainties than the first as the contribution of the transfer standard (a load cell) is a large contribution compared with the uncertainties attainable with deadweight machines. However the laboratory in question may not need uncertainties of 0.002 % or lower, so the method of comparison of machines is often preferred. The advantages are that the laboratory does not have to keep re-weighing the weights and making allowances for any frictional effects that may affect performance.

Many laboratories need a machine capable of uncertainties of less than 0.01 % (as their most accurate machine) to calibrate Class 00 devices, so comparative calibrations are sufficient.

A draft procedure for the calibration of lever machines, hydraulic amplification machines, and reference load cell based hydraulic machines is given in section 8.5.

8.1 Uncertainty of secondary force standard machines

8.1.1 Uncertainty of hydraulic amplification force standard machines

The uncertainties of forces generated by these machines are usually greater than those generated by deadweight machines. A force that is well known at the small piston is less well known in the hydraulic machine's loading space. Factors affecting the magnitude of the uncertainty are:

- friction within the hydraulic circuit
- friction due to mechanical contact, either in the deadweight stack or in the frame supporting the large piston

These frictional forces cannot be accurately predicted. To assess the machine performance, it is necessary to measure the actual forces generated using one or more transducers calibrated in, or traceable to, a deadweight machine. This is known as the 'build-up' technique, and it is discussed in more detail in section 8.2.

8.1.2 Uncertainty of transducer-based hydraulic force standard machines

The uncertainty of the measured force applied by a machine is again determined using force transducers calibrated in another machine.

One of the advantages of a strain-gauged machine is that the sum of the forces in the columns of the machine equals the force applied to the force transducer. The system is therefore unaffected by friction. The columns of the machine are acting like load cells and are subject to the same sources of uncertainty. The columns are not normally optimised for strain gauge application so their performance is usually inferior to that of a purpose made load cell.

Machines using a pressure transducer to indicate the applied force will be subject to additional uncertainties. These include friction in the system, changes in oil properties due to temperature and pressure effects and, distortion of the ram changing the effective area and leak rate.

8.1.3 Uncertainty of lever amplification force standard machines

These machines can be calibrated directly. The masses can be calibrated, the lever ratio measured, and their uncertainties estimated. Unlike a deadweight machine, there will be additional uncertainties due to the friction at the pivots and the bending of the lever arms at different forces.

They can also be calibrated using a calibrated force transducer. If the force transducer is well characterised, the effect of friction can be seen.

8.2 ‘Build-up’

Build-up is the process of using a machine of one capacity to calibrate another of higher capacity. Its most common application is the build-up calibration from a deadweight machine to a secondary machine. High accuracy load cells are needed for the best results. Details of the calibration of the NPL 5 MN machine are given in section 8.4.

Three load cells are calibrated to the highest possible accuracy in the highest capacity deadweight machine available. By placing the load cells in parallel, they can be used to calibrate a secondary machine up to three times their individual capacity. This secondary machine can then be used to calibrate three higher capacity load cells individually, and the process repeated to cover higher force ranges. The positions of the load cells are rotated in the machine to test reproducibility.

The data is best collected from the load cells using a computer interfaced to high precision load cell instrumentation. This enforces the rigorous following of timings and eases the handling of data.

Load cells should be temperature self-compensating to avoid problems with machines operating in different environments. Similar cables should be used for all three load cells. Ideally, the load cells for all the ranges should have the same connectors so that the same cables can be used throughout. This should reduce the variation of any electrical effects.

As previously discussed, the geometry of the cell under load is critical in many machines. This also applies to a set of three cells in parallel. It is therefore important to arrange the cells symmetrically about the centre line of the machine. This can be done in several ways, one being to use a purpose built platen with three locating pins to centre the arrangement, another being to perform an alignment check on the cells under load in order to confirm that the outputs of the cells agree to within a specified tolerance. While the first method guarantees geometrical accuracy, the second provides an actual verification that the force is applied equally to each load cell. It is also very important for uniform distribution of force, that the load cells be closely matching in height and have parallel surfaces. For NPL’s build-up, the heights are matched and surfaces parallel to within

0.1 mm. A large difference can lead to unequal sharing of the force between the load cells affecting the repeatability and particularly the reproducibility as the load shifts between cells and positions⁷. In ‘building-up’ from one machine to another, each machine should have its performance assessed before moving on. While the load cells are linear in their performance to quite a high degree, a second degree fit provides some added confidence in the calibration factors used to analyse machine performance. Once analysis is complete, corrections should be made to the machine in whatever form is appropriate to that machine, whether it be correcting handweights for a hydraulic amplification machine, or changing the calibration factors in a digital readout for a strain gauged hydraulic machine. The machine should be recalibrated where changes are made to an indicator.

A similar situation is found in the calibration of multi-component load cells. These are calibrated by assembling sets of three, or multiples of three, small capacity calibrated load cells in a single unit. A problem arises in this set-up as the top of the force range cannot be directly compared to another force device. A typical nine component cell has three sets of three cells. At the intermediate stage of assembly, when three cells are assembled to form a sub-unit of the final device, the lower third of the force range can be checked against the deadweight machine for verification purposes. As there is more chance of the device performing poorly in this range due to some settling of the cells into position, information on the overall performance of the sub-unit, and the final complete device, can be inferred from this test. A similar test on the lower ninth of the range of the complete device provides some similar information on the integrity of the device’s assembly.

8.3 High accuracy intercomparisons

A high accuracy force standard machine needs to be calibrated using one of the above methods. To maintain confidence in its performance, three additional things are required. The machine must be regularly maintained, properly used, and compared with other machines of similar capacity and performance. The comparison requires a force transducer of higher accuracy than the machine with which it is compared if the machine characteristics are not to be blurred by the characteristics of the transducer.

8.4 Example ‘Calibration of NPL’s 5 MN hydraulic amplification force standard machine’

Table 4 shows the systematic analysis of data from the calibration of NPL’s 5 MN machine up to 3.6 MN, using three 1.2 MN load cells.

The raw data are not shown but have been converted to remove the zero offset for each calibration run (assumed to be a linear drift over measurements separated by a constant time gap). These figures are then averaged for each cell and converted from voltage ratios to force values using a second order fit to give the calibration factor for each cell separately. These values are then summed to give a total force traceable to the 1.2 MN deadweight machine and the error associated with each nominal force value.

The data have also been analysed to give the error associated with each individual reading of force at each position of the cell arrangement. From this, values for the repeatability of force at a fixed position and reproducibility of force at varying positions have been calculated. The figures for repeatability at fixed position have been calculated as the standard deviation of the actual forces read at each position, Equation 8.

$$\text{repeatability} = u_{\text{repeat}} = 2 \left[\frac{\sigma_{n-1}(s_i)}{\sqrt{5}} \right]$$

Equation 8 : repeatability

These results are then averaged across positions to give a mean repeatability at each force value. Reproducibility has been calculated as the standard deviation of force values across the seven runs in three positions, Equation 9.

$$\text{reproducibility} = u_{\text{repro}} = 2 \left[\frac{\sigma_{n-1}(s_j)}{\sqrt{7}} \right]$$

Equation 9 : reproducibility

These figures are then the repeatability and reproducibility of the forces in this calibration and not those due to the machine, i.e. the load cell contributions are mixed in with the machine contributions and should be removed. The contributions of the load cells can only be removed if the combined uncertainty of force at each point in this calibration is greater than the uncertainty in force measured by the load cell at that force. If this is not the case the uncertainty must be taken to be that of the load cell itself. Once these contributions have been extracted the 95 % bandwidth can be calculated and an error/uncertainty profile of the machine can be plotted, (shown in Figure 11). Both repeatability and reproducibility have been treated as normal distributions and so have been added in quadrature. A coverage factor of $k = 2$ has been used to give a confidence level of 95 %.

Table 4: Spreadsheet of uncertainty calculations

Force kN	0°			0°			90°			90°		
	1C	2C	3C	1C	2C	3C	1C	2C	3C	1C	2C	3C
0	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000
300	0.178 976	0.179 653	0.183 742	0.178 693	0.180 019	0.183 591	0.180 630	0.181 209	0.180 692	0.179 694	0.179 242	0.183 522
450	0.267 849	0.269 754	0.275 758	0.267 606	0.269 886	0.275 739	0.269 971	0.268 181	0.275 400	0.269 672	0.267 864	0.275 885
600	0.356 918	0.359 221	0.368 116	0.356 614	0.359 583	0.367 936	0.360 217	0.357 050	0.367 217	0.359 748	0.356 726	0.367 890
900	0.534 875	0.539 020	0.551 776	0.534 393	0.538 971	0.552 169	0.540 739	0.535 105	0.550 147	0.539 884	0.535 156	0.550 784
1200	0.713 011	0.718 856	0.734 864	0.712 515	0.718 782	0.735 268	0.721 333	0.713 708	0.732 017	0.720 092	0.713 961	0.732 843
1800	1.068 886	1.076 926	1.101 595	1.068 257	1.077 219	1.101 744	1.081 488	1.070 511	1.095 650	1.080 385	1.070 919	1.096 407
2400	1.423 178	1.434 267	1.468 785	1.423 335	1.434 911	1.467 881	1.441 236	1.426 885	1.458 780	1.439 887	1.427 062	1.459 764
3000	1.777 805	1.791 440	1.834 077	1.778 319	1.792 134	1.832 869	1.800 876	1.782 865	1.820 353	1.799 411	1.783 243	1.821 264
3600	2.132 826	2.148 265	2.197 479	2.133 304	2.148 831	2.196 333	2.160 393	2.138 606	2.180 372	2.158 810	2.139 382	2.181 086
3000	1.778 951	1.790 317	1.834 066	1.780 058	1.789 810	1.833 330	1.800 659	1.782 039	1.821 304	1.800 096	1.782 321	1.821 474
2400	1.425 477	1.434 923	1.466 085	1.425 122	1.433 870	1.467 424	1.441 436	1.426 224	1.459 406	1.442 596	1.426 642	1.457 723
1800	1.070 140	1.077 462	1.100 284	1.070 219	1.076 501	1.101 181	1.082 162	1.070 191	1.095 857	1.083 928	1.070 633	1.093 618
1200	0.714 353	0.719 070	0.733 796	0.714 219	0.718 702	0.734 313	0.722 682	0.714 320	0.730 589	0.724 099	0.714 316	0.729 166
900	0.536 047	0.539 734	0.550 456	0.535 962	0.539 651	0.550 593	0.542 359	0.536 333	0.547 783	0.542 522	0.536 132	0.547 698
600	0.357 700	0.360 321	0.366 622	0.357 807	0.360 271	0.366 536	0.362 285	0.357 775	0.364 782	0.363 132	0.357 677	0.364 011
450	0.268 458	0.271 092	0.276 140	0.268 571	0.271 284	0.276 140	0.272 074	0.268 606	0.273 144	0.272 994	0.268 799	0.272 058
300	0.179 066	0.180 968	0.182 571	0.179 193	0.181 045	0.182 348	0.181 882	0.179 336	0.181 483	0.182 356	0.179 706	0.180 634
0	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000

Force kN	1C	Mean 2C	3C	1C	Force 2C	3C	Total kN	Error kN	Error %
0	0.000 000	0.000 000	0.000 000						
300	0.177 110	0.186 040	0.179 247	98.02	102.95	99.09	300.06	0.058	0.019%
450	0.265 302	0.278 172	0.269 903	146.86	153.96	149.23	450.05	0.053	0.012%
600	0.353 702	0.370 494	0.360 097	195.84	205.10	199.14	600.07	0.072	0.012%
900	0.530 472	0.555 557	0.539 697	293.83	307.67	298.57	900.07	0.069	0.008%
1200	0.707 380	0.740 836	0.718 566	391.97	410.45	397.67	1200.09	0.093	0.008%
1800	1.060 506	1.110 536	1.076 470	588.11	615.78	596.19	1800.08	0.082	0.005%
2400	1.413 043	1.479 417	1.433 983	784.22	820.99	794.81	2400.02	0.017	0.001%
3000	1.765 446	1.847 498	1.790 572	980.56	1026.08	993.23	2999.86	-0.137	-0.005%
3600	2.117 177	2.215 069	2.146 308	1176.80	1231.22	1191.50	3599.52	-0.481	-0.013%
3000	1.764 356	1.848 479	1.790 752	979.94	1026.62	993.31	2999.86	-0.140	-0.005%
2400	1.412 913	1.481 675	1.432 106	784.10	822.20	793.69	2399.99	-0.011	0.000%
1800	1.061 222	1.112 546	1.074 275	588.43	616.82	594.86	1800.11	0.105	0.006%
1200	0.708 742	0.742 318	0.716 309	392.64	411.18	396.29	1200.11	0.110	0.009%
900	0.531 908	0.557 137	0.537 233	294.54	308.46	297.09	900.09	0.087	0.010%
600	0.355 258	0.371 750	0.357 700	196.63	205.73	197.72	600.07	0.070	0.012%
450	0.266 748	0.279 425	0.267 559	147.61	154.60	147.86	450.06	0.059	0.013%
300	0.177 994	0.186 630	0.178 015	98.47	103.23	98.35	300.05	0.053	0.018%
0	0.000 000	0.000 000	0.000 000						

Force kN	0		90°		Error %		180°		270°		Repeatability at fixed position			average	
											0	90	180	repeatability	reproducibility
0															
300	0.013%	0.001%	0.044%	0.030%	0.001%	-0.007%	0.036%	0.082%	0.087%	0.059%	0.076%	0.007%			
450	0.009%	-0.007%	0.033%	0.017%	-0.007%	-0.009%	0.029%	0.013%	0.008%	0.010%	0.011%	0.007%			
600	0.008%	-0.003%	0.029%	0.018%	-0.006%	-0.009%	0.030%	0.014%	0.005%	0.005%	0.008%	0.006%			
900	0.003%	-0.005%	0.023%	0.013%	-0.007%	-0.012%	0.023%	0.008%	0.006%	0.005%	0.006%	0.005%			
1200	0.004%	-0.003%	0.020%	0.012%	-0.009%	-0.010%	0.024%	0.012%	0.005%	0.006%	0.008%	0.005%			
1800	0.000%	-0.005%	0.008%	0.010%	-0.011%	-0.011%	0.023%	0.009%	0.010%	0.008%	0.009%	0.005%			
2400	-0.005%	-0.008%	0.011%	0.006%	-0.016%	-0.018%	0.019%	0.008%	0.016%	0.006%	0.010%	0.005%			
3000	-0.009%	-0.009%	0.006%	0.002%	-0.026%	-0.029%	0.015%	0.008%	0.016%	0.006%	0.010%	0.006%			
3600	-0.014%	-0.016%	-0.001%	-0.003%	-0.044%	-0.050%	0.011%	0.002%	0.002%	0.002%	0.002%	0.009%			
3000	-0.010%	-0.013%	0.002%	0.000%	-0.023%	-0.022%	0.015%	0.001%	0.002%	0.001%	0.001%	0.005%			
2400	-0.006%	-0.008%	0.008%	0.005%	-0.018%	-0.022%	0.020%	0.001%	0.001%	0.001%	0.001%	0.006%			
1800	0.000%	0.001%	0.010%	0.009%	-0.013%	-0.014%	0.027%	0.003%	0.002%	0.004%	0.003%	0.005%			
1200	0.001%	0.002%	0.019%	0.018%	-0.013%	-0.013%	0.030%	0.012%	0.016%	0.014%	0.014%	0.006%			
900	0.006%	0.004%	0.021%	0.014%	-0.023%	-0.010%	0.033%	0.007%	0.013%	0.009%	0.009%	0.007%			
600	0.005%	0.002%	0.023%	0.021%	-0.013%	-0.013%	0.034%	0.007%	0.018%	0.010%	0.010%	0.007%			
450	0.007%	0.003%	0.024%	0.027%	-0.012%	-0.013%	0.034%	0.004%	0.004%	0.004%	0.004%	0.007%			
300	0.010%	0.007%	0.028%	0.028%	-0.009%	-0.006%	0.042%	0.004%	0.007%	0.003%	0.005%	0.007%			
0															

180°			180°			270°		
1C	2C	3C	1C	2C	3C	1C	2C	3C
0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000
0.175 280	0.189 863	0.177 152	0.174 514	0.190 129	0.177 611	0.174 546	0.194 104	0.173 834
0.262 577	0.284 269	0.266 379	0.261 882	0.284 660	0.266 662	0.261 429	0.290 382	0.261 701
0.350 031	0.378 544	0.355 518	0.349 199	0.379 254	0.355 603	0.348 445	0.386 787	0.349 246
0.524 453	0.567 792	0.533 232	0.523 958	0.568 676	0.532 766	0.522 737	0.579 870	0.523 350
0.699 208	0.757 228	0.709 967	0.698 968	0.758 507	0.708 905	0.696 958	0.772 825	0.697 330
1.048 719	1.134 715	1.063 549	1.048 605	1.137 502	1.060 875	1.043 854	1.158 247	1.045 969
1.397 700	1.511 845	1.416 127	1.397 860	1.515 181	1.412 553	1.390 575	1.542 591	1.393 986
1.746 874	1.887 429	1.768 028	1.747 132	1.891 762	1.763 243	1.736 577	1.925 555	1.742 372
2.094 827	2.262 257	2.119 457	2.095 843	2.267 653	2.112 660	2.080 705	2.307 781	2.091 537
1.745 218	1.892 063	1.765 299	1.745 970	1.895 278	1.761 372	1.731 949	1.928 002	1.744 586
1.396 882	1.518 625	1.410 387	1.397 261	1.518 288	1.410 187	1.387 267	1.547 413	1.392 818
1.049 631	1.140 717	1.057 063	1.049 738	1.138 642	1.059 001	1.041 981	1.163 111	1.043 598
0.701 599	0.760 577	0.704 703	0.701 553	0.758 836	0.706 487	0.695 714	0.776 361	0.695 711
0.526 908	0.570 414	0.528 414	0.526 935	0.569 452	0.529 556	0.522 267	0.582 688	0.521 680
0.352 154	0.380 398	0.351 882	0.352 096	0.379 768	0.352 569	0.348 445	0.388 897	0.347 599
0.264 462	0.285 882	0.263 177	0.264 370	0.285 405	0.263 744	0.261 422	0.292 165	0.260 309
0.176 166	0.191 130	0.175 195	0.176 402	0.190 695	0.175 409	0.174 442	0.195 081	0.173 241
0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000	0.000 000

Error kN						
0°	0°	90°	90°	180°	180°	270°
0.040	0.003	0.131	0.089	0.002	-0.021	0.108
0.040	-0.032	0.147	0.074	-0.029	-0.041	0.133
0.047	-0.021	0.175	0.108	-0.035	-0.056	0.182
0.031	-0.046	0.210	0.117	-0.066	-0.108	0.207
0.054	-0.039	0.238	0.148	-0.111	-0.124	0.292
0.008	-0.096	0.147	0.181	-0.202	-0.200	0.419
-0.124	-0.181	0.257	0.152	-0.396	-0.436	0.451
-0.273	-0.272	0.167	0.068	-0.776	-0.880	0.464
-0.502	-0.558	-0.047	-0.099	-1.578	-1.787	0.401
-0.308	-0.384	0.073	0.010	-0.677	-0.652	0.439
-0.149	-0.188	0.180	0.123	-0.438	-0.525	0.475
0.001	0.010	0.186	0.171	-0.232	-0.251	0.492
0.016	0.023	0.225	0.221	-0.154	-0.157	0.357
0.056	0.039	0.191	0.123	-0.207	-0.093	0.297
0.028	0.013	0.141	0.129	-0.078	-0.079	0.206
0.031	0.013	0.107	0.122	-0.055	-0.057	0.155
0.031	0.021	0.085	0.083	-0.028	-0.019	0.125

95% uncertainty	sd force output	Mean repeatability of cells (imported)	Mean reproducibility of cells (imported)	5 MN Machine		95% uncertainty bandwidth	min %	max %
				repeatability	reproducibility			
0.152%	0.020%	0.055%	0.008%	0.052%	0.000%	0.104%	-0.084%	0.123%
0.025%	0.018%	0.004%	0.005%	0.010%	0.005%	0.022%	-0.010%	0.033%
0.020%	0.017%	0.003%	0.004%	0.007%	0.005%	0.018%	-0.006%	0.030%
0.017%	0.015%	0.002%	0.003%	0.006%	0.004%	0.015%	-0.007%	0.022%
0.019%	0.014%	0.002%	0.002%	0.007%	0.005%	0.018%	-0.010%	0.025%
0.020%	0.013%	0.002%	0.001%	0.009%	0.005%	0.020%	-0.015%	0.024%
0.023%	0.014%	0.001%	0.001%	0.010%	0.005%	0.022%	-0.022%	0.023%
0.024%	0.016%	0.001%	0.001%	0.010%	0.006%	0.023%	-0.028%	0.019%
0.017%	0.022%	0.002%	0.001%	0.001%	0.008%	0.017%	-0.030%	0.004%
0.011%	0.014%	0.002%	0.001%	0.000%	0.005%	0.010%	-0.015%	0.005%
0.011%	0.015%	0.002%	0.002%	0.000%	0.005%	0.010%	-0.011%	0.010%
0.012%	0.014%	0.001%	0.002%	0.003%	0.005%	0.011%	-0.005%	0.017%
0.030%	0.017%	0.002%	0.002%	0.014%	0.006%	0.030%	-0.021%	0.039%
0.024%	0.019%	0.002%	0.003%	0.009%	0.006%	0.023%	-0.013%	0.032%
0.024%	0.018%	0.002%	0.003%	0.010%	0.006%	0.024%	-0.012%	0.035%
0.016%	0.019%	0.002%	0.003%	0.003%	0.006%	0.014%	-0.001%	0.027%
0.017%	0.019%	0.003%	0.005%	0.004%	0.006%	0.014%	0.004%	0.031%

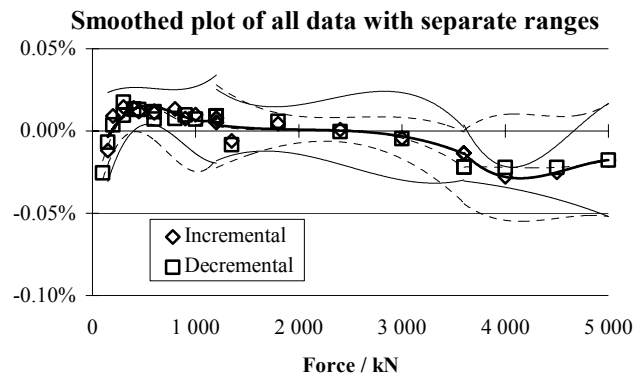


Figure 11: Uncertainty plot of NPL's 5 MN machine

The same process is used to calculate the uncertainty of a load cell calibrated in a previously calibrated machine for the build up procedure, except that the uncertainty of the machine must be removed rather than that of the load cell as performed above.

This method is applicable throughout the range of force standard machines at NPL, using the build-up method to calibrate larger load cells and then calibrating the higher ranges of force.

8.5 Example procedure for the calibration of secondary force standard machines

This procedure is based on a draft being agreed between NPL and UKAS, and has been written for the calibration of secondary force machines at sites other than NPL.

8.5.1 Preparation work at NPL

1. Place the load cell in the machine day before test. Check AC ratio meter using a BN 100 AC bridge calibration unit.
2. Preload 5 times to maximum force, waiting for 2 minutes after a change of force before recording the output ratio.
3. At the 0° position, perform two incremental and decremental calibration runs waiting for 2 minutes after a change of force before recorded the output ratio.
4. Rotate device to the 120° position. Preload once to maximum force waiting for 2 minutes after a change of force before recording the output ratio.
5. At the 120° position, perform two incremental calibration runs waiting for 2 minutes after a change of force before recording the output ratio.
6. Rotate device to the 240° position. Preload once to maximum force waiting for 2 minutes after a change of force before recording the output ratio.
7. At the 240° position, perform two incremental calibration runs and waiting for 2 minutes after a change of force before recording the output ratio.
8. Rotate device to the 360° position. Preload once to maximum force waiting for 2 minutes after a change of force before recording the output ratio.
9. At the 360° position, perform one incremental and decremental calibration run waiting for 2 minutes after a change of force before recording the output ratio.
10. Check AC ratio meter using BN 100.

8.5.2 Work onsite

1. If possible place the load cell in the machine day before test. Check AC ratio meter using BN 100.
2. Preload 5 times to maximum force, waiting for 2 minutes after a change of force before recording the output ratio.
3. At the 0° position, perform two incremental and decremental calibration runs waiting for 2 minutes after a change of force before recording the output ratio.
4. Rotate device to the 120° position. Preload once to maximum force waiting for 2 minutes after a change of force before recording the output ratio.
5. At the 120° position, perform two incremental and decremental calibration runs waiting for 2 minutes after a change of force before recording the output ratio.
6. Rotate device to the 240° position. Preload once to maximum force waiting for 2 minutes after a change of force before recording the output ratio.
7. At the 240° position, perform two incremental and decremental calibration runs and waiting for 2 minutes after a change of force before recording the output ratio.
8. Rotate device to the 360° position. Preload once to maximum force waiting for 2 minutes after a change of force before recording the output ratio.
9. At the 360° position, perform one incremental and decremental calibration run waiting for 2 minutes after a change of force before recording the output ratio.
10. Check AC ratio meter using BN 100.
11. Sensitivity checks on machines.

8.5.3 Return work at NPL

1. Place the load cell in the machine day before test. Check AC ratio meter using BN 100.
2. Preload 5 times to maximum force, waiting for 2 minutes after a change of force before recording the output ratio.
3. At the 0° position, perform two incremental and decremental calibration runs waiting for 2 minutes after a change of force before recording the output ratio.
4. Rotate device to the 120° position. Preload once to maximum once waiting for 2 minutes after a change of force before recording the output ratio.
5. At the 120° position, perform two incremental calibration runs waiting for 2 minutes after a change of force before recording the output ratio.
6. Rotate device to the 240° position. Preload once to maximum once waiting for 2 minutes after a change of force before recording the output ratio.
7. At the 240° position, perform two incremental calibration runs and waiting for 2 minutes after a change of force before recording the output ratio.
8. Rotate device to the 360° position. Preload once to maximum force waiting for 2 minutes after a change of force before recording the output ratio.
9. At the 360° position, perform one incremental and decremental calibration run waiting for 2 minutes after a change of force before recording the output ratio.
10. Check AC ratio meter using BN 100.

8.6 Note on hysteresis

Where significant hysteresis is found, checks on at least two different hysteresis loops should be performed to see if all the required hysteresis cycles need to be calibrated.

9. Calibration of force transducers and materials testing machines

There are various national and international standards concerned with the calibration of force transducers and materials testing machines. These standards are generally paired: the first ensuring that the outputs of force transducers are traceable to national force standards, and the second covering the use of such transducers to measure the forces being generated by testing machines. There are then further standards detailing the use of the testing machines for the determination of material properties, but these standards are not relevant to this document.

Table 5 details the calibration standards most frequently used within the UK.

Table 5: Force transducer and testing machine calibration standards

Standards organisation	Force transducers calibrated in accordance with	may be used to calibrate machines in accordance with
BSI (British)	BS 1610 : Part 2 (see Note) BS EN 10002-3	BS 1610 : Part 1 (compression only) BS EN 10002-2 (tension only)
CEN (European)	EN 10002-3	EN 10002-2 (tension only)
ISO (International)	ISO 376	ISO 7500/1
ASTM (American)	ASTM E 74	ASTM E 4

Note: BS 1610 : Part 2 was superseded in 1995, when EN 10002-3 was adopted by BSI as BS EN 10002-3. However, UKAS have stated that, for transducers calibrated to BS 1610 : Part 2 before a future date still to be specified, they will accept the resulting certificate for the full duration of its calibration period.

Based on the values obtained during the transducer calibration, the transducer will be issued with a calibration certificate, on which a classification (over a specific force range or at specific forces) will be specified. A number of different classifications are possible, depending on the performance of the transducer. The machine calibration will also result in a classification for the machine, but the important rule is that the machine classification cannot be ‘better’ than the classification of the transducer used to calibrate it.

For example, a machine calibrated in accordance with BS EN 10002-2 can only be given a Class 0.5 classification if the transducer used for the calibration had a BS EN 10002-3 Class 00 or Class 0.5 certificate, covering the required range of forces. Transducers classified to Class 1 or Class 2 could not be used for such a machine calibration.

These standards are subject to regular review and amendment, so their procedures and requirements are not fully detailed here. However, the general calibration methods are described. Readers who require further information are advised to consult the latest edition of the relevant standard.

9.1 Calibration of force transducers

The transducer calibration standards specified in Table 5 have similar, but not identical, procedures. In particular, the American standard treats the data quite differently to the method specified in the British, European, and International standards. The areas common to all standards are dealt with first.

Most standards recommend the temperature range in which the calibration should be performed, and give limits on the temperature stability throughout the calibration. They also cover items such as the warm-up time for electrical transducers, the determination of indicator resolution, and some specify the minimum calibration force.

All standards state that the transducer should be set up in a force standard machine, and a range of output readings taken over a range of increasing forces. BS EN 10002-3 specifies that decreasing forces should also be applied - in all other standards, the application of decreasing forces is either not called for or optional. To provide enough data to produce an accurate interpolation curve, each standard requires the application of a minimum of at least eight different forces. At each force, the deflection of the transducer is calculated by subtracting the output at zero load from the output obtained at the force. For transducers which are not compensated for temperature effects, this deflection may be subjected to a correction to allow for the difference between the actual temperature and the nominal calibration temperature.

This procedure is repeated at various orientations of the transducer in the machine, resulting in three or four sets of deflections.

It is useful if an equation linking the transducer deflection to the applied force can be calculated, as it is then possible to calculate the deflection which would be obtained at any applied force within the range, not just at the calibration forces. If this is possible, the transducer is said to be classified for interpolation, or as a continuous-reading device. For some transducers, particularly those using dial gauges, the deflections do not follow a smooth curve - this is due to the periodic error of the dial gauge mechanism. Such transducers can only be classified for specific forces, and only used at these forces for the calibration of testing machines.

9.1.1 British, European, and International standards

As the surface profile of the compression faces of testing machines may not be well controlled, it is important that compression force transducers are fairly insensitive to the distribution of force over their loading surfaces. These standards test this sensitivity by requiring that compression load cells are subjected, once in their lifetime, to a bearing pad test. This test loads the transducer on flat, concave, and convex pads, and compares the deflections obtained at both maximum and minimum forces. The level of agreement obtained is a factor in the determination of the transducer classification.

Other factors in this determination include:

- the spread of the deflections obtained at each force
- the resolution of the indicator at each force
- the agreement between the mean deflection at each force and the value obtained from the calibration equation (for transducers classified for interpolation)
- the difference between increasing and decreasing deflections at each force (for transducers calibrated to BS EN 10002-3)
- the maximum change in the transducer output at zero force, between the beginning and end of each run
- the uncertainty of the calibration force

At each force, all factors affecting the classification are determined. The overall transducer classification is then worked out from the maximum force downwards. Each classification range ceases at the last force for which all classification requirements are met.

These standards also cover the criteria which need to be satisfied if the transducer is to be used with a replacement indicator, without the need for the system to be recalibrated.

The maximum period of validity of certificates calibrated in accordance with these standards does not exceed 26 months.

9.1.2 American standard

A polynomial equation is used to fit all data obtained during the calibration runs against the calibration forces. The differences between the values obtained from this equation and the observed values are then used to calculate a standard deviation associated with the fit. This standard deviation is converted into an uncertainty, expressed in units of force. This uncertainty is multiplied by different factors to give the lower force limits of the loading ranges for the different classifications.

This standard thus gives one value of uncertainty, expressed in terms of force, to cover the whole calibration range. This appears to make the assumption that the uncertainty is constant over the range, whereas plots of specimen calibration results normally show an increase in the spread of deviations from the fitted value with applied force.

For specific force transducers, the standard deviation is calculated from the mean spread of deflections at all forces. The uncertainty is calculated from this standard deviation, together with the resolution of the indicator. The transducer may only be used at those calibration forces which fall into a loading range whose lower limit is calculated from this uncertainty.

The recalibration interval is either one or two years. This is dependent upon the type of instrument, the use to which it is put, and, if available and suitable for comparison, the agreement between the calibration results and those of the transducer's previous calibration.

9.1.3 InstMC calibration document

The Institute of Measurement and Control have produced a very useful document entitled 'A procedure for the specification, calibration and testing of strain gauge load cells for industrial process weighing and force measurement'⁸ A full description of this procedure is given in section 10.2.

9.2 Calibration of testing machines

As with the transducer calibration standards, there is much consistency within the testing machine calibration standards listed in Table 5, particularly between the British, European, and International documents. In fact, a revised version of ISO 7500/1 could well supersede the British and European standards within the next few months.

All the standards cover the verification of the force-measuring systems of static testing machines. The verifications use either calibrated force transducers or, for small forces (for all standards but BS 1610 : Part 1), known masses.

Two different methods may be used for the verification - these are the constant indicated force (Follow-the-Force) and constant true force (Set-the-Force) methods. In the constant indicated force method, a specified force is maintained on the machine indicator, and the reading of the calibrated force transducer is recorded. In the constant true force method, the machine is controlled to obtain a specified force in the calibrated force transducer, and the reading of the machine indicator is recorded.

All of the standards give detailed instructions on the range of forces to be covered, the resolution of the indicator, and the number of runs to be undertaken. They all specify classes of machine related to their performance, most importantly the errors in applied force and the spread of values measured at each calibration force.

Yearly re-verification periods are either recommended or specified in all standards. The American standard also gives recommended methods for spot checks on machine accuracy between machine verifications.

An annex to ISO 7500/1, which details a method for the calculation of uncertainty, is being drafted. It will give an example of how to extract an uncertainty budget from the verification data. This is considered in detail in section 9.3.

9.3 Uncertainty of materials testing machines

The maximum permissible values of relative errors of accuracy, repeatability and reversibility according to ISO 7500/1 and the corresponding maximum uncertainties (for a coverage factor $k = 2$) are shown in Table 6.

Table 6 : Classification according to ISO 7500/1

Class of machine	Maximum permissible value, %				
	accuracy q	repeatability b	reversibility $ u $	zero f_0	Relative resolution a
0	± 0.5	0.5	0.75	± 0.05	0.25
1	± 1.0	1.0	1.5	± 0.1	0.5
2	± 2.0	2.0	3.0	± 0.2	1.0
3	± 3.0	3.0	4.5	± 0.3	1.5

9.3.1 Influence of temperature variation

Laboratory temperatures are often in the range 22 ± 1 °C but ISO 7500/1 allows variation between 10 °C and 35 °C. The uncertainty contribution to this temperature variation should be calculated from the variance given below:

$$w^2(t) = \frac{(\alpha \cdot a_{temp})^2}{12}$$

Equation 10

where α is the temperature coefficient for the change in sensitivity of the force-proving device (see manufacturer's specification) and a_{temp} is the range of temperature variation. The temperature

distribution in an environmentally controlled laboratory is likely to be rectangular (as in Equation 10) although this should not be assumed. The number 12 should be replaced by 8 for a normal distribution, 24 for triangular distributions or 6 for U-shaped distributions. Ambient outdoor temperatures may well follow a non-rectangular distribution.

9.3.2 Influence of long term instability of sensitivity

Manufacturer's specifications can be used to estimate this uncertainty contribution or long-term observations can be made. A rectangular distribution is often a good approximation. Experience or other influences may indicate a different distribution. Equation 11 below assumes a rectangular distribution with $a_{\text{sensitivity}}$ being the range of sensitivity.

$$w^2(S) = \frac{a_{\text{sensitivity}}^2}{12}$$

Equation 11

9.3.3 Influence of linear approximation

A second or third order polynomial is usually used to fit the machine's reading to that of the calibrated force transducer. If a linear approximation is used, the square of the relative deviation between the polynomial and the linear approximation becomes the variance of the contribution to the overall uncertainty of the measured force at that point.

9.4 Uncertainty Statement

This section is taken from a draft annex to ISO 7500/1. It is intended to illustrate the use of routinely taken data to calculate uncertainties compatible with "GUM".

9.4.1 Aim of Uncertainty Annex

This annex is written to enable a calibration to include a statement of uncertainty on an ISO 7500/1 certificate. This statement could be of the form:

At a given force F_{nom} , the expected error (e_{exp}) in the generated force is given by:

$$e_{\text{exp}} = (x \pm y) \%$$

where x is an estimate of the mean error (bias)
 $\pm y$ is the 95 % confidence interval within which the error will lie

This statement agrees with the concept of uncertainty as a range of values within which the error is expected to lie. Whether the machine user corrects for the stated bias value or not is up to him - the certificate can simply report the uncertainty values.

The uncertainty statement should be:

- Simple to calculate
- Statistically correct
- Ideally, based only on the values obtained during a standard verification

The verifying authority should also have the option of specifying, on the certificate, the worst case uncertainty possible for a given machine classification, instead of an uncertainty based on the results obtained.

9.4.2 The Model

Our assumption is that, if the machine is operated to generate the same nominal force on a large number of occasions, the actual force generated will follow a normal distribution (Figure 12). The difference between the mean force generated and the nominal force is termed the bias (mean error). The aim of the analysis is to obtain estimates both for the bias and also for the variation in generated force either side of this value (repeatability).

We are not particularly interested in the confidence interval associated with the bias value, but rather with the confidence interval associated with all forces generated by the machine - i.e. it is no use knowing the bias value to a high degree of precision (from many tests) if the repeatability around this value is unacceptably high.

NB The distribution is unlikely to be perfectly normal due to the resolution of the machine indicator. However, the effect of this is likely to be insignificant in comparison to the uncertainty due to the indicator resolution introduced later in the analysis.

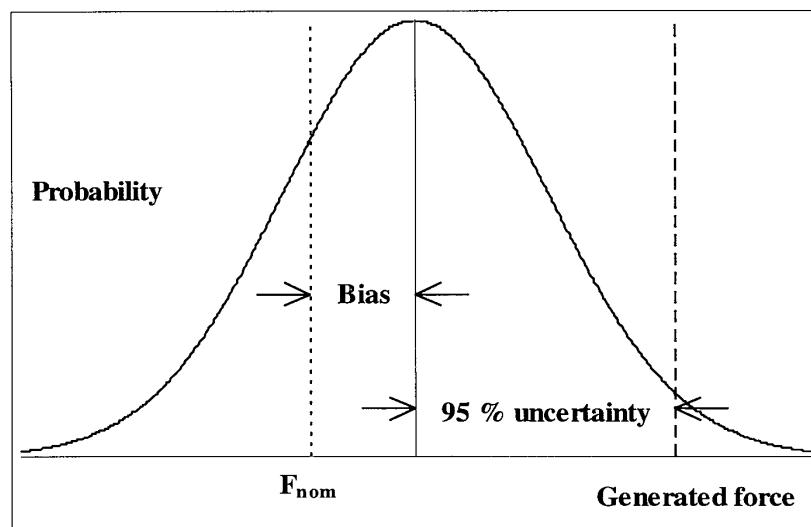


Figure 12: Probability distribution of generated force

Taking only three readings at each nominal force value will give estimates for both the bias and repeatability, but such a small number leads to a large uncertainty in these estimates. Large coverage factors are therefore required to compensate for the small number of readings. For three readings, we have only two ($n-1$) degrees of freedom for the Type A uncertainty contribution (the measured standard deviation of the mean result). This is the worst case value of v_{eff} (giving a 95 % coverage factor (k_{95}) of 4.53) - if there are significant Type B uncertainty contributions (of infinite degrees of freedom - i.e. very well known), the value of v_{eff} can be calculated using a simplified version of the Welch-Satterthwaite equation:

$$v_{\text{eff}} = (\text{combined uncertainty})^4 \bigg/ \frac{(\text{Type A uncertainty})^4}{(n-1)}$$

Equation 12: simplified Welch Satterthwaite equation

giving the value of k_{95} (based on the t-distribution) for different values of v_{eff} as in Table 7.

Table 7: Coverage factors for various degrees of freedom

v_{eff}	1	2	3	4	5	6	7	8	10	12	14	16
k_{95}	13.97	4.53	3.31	2.87	2.65	2.52	2.43	2.37	2.28	2.23	2.20	2.17

v_{eff}	18	20	25	30	35	40	45	50	60	80	100	∞
k_{95}	2.15	2.13	2.11	2.09	2.07	2.06	2.06	2.05	2.04	2.03	2.02	2.00

Experience has shown that either the bias (Figure 13) or the repeatability (Figure 14) can be the dominant uncertainty effect, and that it is not uncommon for both to be major contributors, possibly in different parts of the range (Figure 15).

The analysis of the data should therefore take into account the fact that either of the contributory effects may be the predominant one.

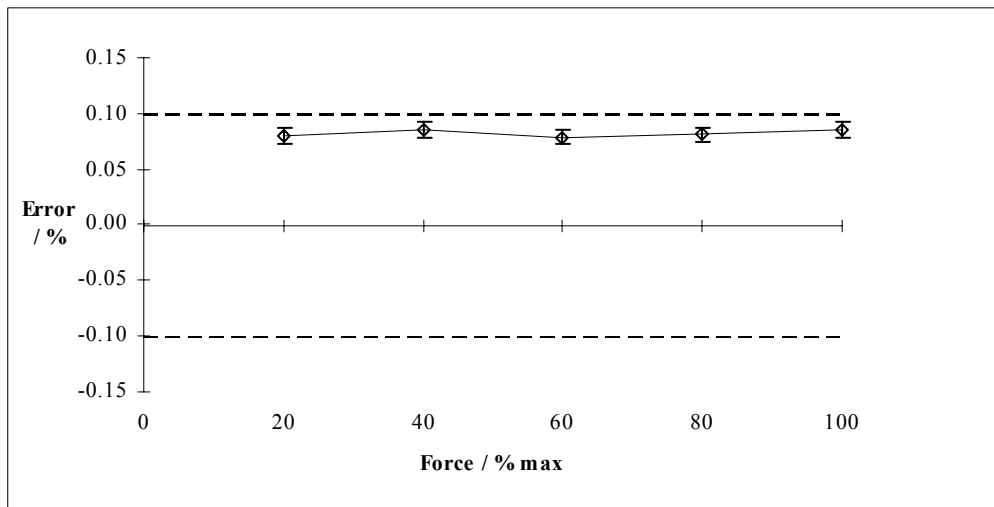


Figure 13: Predominant bias effect

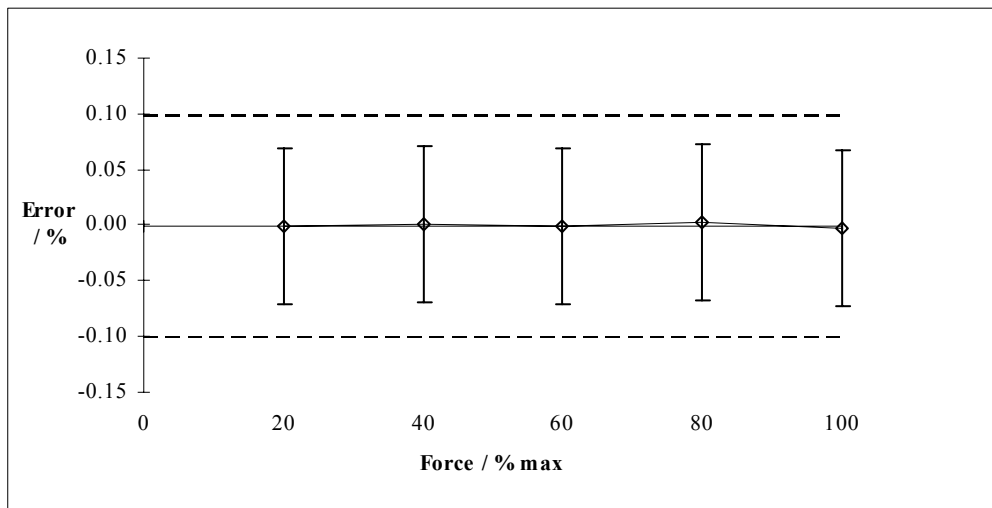


Figure 14: Predominant repeatability effect

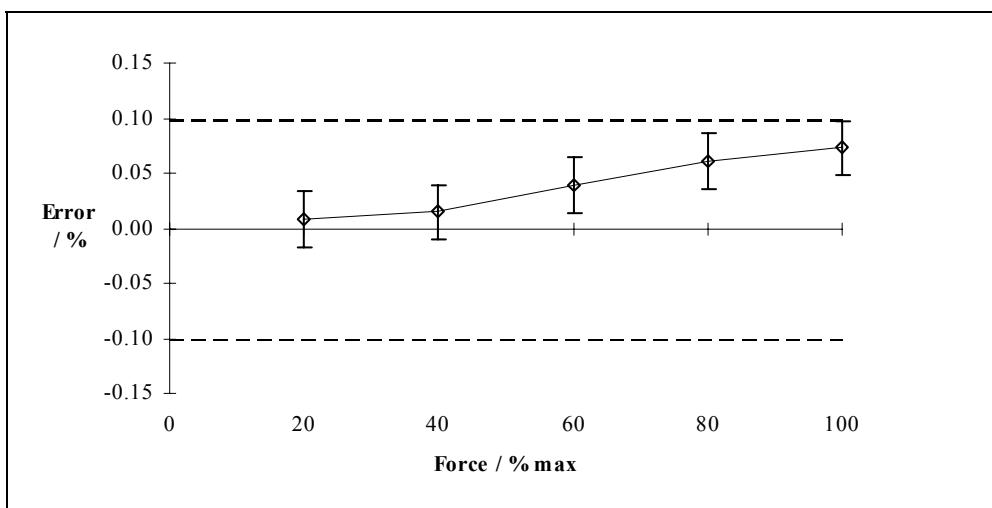


Figure 15: Neither effect predominant

9.4.3 Statistical analysis

The aim of the statistical analysis is to estimate the probability distribution (as in Figure 12 etc.) for each nominal force value, using the values obtained during the verification, and report this as an expected range of errors. The following procedure should be followed for each nominal force:

- Calculate the percentage error for each run
- Calculate the mean percentage error
- Calculate the standard deviation of the errors (using $n-1$ as a divisor) - this is the Type A input to the next phase
- Determine the magnitudes of the Type B inputs (uncertainty of proving device, resolution of machine indicator). If the temperature and/or drift effects of the proving device and/or machine are known or can be estimated, these should also be included. If not, they will have to be allowed for at a later stage.
- Combine all standard uncertainties in quadrature to calculate the combined uncertainty
- Determine the coverage factor from the number of runs and Table 7
- Multiply the combined uncertainty by the coverage factor to give the expanded uncertainty

At each nominal force, the bias and expanded uncertainty can be reported in at least six ways e.g. at $F_{\text{nom}} = 200 \text{ kN}$:

Table 8: Different methods of reporting a force

	Generated force kN	Error kN	Error %
Mean and variation	201.2 ± 0.6	1.2 ± 0.6	0.6 ± 0.3
Minimum to maximum	200.6 to 201.8	0.6 to 1.8	0.3 to 0.9

As this method is based on the individual percentage errors, it is equally applicable to the determination of machine uncertainty using the alternative method of classification given in Annex C of ISO 7500-1.

9.4.4 Example Machine Uncertainty Calculation

This is an example uncertainty calculation of a machine which could be verified to meet (but only just) Class 1 of ISO 7500 at a nominal force of, e.g., 100 kN.

Measured forces in 3 runs: 100.66 kN, 100.66 kN, 101.66 kN

Analysis: Spread = 1.00 kN (less than 1 % of nominal force so within specification)
 Individual errors = 0.66 %, 0.66 %, and 1.66 %
 Mean error = 0.99 % (less than 1 % of nominal force so within specification)
 Standard deviation of errors = 0.577 %

With no significant Type B contributions $v_{\text{eff}} = 2$ in Table 7 gives the worst case value of $k_{95} = 4.53$. The divisors have been chosen in accordance with Table 3 for the appropriate distributions. (1 is used instead of 2 for the Type A uncertainty because the standard deviation has been used rather than the expanded, $k = 2$ value. This is necessary wherever the input Type A uncertainty has not been expanded.)

Table 9: Uncertainty summary with no significant Type B uncertainties

	$\pm$ / %	Divisor	u / %
Type A	0.577	1	0.577
Type B - device	0.000	2	0.000
Type B - resolution	0.000	$\sqrt{3}$	0.000
		Combined:	0.577
		$k_{95} = 4.53$	
		Expanded:	2.61

With significant Type B contributions, Table 10, Welch-Satterthwaite Equation 12 gives

$$v_{eff} = \frac{0.580^4}{(0.577^4/2)} = 2.042$$

Equation 13

Linear interpolation between the k_{95} values in Table 7 gives $k_{95} = 4.48$. This shows how extra terms in the uncertainty budget that are well known (infinite degrees of freedom) can actually reduce the uncertainty at the 95 % confidence level.

Table 10: Uncertainty summary with significant Type B uncertainties

	$\pm$ / %	Divisor	u / %
Type A	0.577	1	0.577
Type B - device	0.120	2	0.060
Type B - resolution	0.025	$\sqrt{3}$	0.014
		Combined:	0.580
		$k_{95} = 4.48$	
		Expanded:	2.60

This value can then be combined with the calculated mean error to give the range where 95 % of values lie. It is not true that such a range will be symmetric, indeed this will only be the case if there is no mean error.

Error = +1 % $\pm$ 2.6 % = - 1.6 % to + 3.6 %

Alternatively, if all errors were negative, the range would become -3.6 % to + 1.6 %

So, for Class 1, generated force = nominal force $\pm$ 3.6 % (for incremental forces only)

Decrementally, all forces could be 1.5 % different from incremental ones. This tolerance should, for the worst case in which the hysteresis is repeatably on the limit, be added to the incremental uncertainty:

Generated force = nominal force $\pm$ 5.1 % (for decremental forces)

Worst case uncertainties for other classes can be calculated similarly, giving the values in Table 11:

Table 11: Worst case uncertainties for different classes

	Class 0.5	Class 1	Class 2	Class 3
Incremental	± 1.8 %	± 3.6 %	± 7.2 %	± 10.8 %
Decremental	± 2.6 %	± 5.1 %	± 10.2 %	± 15.3 %

These values may be quoted on the machine certificate. If they are too high for the machine user, the actual machine uncertainty should be calculated using the procedure outlined previously (either

using the worst case $k_{95} = 4.53$ or calculating v_{eff} from the Welch-Satterthwaite equation, Equation 12, and determining k_{95} from Table 7). If these methods also give unacceptably large values due to the repeatability component, it may be necessary to perform further tests to increase the effective degrees of freedom and hence reduce the required coverage factor.

Table 12: Example calculation

Indicated Force ¹	Measured values			Mean Force	Measured errors			Mean Error
	Test 1	Test 2	Test 3		Test 1	Test 2	Test 3	
kN	kN	kN	kN	kN	%	%	%	%
50	50.2	50.1	50.4	50.2	0.40	0.20	0.79	0.46
100	100.4	100.3	100.7	100.5	0.40	0.30	0.70	0.46
150	150.6	150.6	150.9	150.7	0.40	0.40	0.60	0.46
200	200.8	200.8	201.1	200.9	0.40	0.40	0.55	0.45
400	402.1	401.9	402.3	402.1	0.52	0.47	0.57	0.52
600	603.4	603.0	603.5	603.3	0.56	0.50	0.58	0.55
800	804.7	804.1	804.9	804.6	0.58	0.51	0.61	0.57
1 000	1 006.2	1 005.4	1 006.0	1 006.0	0.62	0.54	0.63	0.59

¹ As shown on the machine.

Classification: Class 1: 1 000 kN down to 50 kN

Worst case uncertainty = ± 3.6 % incrementally

Type A uncertainties have been calculated as the standard deviation of the measured errors, σ_{n-1} .

Calculating uncertainties from obtained values in Table 12, using $v_{eff} = 2$:

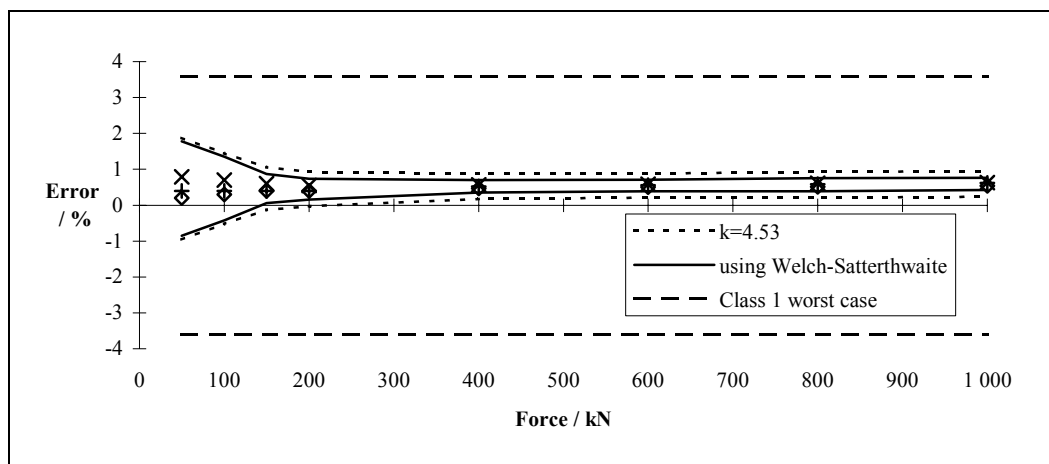
Table 13: Uncertainties calculated with $v_{eff} = 2$

Indicated Force	Type A	Type B		Combined Uncertainty	v_{eff}	k_{95}	Expanded Uncertainty	Range	
kN	%	Device %	Res'n %	%			%	Min %	Max %
50	0.30	0.06	0.06	0.31	2.0	4.53	1.42	-0.96	1.88
100	0.21	0.06	0.03	0.22	2.0	4.53	0.98	-0.52	1.45
150	0.11	0.06	0.02	0.13	2.0	4.53	0.59	-0.13	1.06
200	0.09	0.06	0.01	0.11	2.0	4.53	0.48	-0.03	0.93
400	0.05	0.06	0.01	0.08	2.0	4.53	0.35	0.17	0.88
600	0.04	0.06	0.00	0.07	2.0	4.53	0.34	0.21	0.88
800	0.05	0.06	0.00	0.08	2.0	4.53	0.36	0.21	0.93
1 000	0.05	0.06	0.00	0.08	2.0	4.53	0.35	0.24	0.94

Calculating uncertainties from obtained values, with v_{eff} derived from the Welch-Satterthwaite equation, Equation 12.

Table 14: Uncertainties calculated obtaining ν_{eff} from Welch-Satterthwaite equation

Indicated Force	Type A	Type B		Combined Uncertainty	ν_{eff}	k_{95}	Expanded Uncertainty	Range	
		Device %	Res'n %					Min %	Max %
50	0.30	0.06	0.06	0.31	2.3	4.2	1.32	-0.85	1.78
100	0.21	0.06	0.03	0.22	2.4	4.1	0.89	-0.42	1.35
150	0.11	0.06	0.02	0.13	3.4	3.1	0.40	0.06	0.87
200	0.09	0.06	0.01	0.11	4.6	2.75	0.29	0.16	0.74
400	0.05	0.06	0.01	0.08	12.4	2.22	0.17	0.35	0.70
600	0.04	0.06	0.00	0.07	16.9	2.16	0.16	0.39	0.71
800	0.05	0.06	0.00	0.08	11.2	2.25	0.18	0.39	0.75
1 000	0.05	0.06	0.00	0.08	12.7	2.22	0.17	0.42	0.76

**Figure 16: Summary plot of different methods**

10. Uncertainty of force transducers

Force transducers are classified according to their ability to correctly indicate the force applied to them. There are many factors affecting their performance including: the materials from which they are made, their geometry and surface finish, the strain gauges, the strain gauge bonding, and their history. These factors are difficult to separate. Force transducers are calibrated in a calibrated force machine. The measured performance of the force transducer will be affected by the characteristics of the force machine.

10.1 EA-4/15

EA (formerly EAL) is the European organisation made up from the accreditation authorities in the different countries. The UK is represented by UKAS.

EA have produced a guidance document EA-4/15 (formerly EAL G22 ‘Uncertainty of calibration results in force measurements’²). This document is intended to apply the methods of GUM to the field of force calibrations.

10.2 InstMC procedure for calibration and classification of a force transducer

The Institute of Measurement and Control have produced a very useful document entitled ‘A procedure for the specification, calibration and testing of strain gauge load cells for industrial process weighing and force measurement’⁸. It is intended to provide a unified procedure for the calibration and testing of strain-gauged load cells in areas not covered by existing standards. It is targeted at the industrial sector of force measurement and should be implemented by technical personnel in a suitably accredited laboratory.

Properly implemented, this document provides guidelines for the calibration and testing of load cells as part of the production process or for evaluation of the load cell. It should be noted that the procedure does not cover systems which include load cells, only the load cells themselves.

10.2.1 Summary of InstMC Guide’s intended scope

The procedure should be applied where there are no existing standards or other statutory control. It provides terms and definitions which are commonly used in the field. In addition to background information, specimen data sheets and an example certificate are provided with the guidelines on how to calibrate a load cell.

The information provided by the InstMC guide covers many important areas in some detail. Specific instructions for the different loading conditions, *concentric inclined loading* and *eccentric inclined loading* are provided. Also covered are:

- *Determination of eccentric loading effects,*
- *Determination of rotational effects on tension load cells,*
- *Determination of the temperature coefficients for zero load output and rated output,*
- *Determination of temperature coefficient of zero load output only,*

- *Determination of creep, creep recovery, residual zero and zero return.*
- *Determination of zero stability and rated output stability*

A table is given indicating the time required for adjustment of load and correct reading of that load:

Table 15 Determination of load cell deflection

Change in load		Time
Greater than	to and including	
0 kg	10 kg	10 seconds
10 kg	100 kg	15 seconds
100 kg	1 000 kg	20 seconds
1 000 kg	10 000 kg	30 seconds
10 000 kg	100 000 kg	50 seconds
100 000 kg	-	60 seconds

Instructions on the processing of calibration data are given, covering calculation of:

- non-linearity using the best straight line method
- non-linearity using the terminal line method
- hysteresis
- combined error, using the best straight, and terminal, line methods
- calibration repeatability

These provide a useful explanation of the different methods of analysis and the errors associated with each.

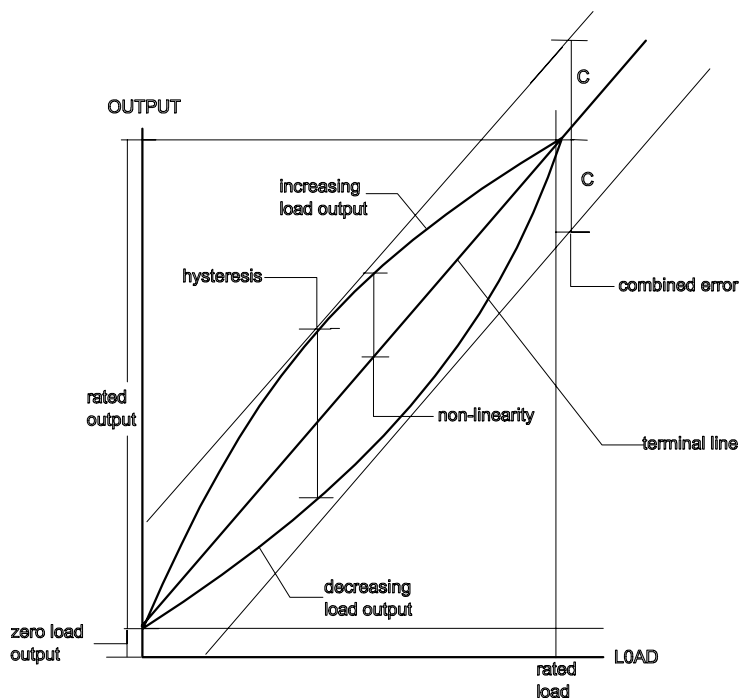


Figure 17: Hysteresis and the terminal line method

Figure 17 shows the implications of using the terminal line method. It can be seen that large combined errors are inherent with the adoption of a straight line for data with hysteresis. Modern devices are better equipped to interpret such data, either using a second degree fit or a multiple straight line fit (reducing each curve to a series of straight lines). Use of either of these techniques will greatly reduce the combined error for non-linear transducers.

A section covering processing of test data instructs on the calculation of:

- rated output and rated output repeatability
- concentric inclined loading effects
- eccentric angular loading effects
- eccentric loading effects
- rotational effects on tension load cells
- zero load temperature coefficient
- rated output temperature coefficient
- zero stability and rated output stability
- creep, creep recovery, residual zero and zero return

The load cell is also given gradings on its degree of environmental protection. The suitability of a load cell to a particular working environment is required to be considered, with the recommendation that the supplier of the load cell be consulted.

Typical units to be used, calculations based on sample data, data sheets and example certificates of performance are included in the InstMC Guide.

10.3 Interchangeability of indicators

BS 1610 : Part 2 : 1985 states that ‘The indicator may be replaced by another one and the proving device need not be recalibrated provided the following conditions are met:

- (a) The original indicator has a calibration certificate, traceable to national standards, which gives the results of a calibration made in terms of the electrical base unit (volt) or derived units (e.g. ampere, ohm, millivolt/volt). The indicator shall have been calibrated over a range equal to or greater than the range over which it will be used with the proving device and the resolution of the indicator when calibrated shall be equal to or better than when used with the proving device.
- (b) The replacement indicator shall have a resolution equal to or better than the indicator it is replacing and shall have a calibration certificate, traceable to national standards, in terms of the same electrical units and covering the range over which it will be used with the proving device.
- (c) The date on the certificate for the original indicator shall not precede that on the certificate for the replacement indicator by more than 12 months.
- (d) The certificates for the two indicators show that the deflections of the proving device, as measured by the two indicators, shall agree within ± 0.1 % over the range of the grading of the device.’

This permits the separation of load cells and indicators for independent calibration, greatly simplifying the calibration process.

10.4 Example calculations of uncertainty for force transducers

It is important to understand that, while a single measurement with a calibrated force transducer can give a very precise value to that force, an accurate picture of how the force is reproduced on subsequent occasions cannot be determined from one measurement. Table 16 and Table 17 contain specimen data and act as examples for this section.

A calibrated load cell uses certified calibration factors to interpret the cell output, which is read as a voltage ratio, in units of force. These can be used with the quoted uncertainty to calculate the force measured by the load cell during that particular measurement, and no other, with an uncertainty that is only dependent on the indicator resolution and the load cell uncertainty, Table 16.

The terms are summed in quadrature to give the combined uncertainty and a coverage factor of 2, as below. The v_i are the degrees of freedom of each of the contributions, v_{eff} is the final effective degrees of freedom.

Table 16 : Uncertainty of a single force reading

Contribution	Value %	Distribution	Divisor	u_i %	v_i
Transducer Uncertainty	0.150	Normal ($k = 2$)	2	0.075	∞
Resolution of indicator	0.050	Rectangular	$\sqrt{3}$	0.029	∞
Combined Uncertainty		Normal		0.080	∞
			k₉₅	2.00	
Expanded Uncertainty		Normal (95 %)		0.161	

Taking more measurements of a force enables the repeatability of the force to be assessed. A given nominal force, i.e. the intended force, when applied six times can be analysed as shown below.

Table 17 : Uncertainty of six readings of a force

Contribution	Value %	Distribution	Divisor	u_i %	v_i
Repeatability	0.036	Normal	1	0.036	5
Transducer Uncertainty	0.150	Normal ($k = 2$)	2	0.075	∞
Resolution of indicator	0.050	Rectangular	$\sqrt{3}$	0.029	∞
Combined Uncertainty		Normal		0.088	v_{eff}
			k₉₅	2.00	179
Expanded Uncertainty		Normal (95 %)		0.176	

Table 17 above shows how six measurements of a force with a calibrated load cell are analysed to give the measured force a 95 % uncertainty bandwidth. The figure for repeatability is the population standard deviation $\sigma_{(n-1)}$ divided by the square root of the number of readings (Equation 2) to give the standard deviation of the mean force value (all measured in percentages) with a divisor of 1, this is the Type A uncertainty contribution.

Repeatability has 5 degrees of freedom ($n-1$), unlike the other contributions which have an infinite number.

The transducer uncertainty is the maximum permissible uncertainty, of indicated force, for the class of load cell used to make the measurements. This has a normal distribution, unless stated otherwise, and a corresponding divisor of 2 for an uncertainty quoted at the 95 % confidence limit.

Indicator resolution is the last digit of the display read during the measurements, with a rectangular distribution and a divisor of $\sqrt{3}$. The above table has one term for resolution, which is correct for a deadweight machine where the applied force is known without an indicator. However, a hydraulic machine with its own indicator would need another resolution term added for the machines indicator.

These three terms are then summed in quadrature to give the combined uncertainty. The effective degrees of freedom for the overall distribution can be calculated from the Welch-Satterthwaite equation.

$$v_{eff} = (n - 1) \frac{(\text{combined uncertainty})^4}{(\text{Type A uncertainty})^4}$$

Equation 14: simplified Welch Satterthwaite equation

For the terms shown in Table 17 the calculations are shown below:

$$\text{Combined Uncertainty} = \sqrt{0.036^2 + 0.075^2 + 0.029^2} \approx 0.088 \%$$

$$v_{eff} = 5 \frac{0.088^4}{0.036^4} \approx 179$$

This is used to find k_{95} from Table 7, which is then multiplied together with the combined uncertainty to give the expanded uncertainty with a confidence limit of 95 %.

An uncertainty calculated in this way can be used to indicate the expected uncertainty in a force applied when the load cell is not present but the machine is operated in the same way. The former (single measurement) case, gives no information on the performance of the machine when the load cell is removed or not used to indicate the applied force.

The user can decide how many readings (n) to take. The repeatability depends on $1/\sqrt{n}$ so more readings will improve the repeatability. In practice, these improvements will level off after 3 or more readings, depending on the stability of the force. In general, the more stable a force, the fewer readings required to assess its stability.

11. Conclusions, and introduction to the appendix

The report so far has given an introduction to the basics of force, its generation and the principles of calibration. Examples of calibrations have been given, at the end of each section, which guide the reader through the required procedure and explain the calculation of the relevant uncertainties.

The Appendix gives an in depth explanation of many sources of uncertainty that can be generated by the different characteristics of strain-gauge load cells. This section will be familiar to those with experience in the area and serves as a reminder. For those new to the area it will hopefully serve as a useful introduction.

12. Acknowledgements

The authors would like to thank Ray Jenkins, formerly of NPL, who wrote large sections of the text used in this guide. We also acknowledge the financial support of the National Measurement Systems Policy Unit of the UK Department of Trade and Industry.

Appendix 1 Characteristics of force transducers

This appendix was originally provided as course notes by Ray Jenkins as a summary of the characteristics of strain gauge load cells that limit their accuracy. Various techniques are described to reduce the errors from these characteristics, enabling force standard machines to be intercompared with an uncertainty better than 0.005 %.

A1.1 Introduction

During the past 20 years, strain gauge load cells have been used with high resolution digital indicators as high accuracy force transfer standards for the international intercomparison of force standard machines. The uncertainties of the forces applied by these machines are in the region of 0.001 % to 0.002 % and it has been found possible using strain gauge load cells to show agreement between different machines within 0.005 %⁹. As well as the intercomparison of force standard machines, there are other applications of load cells that require high accuracy force measurement. These include the calibration of precision lever and hydraulic machines, the measurement of rocket thrust and the weighing of aircraft. In each case, the accuracy obtained will be limited by the conditions of use of the load cell and its performance characteristics. Some of the characteristics of a load cell that are known to be important are summarised in later sections, together with measurement techniques that enable the resulting errors to be reduced.

A1.2 Repeatability

Repeatability is a measure of a load cell's ability to give the same output under the same conditions. OIML define it as the agreement between successive measurements of the differences of load cell output for given applications of the same force. This force should be in the same direction and in the range of the load cell's calibration. The tests should be made by the same observer, with the same measuring equipment, on the same occasion and without mechanical or electrical disturbance, i.e. calibration conditions such as temperature, axiality of loading and the timing of readings should be held constant as far as possible. Although many manufacturers quote a value for repeatability as a basic characteristic of a load cell, it can be seen from the definition that repeatability should not be considered as such. The value obtained for a given load cell in a given force standard machine will depend on the true characteristics of the load cell such as its creep, sensitivity to bending moments and temperature gradients. It will also depend on the resolution and repeatability of the electrical measuring equipment and the degree to which the conditions of the tests, which are characteristics of the test procedure, are held constant. The value of repeatability obtained is important as it limits the accuracy to which the characteristics of the load cell can be measured.

By using high stability digital indicators which have resolutions better than 0.001 % (currently 0.000 1 % is obtainable) and by carefully controlling the calibration conditions, it is possible to achieve a transfer of the standard of force within 0.005 %, which is better than the repeatability of the load cells claimed by the manufacturer. Such a low uncertainty could not be claimed for a force standard machine which used an in built strain gauge load cell as the means of defining the force applied, because the general conditions of use of the load cell would not be so well defined in practice.

A1.3 Non-Linearity

There are several ways of defining non-linearity. The following definition, however, is one which defines it in a simple way that is not open to misinterpretation: the non-linearity is the deviation of the measured output, obtained for increasing forces only, from the straight line passing through the outputs at zero and the rated force. For high accuracy force measurements, corrections should always be applied for non-linearity, either directly or within the instrumentation. The relationship between the output of a load cell and the force applied can generally be expressed by a third order polynomial equation such that the maximum residual - the magnitude of the difference between a measured output and the corresponding output determined by the equation - is close to the repeatability of the measurements. This will reduce errors due to non-linearity to a level that will not be significant. Nevertheless, for force measurement of the highest accuracy, the load cell should be calibrated and subsequently used at the same nominal values of force.

A1.4 Creep

The creep of a load cell is usually defined as the change of output with time following a step increase in force from one value to another. Most manufacturers specify the creep as the maximum change of output over a specified time after increasing the force from zero to the rated force (e.g. 0.03 % of rated output over 30 minutes). Creep recovery is the change of output following a step decrease in the force applied to the load cell, usually from the rated force to zero. For both creep and creep recovery, the results will depend on how long the force applied has been at zero or the rated value respectively before the change of force is made.

A creep test requires a machine that can hold the force constant within close limits; generally a deadweight or a lever machine is required although some of the precision hydraulic machines at the various national institutes of metrology are suitable. For a creep recovery test, the force can be held within 1 % by a hydraulic testing machine and then reduced to zero very quickly. The creep recovery characteristic can usually be measured more accurately than the creep characteristic because it is easier to determine the moment at which the force is completely removed than that at which it is applied.

Several different factors contribute to the overall creep behaviour of a strain gauge load cell, each factor arising from the performance of one of the several components of the load cell that undergo a change of strain when the force applied is changed¹⁰. These components will include some or all of the following:

The basic load-carrying elastic element together with any supporting diaphragms and outer case.

The resistance strain gauges, each comprising a metal foil grid with an appropriate backing and adhesive layer.

Wire connecting the strain gauges to form a complete bridge circuit and any precision resistors used to adjust the bridge sensitivity and the temperature coefficients of zero and sensitivity.

When a force is applied, the components that are deformed will undergo a change of temperature due to the change of internal energy with applied strain¹¹. As thermal equilibrium is regained, the temperatures of the different components will change, resulting in possible changes in the output of

the load cell. The magnitudes of these changes depend on the component's function and the amount of its temperature change. This depends on the magnitude and direction of the strain as well as the material of the component. For steel, a tensile strain will cause a fall in temperature and a compressive strain a rise in temperature of about $0.19\text{ }^{\circ}\text{C}$ for a strain of 0.001.

Figure 18 shows the change of deflection with time, following the application of the rated compression force, for two elastic elements commonly used in load cells - a hollow steel column and a proving ring. The deflection measurements were made by displacement transducers that were isolated from any temperature change¹². In the case of the steel column, the application of a compression force causes an increase in the temperature of the column, resulting in an immediate thermal expansion. Thus the deflection immediately after loading, the adiabatic deflection, will be equal to the deflection due to the applied force less the thermal expansion. As the temperature falls as thermal equilibrium is regained, the thermal expansion reduces to zero and the deflection of the column increases until the isothermal value is reached (this increase will not be exactly equal to the thermal expansion as the Young's modulus of the steel will also fall slightly with the fall in temperature). If the column is then unloaded, a reverse sequence of events takes place.

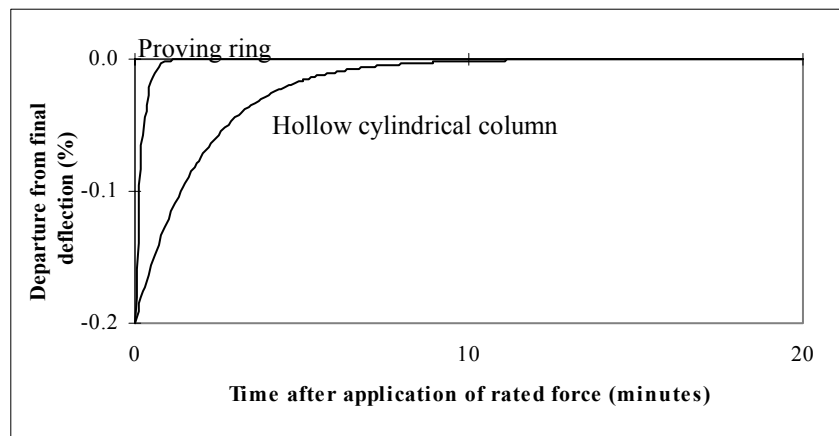


Figure 18. Change of deflection after applying the rated force to two different elastic elements

In the case of the proving ring, there is a more complicated stress distribution with both compression and tension strains which give rise to instantaneous heating and cooling respectively. Thermal expansions and contractions are produced in different parts of the ring and these dimensional changes combine to produce an adiabatic deflection which is less than the isothermal deflection.

For elastic elements, such as proving rings and columns, where the deflection is determined by the value of Young's modulus, the magnitude of the difference between the adiabatic and isothermal deflections is independent of the geometry of the element and depends only on the material. Effectively there is a difference between the adiabatic and isothermal Young's modulus; for steel this is theoretically 0.21% ¹³. The rate at which thermal equilibrium is regained, however, will depend on the geometry and stress distribution in the elastic element. In the case of the column, there is a general rise in temperature of the elastic element and heat transfer takes place with the external environment mainly by conduction and, to a much lesser extent, by convection. About 20 minutes are required before thermal equilibrium is reached. For the proving ring, there will be internal heat transfer taking place by conduction between the parts of the ring in compression and those in tension. A relatively smaller amount of heat transfer will take place with the external environment and thermal equilibrium is regained within about 4 minutes.

A force applied to a strain gauge load cell will cause a temperature change not only in the elastic element, but also in the strain gauges, interconnecting wires and any temperature compensating resistors that are strained. The difference between the adiabatic and isothermal output will therefore depend on the type of elastic element, the type of strain gauge used, the configuration of the strain gauges in the Wheatstone bridge circuit and details of the bridge completion and temperature compensating resistors. In the case of a precision load cell, the output at zero force and the sensitivity are both compensated for temperature changes in the elastic element. Due to their low thermal masses, the strain gauges and temperature compensating resistors can be considered to be at the same temperature as the elastic element and in this case there should be no difference between the adiabatic and isothermal output voltage. Figure 19 shows the change of output voltage after loading for a strain gauge load cell having a columnar type of elastic element. In practice, temperature compensation is only achieved within stated limits and there may be some time required for the strain gauges and resistors to reach the temperature of the element.

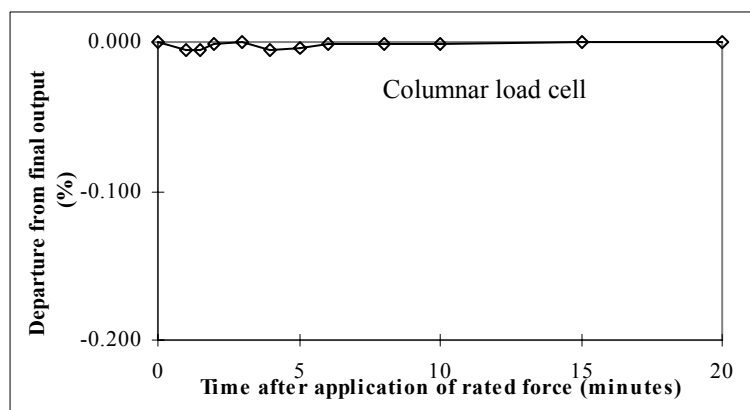


Figure 19. Change of output after applying the rated force to a 500 kN load cell

The overall creep response of a load cell will also depend on the conventional engineering creep of the different components that are strained. The high shear stresses in the backing and adhesive layers of the strain gauges result in visco-elastic relaxation in these layers, causing the output of the load cell to decrease with time. Creep in the elastic element itself and the metal foil of the strain gauges causes the output to increase with time. The net effect may be a positive or negative change with time; the direction, together with the magnitude, will depend on the materials used, the thicknesses of the different layers of the strain gauge and the size and pattern of the strain gauge grid. Some strain gauge manufacturers can provide strain gauges that, when used with a specific material for the elastic element and a particular bonding procedure, minimise the overall effects of creep.

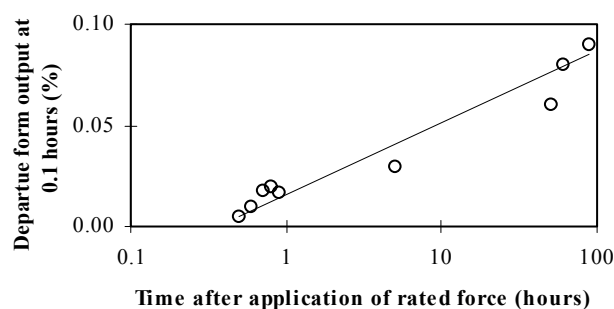


Figure 20. Long term creep of a 500 kN load cell

Visco-elastic creep is proportional to the logarithm of the time after applying a force and can be studied by undertaking a creep test over a time period much longer than that required for thermal equilibrium to be regained after the initial application of the force. Figure 20 shows the results of a longer-term creep test on a 500 kN compression load cell. For such a load cell, the results obtained over a period of 10 hours can be used to predict the creep over 100 hours or longer.

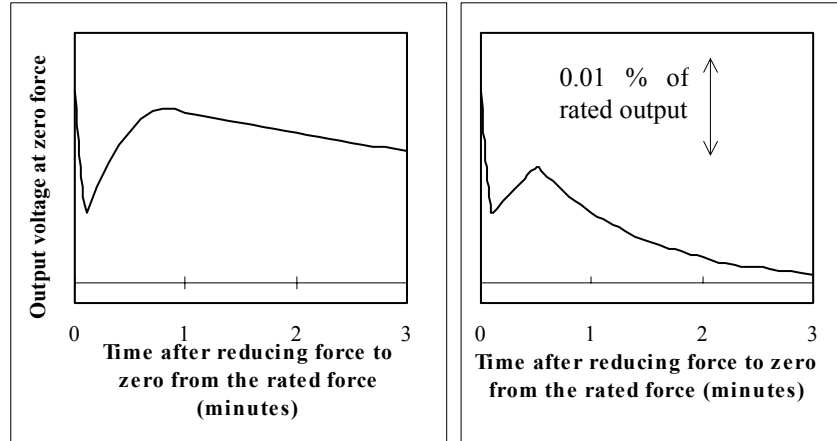


Figure 21. Short term creep recovery for two load cells of the same type

Clearly, the creep of a load cell is a complicated phenomenon with several different factors contributing to the overall effect. Figure 21 shows the creep recovery of two different load cells of the same type during the three minute period immediately after reducing the force to zero from the rated force, this having been applied for two minutes. For high accuracy force measurements, errors due to creep are reduced by carefully completing a timed loading sequence, taking readings of the output of the load cell at well-defined points in the sequence, preferably where there is little change occurring in the output voltage. The loading sequence must be chosen to suit both the force calibration machine and the machine or loading rig in which the load cell will subsequently be used. The loading sequence should include a well-defined pre-loading schedule usually consisting of between 3 and 6 pre-loads to the rated force as in practice there will be a small residual temperature rise after the completion of each load cycle. The magnitude of this rise falls with the number of cycles until a stable condition is reached.

The importance of creep as a factor limiting the accuracy obtainable with a strain gauge load cell is illustrated by the fact that if the force applied can be held constant for a long period of time, it is possible to use a load cell as a high accuracy force or mass comparator capable of a resolution of 1 part in a million¹⁴.

A1.5 Hysteresis

The hysteresis of a load cell is usually defined as the difference between measurements of load cell output for the same applied force, one measurement obtained by increasing the force from zero and the other by decreasing the force from the rated force. Most load cells exhibit the conventional cigar-shaped hysteresis loop (see Figure 17), the width of the loop being dependent on the amplitude of the load cycle which must therefore be specified when quoting the magnitude of the hysteresis. As the amplitude of the load cycle tends to zero, the hysteresis tends to a value which is less than can currently be measured electrically. If a universal load cell is used from maximum compression force to maximum tension force, the maximum hysteresis, occurring near zero, will be much larger than the hysteresis quoted for a force applied in one mode only.

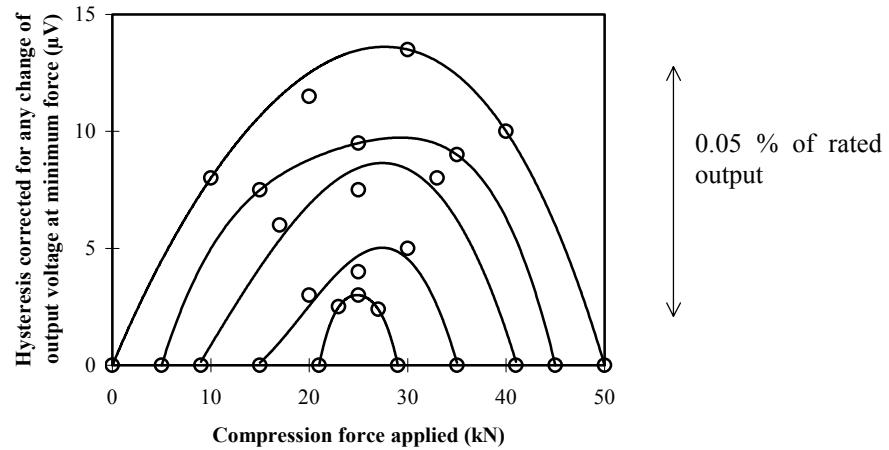


Figure 22: Hysteresis of a 50 kN load cell

The hysteresis of a load cell can only be measured by reference, either directly or indirectly, to a force standard machine which has no hysteresis itself. The only machine of this type at present is the deadweight machine. It is interesting to note that a force applied by a deadweight machine is not truly static. A load cell with a deadweight force applied is essentially a mass spring system with very low damping and there will therefore be a constant oscillation of force due to the general level of ground vibration. The amplitude of force oscillation, however, will generally be small enough not to affect the measurement of the hysteresis characteristic. With any deadweight machine it is not possible to calibrate a device through zero, i.e. to go from tension to compression or vice versa, without involving the force due to the mass of the device itself. At present, the best that can be done is to calibrate a device in one mode and then carefully re-position the device in the machine to continue the calibration directly in the other mode. The forces due to the mass of the different fittings needed for each mode will have to be taken into account together with the force due to the mass of the device itself.

When measuring hysteresis, there will always be some masking due to creep and creep recovery. Normally, a hysteresis test is completed in a short time, consistent with smooth operation of the deadweight machine. Figure 22 shows the hysteresis of a 50 kN load cell for different amplitudes of load cycle symmetrical about 25 kN. For each amplitude chosen, the load cell was cycled from the minimum to the maximum force and back three times before completing a test. At the beginning and end of the test, the output voltage at minimum force was measured and its value corresponding to each force in the test was calculated assuming any change to be uniform with time. The calculated output voltage at minimum force was subtracted from the output voltage at each force to give the difference of output voltage for that force; the hysteresis was then determined by subtracting the difference of output voltage for increasing force from that for decreasing force. The results obtained confirm that, for the load cell tested, the maximum hysteresis in a given cycle is approximately proportional to the amplitude of the cycle.

For high accuracy force measurement, the loading cycle has to be *well* defined in order to minimise errors due to hysteresis. The hysteresis characteristic of load cells used as force transfer standards is sufficiently repeatable, for a given load cycle, to enable the hysteresis in precision lever and hydraulic machines to be measured¹⁵.

A1.6 Temperature Coefficients of Zero and Sensitivity

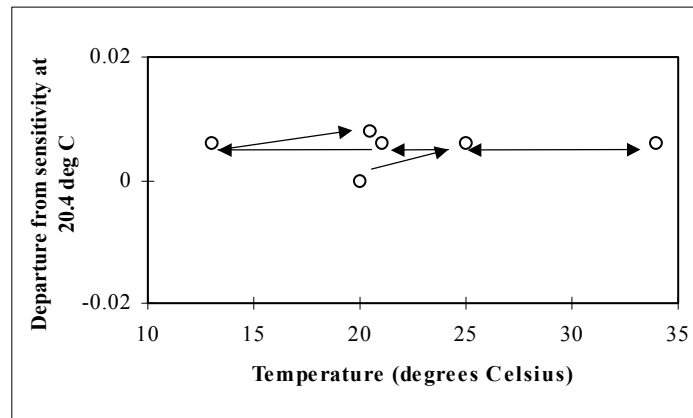


Figure 23: Effect of temperature on sensitivity

The temperature coefficients of the output at zero force and the sensitivity of a precision load cell, over a temperature range of about 50 °C, can be made very small by choosing appropriate values for compensating resistors used in the bridge circuit. Typically, within the range -10 °C to 50 °C, the change of sensitivity can be made to be less than 0.001% per °C and the change of the output at zero less than 0.001% of rated output per °C. It is usually the temperature coefficient of sensitivity that is more important for high accuracy force measurement as the output of the load cell at zero force can be measured at regular intervals in the loading sequence. Figure 23 shows the effect of temperature on the sensitivity of a precision 500 kN load cell. The sensitivity at each temperature was determined by pre-loading the load cell five times to 500 kN and then determining the average difference of output voltage for three applications of a force of 500 kN. Each difference of output voltage was calculated by subtracting the average output voltage at zero, before and after the application of a force, from the output voltage with that force applied. The results show that the temperature coefficient is less than 0.001% per °C and that the relationship between sensitivity and temperature, within the repeatability of the measurements, is reversible. As it is normally possible, when undertaking intercomparisons of force standards, to control the temperature within $\pm 1^\circ\text{C}$ of a reference value (20 °C at NPL), errors due to differences of ambient temperature should not be significant. This will only be true, however, if there is no significant temperature gradient in the load cell. Depending on the material of the elastic element and the type of strain gauge used, a temperature difference of 0.1 °C between the elastic element and the resistors compensating for the change of sensitivity with temperature will cause an error of about 0.003%. To avoid such errors when obtaining the results in Figure 23, the load cell was left overnight to stabilise following a change of temperature.

The temperature of a load cell will increase slightly and a small temperature gradient be induced after the strain gauge bridge is energised, due to energy dissipation in the strain gauges. For high accuracy work, a load cell should be set-up and left energised overnight to reach a state of thermal equilibrium before being used. An insulating box surrounding the load cell reduces the magnitude of any thermal gradients caused by short-term changes of the ambient temperature.

It is possible to use a load cell which has not been compensated for change of sensitivity with temperature provided the change with temperature is reversible and the temperature coefficient has been determined with sufficient accuracy. The temperature of the load cell in use will also have to be measured with sufficient accuracy, generally better than 0.1 °C, and a check will need to be made

that thermal gradients are within acceptable limits. In this latter respect, the same accuracy of temperature measurement is required for both a compensated and an uncompensated load cell.

A1.7 End Loading Conditions

In general, a load cell has two interfaces through which a force is applied. These may be the upper and lower loading surfaces of a compression load cell or the upper and lower screw threads of a tension load cell. In some load cells, one or both interfaces are part of the elastic element to which the strain gauges are bonded; in other load cells the interfaces are remote from the elastic element, e.g. a permanently attached base pad for a low profile, shear force load cell. At each interface, there will be a force distribution which will depend on the end loading conditions. A change in these conditions, therefore, may cause a change in the force distribution resulting in a change of the sensitivity of the load cell, even though the resultant force at the interface remains unchanged.

For compression load cells, the end loading conditions will be determined by:

Properties of the materials in contact at the loading surface of the load cell such as hardness and coefficient of friction.

The shape of the surfaces in contact at the interface.

Deformation of the surfaces under load.

For tension load cells with interfaces at screwed threads, the end loading conditions will be determined by the accuracy of the screw threads of the load cell and the tension adapters and the amount of thread engagement. For beam load cells, the type of support bracket and loading saddle determine the end loading conditions.

The British Standard concerned with the calibration of proving devices for the verification of materials testing machines (BS 1610) recognises the importance of end loading conditions by requiring compression proving devices to pass a bearing pad test. In this test, a device is loaded through a flat steel pad and then through each of two steel pads that are conically convex and concave respectively by 1 part in 1 000 of the radius. The maximum permitted difference between the sensitivity obtained at maximum force on either conical pad and that obtained on the flat pad is 0.2 % for a Grade 1 proving device with a capacity of 500 kN or less.

Depending on the design of load cell, the change of sensitivity caused by a change of end loading conditions can be quite large; some precision compression load cells with low creep, hysteresis and temperature coefficients can show differences of sensitivity in the bearing pad test of 0.3 %, others less than 0.05 %¹⁶.

For tension and compression load cells with a columnar type of elastic element having strain gauges bonded at its mid-length, the length to diameter (l/d) ratio is the main parameter that determines the magnitude of the influence of end loading conditions: as the l/d ratio increases, the influence of end loading conditions is reduced. NPL 500 kN compression load cells having a l/d ratio of 3.7 (well below the buckling ratio for the design of element) show changes in the bearing pad test of less than 0.005 %. Some commercial load cells with l/d ratios near unity show changes greater than 1 %. In many designs of compression load cell, the load sensing element is located in a base plate and supported at the top by a diaphragm which is mounted on a robust outer case integral with the base. If the lower loading surface of the base plate is larger than the cross-section of the element, there is the possibility that the base and casing will distort when the load cell is loaded on a conically

depressed surface and cause a change of the sensitivity. This change may be reduced if the base plate is machined so that the force is concentrated beneath the element.

Many load cells, especially with capacities less than 200 kN, do not have columnar elements. Instead, the element may be of ring form, where bending strains are measured, or may be of a more complicated design where shear strains are measured. Some designs may be less sensitive to changes of end loading conditions, especially where the strain measurement is made at a point that is well removed from the loading interfaces. It is important, however, to undertake specific tests to show that this is the case. These tests should be applied not only to each type of load cell, but also to different capacity load cells of the same type. The sensitivities of some of the low profile, shear force load cells that are claimed to be insensitive to changes in end loading conditions depend on whether a compression force is applied through the screw thread in the central boss or through its flat upper loading surface.

For high accuracy force measurement, the end loading conditions during calibration should represent, as closely as possible, the conditions for the subsequent use of the load cell. Load cells for intercomparison measurements are used with specially designed loading pads that have ground loading surfaces and are sufficiently rigid for the forces applied.

A1.8 Sensitivity to Moments and Side Forces

Load cells used to measure a single force component are designed to be insensitive to the orthogonal force components and corresponding moments, provided these are within specified limits. The output of such a load cell should depend only on the magnitude of force along or parallel to a given datum axis. For compression load cells, the datum axis is usually the axis which is perpendicular to the lower loading face and passes through its centre. For a typical beam load cell, a flat surface at the fixed end of the beam may define the direction of the datum axis and a scribed mark on the beam the position of the axis.

For a load cell to be sensitive to the magnitude of force in one direction only, it is important to ensure symmetry in both the machining of the elastic element and the positioning of the strain gauges. In practice, there is a limitation to the degree of symmetry that can be achieved and all load cells are sensitive, to some degree, to moments and side forces superimposed on the main force component¹⁷. The magnitude and sign of the sensitivity of a load cell to a moment or side force, in a given direction relative to the load cell, is not predictable and will vary from one load cell of the same type and capacity to another. The maximum sensitivity in any direction, for a given design and capacity of load cell, will, however, be limited by the tolerances in the machining of the element and the positioning of the strain gauges. The design and capacity of a load cell are important factors. For example, if the external diameter of a loadcell with a hollow cylindrical element is fixed, the larger the internal diameter, the more sensitive the load cell is likely to be to bending moments. This is because for a given absolute concentricity tolerance, a larger internal diameter can shift the neutral axis further from the nominal position.

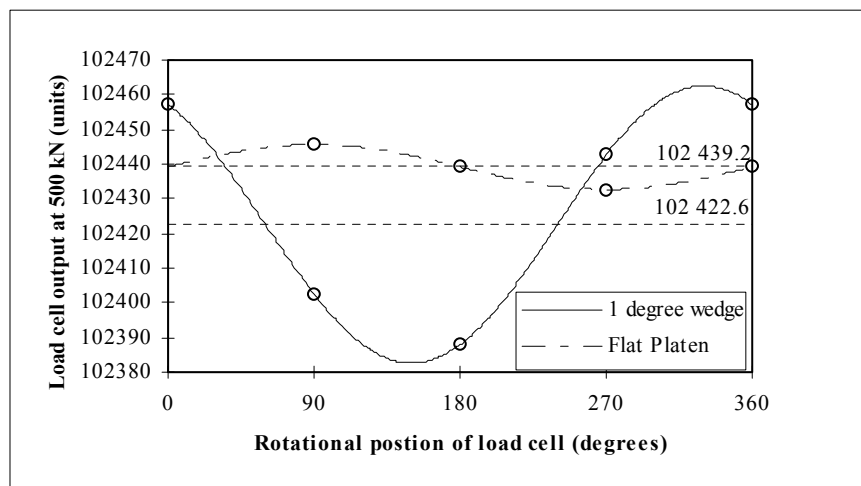


Figure 24: Effect of rotation on load cell output

In addition to the main component of force, force standard machines apply small moments and side forces to load cells being calibrated. In a deadweight machine, there may be uneven distortion of the framework supporting the device and also some uncertainty regarding the positions of the centres of gravity of the weights relative to the assumed loading axis of the machine. Friction in alignment fixtures used to apply the deadweight force to the load cell permits the application of bending moments. The result may be, as well as an insignificant cosine error in the magnitude of the nominal force applied, small moments and side forces which may be significant. To show the significance of any side force or bending moment applied during the calibration and subsequent use of a load cell, measurements should be made for different positions of the load cell in the machines involved. Figure 24 shows the effects of rotating a 500 kN compression load cell about its longitudinal axis in the NPL 500 kN deadweight machine. Results are given with the load cell and its loading pads on the flat platen of the machine and also on a 1° wedge placed between the platen and the lower loading pad. During such rotational tests, it is important to rotate the load cell without introducing a translational movement; special jigs at NPL provide an accurate rotation with translational movements less than 0.1 mm.

If it is assumed that the sensitivity of a load cell to side forces and bending moments is linear and that these have a magnitude and direction which are independent of the rotational position of the load cell, there will be a sinusoidal relationship between the load cell's output and its rotational position. The amplitude will be determined by the maximum sensitivity of the load cell in any direction to side forces and moments and also the magnitude of these applied by the machine. The mean value of the sinusoidal relationship is theoretically the value that would be obtained if no side force or bending moment was applied in addition to the main component of force. This is confirmed by the results in Figure 24 where the mean value obtained on the 1° wedge is 0.016% less than that obtained on the flat platen; the expected difference, due to the concurrent cosine error in the magnitude of the applied force, is 0.015%. The good agreement of the results at 360° with those at 0° indicates that no significant translation of the load cell has occurred during its rotation and that the side forces and moments applied by the machine are repeatable.

Different force standard machines will apply side forces and moments that differ both in magnitude and direction and it is therefore important, when comparing the magnitudes of nominal forces applied by different machines, to complete a rotational test at each force and obtain the mean output of the load cell⁹. Theoretically, any number of equi-spaced positions will give a satisfactory mean, two positions being the minimum. For a qualitative comparison of the side forces and moments

applied by different machines, four or more positions of rotation are required. An attempt at a quantitative comparison may be made by obtaining results, as shown in Figure 24, with the load cell on a known wedge. Such a comparison, however, must inevitably be of limited accuracy due to the low sensitivity to side forces and bending moments of the load cell.

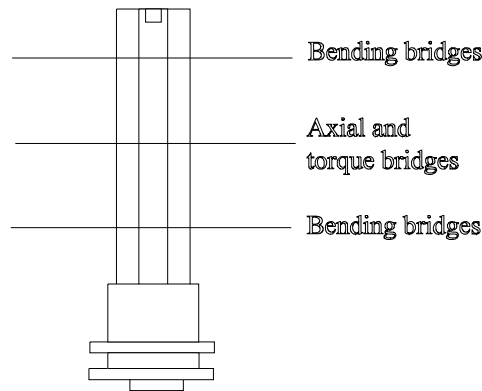


Figure 25: Load cell for measuring bending moments

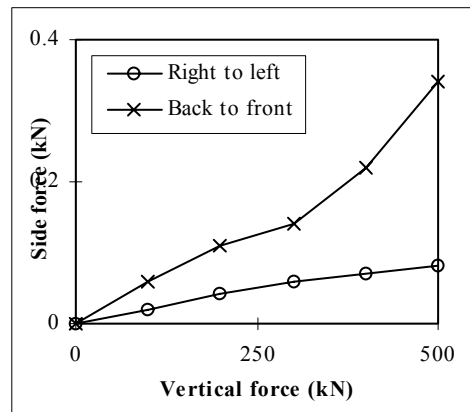


Figure 26: 500 kN machine side forces

The load cell shown in Figure 25 has been constructed at NPL and has strain gauge bridges that are deliberately sensitive to bending moments in two orthogonal directions. The load cell also has bridges to measure the applied torque and compression force. By subtracting the output from a bending moment bridge at the top of the load cell from the corresponding bridge at the base, a result is produced that is proportional only to the magnitude of the shear or side force. In order to calibrate the load cell it is important to determine the cross-sensitivity of the outputs of the bending moment bridges to the compression force and this is done in the deadweight machine by completing a rotation test similar to that described for a single component load cell. Once calibrated, the multi-component load cell can measure the applied side forces, provided these are not so large that second order effects, due to elastic deformations, become significant. Figure 26 shows the measured side forces applied by NPL's 500 kN machine; the results indicate small tilts of the machine's platen up to a maximum of 0.040. The corresponding cosine error of axial force applied is less than 1 part in a million.

A1.9 Long Term Stability

The long-term stability of the sensitivity of strain gauge load cells is clearly important if they are to be used in an intercomparison exercise which may span a period of several weeks or even months.

The long-term stability will be determined by several factors including the stability of the load cell's many components, the protection of the strain gauges against humidity and the conditions under which the load cell is stored, transported and used. One important factor for a load cell with a four-way connection is the stability of the lead resistance and contact resistance at the end connections of the lead; where possible, a six-way connection should be used to avoid this problem.

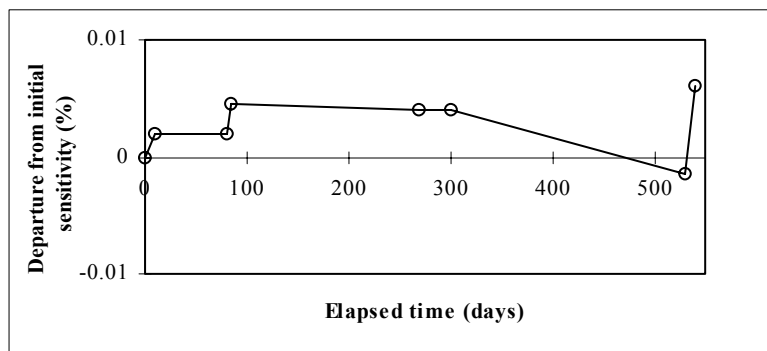


Figure 27: Long term sensitivity of a 500 kN load cell

The long-term stability of the sensitivity of strain gauge load cells used for intercomparison work can be very good. Figure 27 shows all the results obtained over a period of over 500 days for a 500 kN load cell calibrated in the NPL 500 kN deadweight machine. During this period, the load cell was transported to different locations, including one abroad. There does not appear to be any consistent drift with time. Instead, short-term changes following the dismantling and re-assembly of the calibration equipment appear to be more significant.

A1.10 Conclusions

The characteristics of strain gauge load cells that are known to be important in determining the accuracy obtainable with them have been discussed. These should always be considered when using load cells as force transfer standards. Other characteristics may be found to be important, especially if accuracy requirements are increased.

These factors are also relevant to applications of load cells where accuracies of an order or so less than those discussed are required. In such applications, it is likely that both the performance characteristics of the load cells and their conditions of use will be inferior to those described in this paper, giving rise to greater errors.

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