# Deliverable D6

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| Title<br>Guidelines detailing recommendations and standards for force calibration of testing machines under continuous forces taking into account parasitic influences from multi-component forces and temperature effects. | |
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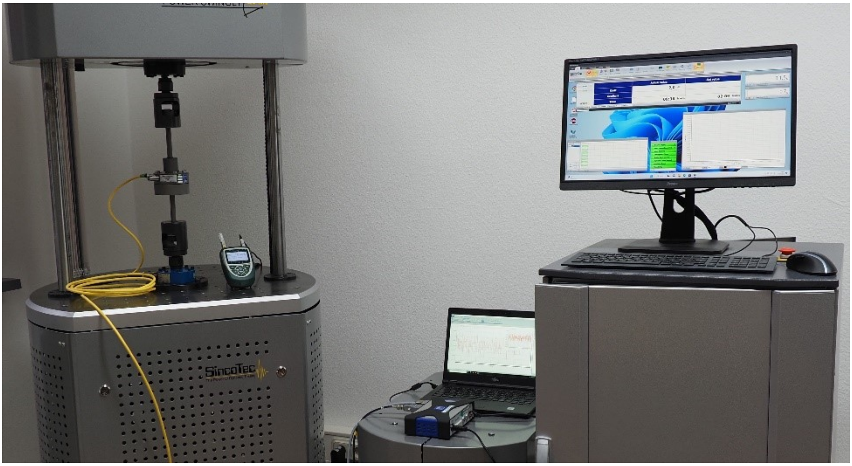
ComTraForce

# Guidelines detailing recommendations and standards for force calibration of testing machines under continuous forces taking into account parasitic influences from multi-component forces and temperature effects

EN

## Guidelines

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# Section 1

# Continuous calibration of the force-measuring system

## Initial requirements

### Machine

The machine shall be capable of providing a post-run time v force record in digital format for subsequent data analysis – it is likely that this record will come from a load cell (either strain gauge or piezoelectric) but other measurement systems, such as strain gauge-based pressure gauges, are not precluded.

The signal conditioning (e.g. filter type, filter frequency) associated with the force data acquisition channel shall be known and, ideally, settable.

The machine shall be capable of generating ramp force profiles over a range of different loading rates. There shall be minimal overshoot at the maximum calibration force $F_{\text{max}}$ and the shape of the profile from $0{,}02F_{\text{max}}$ to $0{,}98F_{\text{max}}$ shall be virtually linear.

### Force-proving instrument

The force-proving instrument shall be calibrated in accordance with the static calibration procedure detailed in ISO 376. Its static calibration classification shall be better than or equal to the classification awarded to the machine being calibrated.

The force-proving instrument shall also be either continuously calibrated in accordance with section 2 or meet the requirements of a reference standard as detailed in section 3. If calibrated in accordance with section 2, its classification shall be better than or equal to the classification awarded to the machine being calibrated.

The force-proving instrument shall be capable of providing a post-run time v force record in digital format for subsequent data analysis.

The force-proving instrument's signal conditioning settings (e.g. filter type, filter frequency) shall be known and, ideally, settable.

# Additional recommendations

## Temperature effects

When a significant heat transfer (e.g. radiation → sunlight; conduction → oil of the servohydraulic machine; convection → hot / cold circulating air near the machine) on the force-proving instrument is suspected, it is recommended to not only observe the temperature near the transducer, it is important also to monitor the temperature directly on the force-proving instrument (best directly on the spring element, when using a strain gauge transducer).

It shall also be taken care of that no temperature gradient higher than 2 K across the force-proving instrument is applied during the whole calibration.

Proper shielding from heat transfer due to conduction between force-proving instrument and the machine can be achieved e.g. by using additional PEEK plates between force-proving instrument and machine. The detection of temperature gradients can be achieved e.g. by using a thermal camera or temperature sensors which are applied directly on the force-proving instrument.

If no shielding is possible an additional uncertainty needs to be taken into account.

## Multicomponent forces

The calibration of testing machines could be affected by the presence of spurious parasitic force and moment components. These might be generated by the testing machine itself or by the force-proving instrument due to mounting operations. For this reason, it is recommended to mount the force-proving instrument in such a way that the centre is aligned with the axis of the machine, with a suitable adapter when used, in order to minimise parasitic components.

If suspected, the presence of parasitic transverse forces on the force-proving instrument can be found by performing measurements at a same maximum load by rotating the transducers with different angles (45° steps are recommended) and checking if a sinusoidal trend in the transducer's output arises. In this case, it is recommended to find the cause of spurious side forces and compensate it, otherwise errors might be higher.

Parasitic bending moments, on the contrary, might not be visible during rotational tests but affect the output of the force-proving instrument. In particular, at increasing loads, bending moments increase and transducer's output might increase or decrease depending on the transducer's type generating a systematic effect which cannot be compensated if not exactly known. If the presence of spurious bending moment components is suspected, these can be only evaluated with a multicomponent force and moment transducer integrated into the machine. By performing measurements at increasing loads, outputs associated to bending moments shall linearly increase. In this case, it is recommended to find the cause of spurious bending moments and compensate it, otherwise errors might be higher.

## Procedure

Set the testing machine and proving instrument filters to the same type and frequency – if this is not possible, the machine cannot be calibrated continuously. Ideally these values shall be the same as those to be routinely used during the subsequent operation of the machine. It is recommended that the data logging frequency for both the testing machine and proving instrument is fast enough to take at least one reading for every 1 % of $F_{max}$.

Immediately prior to the calibration procedure, the proving instrument, in position in the machine, shall be preloaded at least three times between zero and the maximum force to be measured, followed by a dwell time of at least 30 s at zero force.

Prior to each test, when no force is applied to the proving instrument, zero the force reading from the testing machine's force indicator.

Start logging data from both the testing machine and proving instrument.

Apply a small force of approximately $0{,}01F_{max}$ to the proving instrument.

For each force rate of interest, apply an incremental ramp followed by a dwell of between 5 s and 30 s at maximum force and then a decremental ramp at the same rate, waiting 30 s after the force is removed then taking a final machine indicator zero reading. Re-zero the machine indicator then repeat this test to obtain two sets of data at each nominal force application rate. Where it is necessary to perform the calibration with the proving instrument at different orientations, this need be done for only a single loading rate, as the effects of orientation and loading rate are likely to be independent. Where decremental performance is to be determined, perform an additional third test at each force rate with no dwell time at maximum force.

NOTE To give traceability to the forces recorded during the initial periods of materials tests, it is likely that, for the fastest rate verified, the maximum force will need to be applied within no more than 5 s.

In a final test, while still continuously logging data, apply a set of at least five incremental and then decremental step force changes, pausing long enough for the readings to stabilise at each level, and waiting at $F_{max}$ for at least 30 s – the results of this test are used to determine the relative clock speeds of the data-logging instrumentation of the testing machine and of the proving instrument.

## Data analysis

For all proving instrument traces, determine the deflections by subtracting the initial zero output then convert these deflections to force values, using the incremental and, if applicable, decremental coefficients determined during its continuous calibration at the loading rate closest to that used in each specific test (note that, for the decremental coefficient values to be valid, the same maximum calibration force needs to be applied). When the force-proving instrument was calibrated as described in section 3 the statically estimated coefficients can also be used.

NOTE 1 If the machine is being calibrated only for incremental forces using a proving instrument continuously calibrated only with incremental forces, the decremental force values should still be calculated, using the incremental coefficients, to enable synchronisation of the machine and proving instrument data records.

Determine any difference in the clock speed between the testing machine and the proving instrument data acquisition hardware – this is best done by aligning the machine and proving instrument force traces for the first incremental step in the final test, then scaling one time series until the final decremental step is also aligned.

NOTE 2 This step could be avoided by logging the proving instrument's analogue output as an external input to the testing machine's instrumentation. However, it needs to be borne in mind that:

- not all proving instruments provide suitable analogue output channels
- not all testing machines provide suitable external input channels
- if both channels are available, each would need an accurate DC voltage calibration
- there will still be a time delay associated with this input that will need correcting for
- it would need to be ensured that the signal was being correctly filtered

Correct all test results for any time-scaling differences.

For each ramp test result, roughly synchronise the machine and proving instrument force traces then calculate and plot the machine force error as a function of force at the forces of interest.

Adjust synchronisation of the two traces by, for example, minimising the standard deviation of the errors after stabilisation at maximum force over a 5 s range or setting the incremental and decremental errors to be equal close to the maximum force but at a value unaffected by inertial effects.

NOTE 3 It is also possible to combine the time-base check with each force rate test by adding small force steps at the beginning and end and the force rate time profile, then analysing the resulting profiles to determine both time-base differences and trace synchronisation.

To determine an estimate of the error at specific force values, the following procedure is recommended:

- determine the time at which this force was recorded by the machine by interpolating between the {time, force} data pairs either side of the required force
- determine the generated force at this time by interpolating between the proving instrument's {time, force} data pairs either side of this time
- compare this value of generated force with the specified value to determine the error
- if there are significant noise or resolution effects, and also in order to determine a value of uncertainty associated with this estimation of error, these interpolations should be carried out using least-squares linear fits over a larger number of data pairs equally spaced around the force or time of interest

## Classification

The machine classification is determined from its indicator's relative resolution (see ISO 7500-1 6.3), the proving instrument classification (see ISO 7500-1 6.1), and the ramp force test results.

For each ramp test, plot the percentage machine error against the applied force and consider the force range from 0,05 $F_{max}$ to 0,95 $F_{max}$.

The maximum error in this range defines the best possible classification for that force rate in line with the maximum permissible value for relative error of indication given in ISO 7500-1 Table 2.

For each pair of tests performed at the same nominal rate, the difference in relative error of indication throughout the range shall not exceed the maximum permissible value for relative error of repeatability given in ISO 7500-1 Table 2. The mean error of indication at $F_{max}$, calculated at the end of the dwell periods from the proving instrument's static calibration results, shall not exceed the maximum permissible value for relative error of indication given in ISO 7500-1 Table 2.

The classification shall also consider the relative errors of zero based on the final machine indicator zero readings and the maximum permissible values specified in ISO 7500-1 Table 2.

When the machine is also to be classified for decremental loading, the differences between the incremental and decremental errors shall be calculated and the classification for this force rate shall also consider the maximum permissible value for relative error of reversibility values given in ISO 7500-1 Table 2.

For rates in between two tested ones, the machine is classified for the worse of the two classifications.

Prepare a machine calibration certificate specifying its classification as a function of loading rate.

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# Uncertainty

For each force rate at which the machine has been calibrated, determine an uncertainty interval either side of the mean error at each applied force. This uncertainty interval shall take into account, as a minimum, the contributions shown in figure 1:

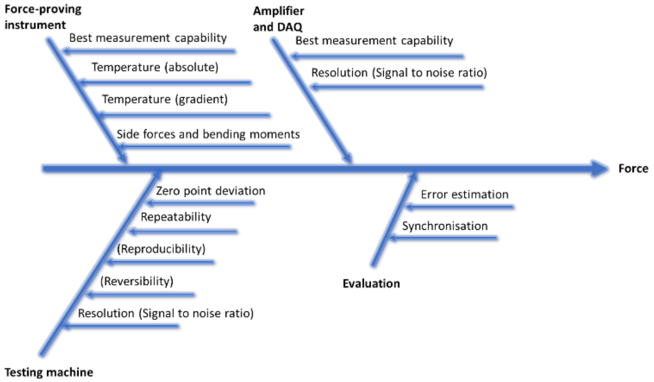


*Figure 1 Ishikawa - Influences testing machine calibration*

These uncertainty intervals shall be specified in the calibration certificate. Guidance on estimating the magnitude of standard uncertainty contributions associated with the above parameters, which should then be combined in quadrature and multiplied by a coverage factor $k$= 2 to give a 95 % uncertainty interval, is given in the following sections.

## Uncertainty of proving instrument

Is given by the section 2 or section 3 calibration of the force-proving instrument.

$$u_{\mathrm{bmc}} = \frac{U_{\mathrm{bmc}}}{k}$$

with

$U_{\mathrm{bmc}}$ as the best measurement capability of the force proving instrument

$k$ as the coverage factor

## Temperature

The maximum deviation between the temperature of the force-proving instrument in its section 2 or section 3 calibration and the section 1 calibration. The temperature coefficient can be measured by calibrating the force-proving instrument according to section 3 at different temperatures. Then the error due to temperature can be corrected. Otherwise, and more likely be the case, when only the temperature coefficient given by the manufacturer is known an uncertainty due to temperature shall be calculated

$$u_{\mathrm{temp}} = K_{\mathrm{temp}} \times \Delta T \times a_{\mathrm{priori}} \times \frac{1}{\sqrt{3}} \times 100\ \%$$

with

$K_{\mathrm{temp}}$ as the temperature coefficient of the transducer given by the manufacturer, in $\frac{1}{°\mathrm{C}}$

$\Delta T$ as the maximum temperature difference between calibration temperature and temperature in application, in °C

$a_{\mathrm{priori}}$ as a factor relying on the trustworthiness of the given temperature coefficient

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*Table 1 A priori factors according to DKD-R 3-3*

| | | |
|---|---|---|
| I. | Calibration of force measuring devices carried out in own FSM with different temperatures of the same type (type test) | t-factor 2 … 4.3 |
| II. | Values to be supplemented as measured value-related data sheet specifications (as upper limits) according to definitions of VDI/VDE/DKD 2638 | Factor 2 |
| III. | Other measured value-related data sheet specifications (as upper limits) | Factor 3 |
| IV. | Other measured value-related data sheet specifications (as typical data) | Factor 5 |

## Temperature gradient

If it is not possible to shield the force-proving instrument from temperature gradients higher than 2 K, the effect of temperature gradients on the force-proving instrument should then be investigated and an appropriate uncertainty due to this effect should then incorporated into the measurement uncertainty budget.

## Side forces and bending moments

If side forces and bending moments are generated by the machine itself or by the force-proving instrument, these influence the responses of the force transducers involved, entailing larger errors between the machine and the force-proving instrument and increased uncertainty due to reproducibility when performed.

$$u_{rot} = \frac{1}{\overline{q_r}} \times \sqrt{\frac{1}{n(n-1)} \times \sum_{i=1}^{n} (q_i - \overline{q_r})^2} \times 100\%$$

with

$q_i$ as the error at a specific installation position

$\bar{q}_r$ as the mean error at different installation positions

$n$ as the number of installation positions

The presence of parasitic side forces and bending moments can be known a priori or can be checked and evaluated according to previous recommendations. In this case, they shall be mechanically compensated or the results mathematically corrected if sensitivity coefficients due to side forces or bending moments of the transducers involved are known. In any case, an uncertainty associated with side forces and bending moments shall be considered:

$$u_{\text{side}} = K_{\text{side}} \times a_{\text{side}} \times \frac{1}{\sqrt{3}} \times 100\ \%$$
$$u_{\text{bend}} = K_{\text{bend}} \times a_{\text{bend}} \times \frac{1}{\sqrt{3}} \times 100\ \%$$

with

$K_{\text{side}}$ as the side forces coefficient of the transducer given by the manufacturer or scientific literature, in $\frac{1}{\text{N}}$

$a_{\text{side}}$ as the half-width variability interval of spurious side forces, in N

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$K_{\text{bend}}$ as the bending moments coefficient of the transducer given by the manufacturer or scientific literature, in $\frac{1}{\text{N·m}}$

$a_{\text{bend}}$ as the half-width variability interval of spurious bending moments, in N·m

## Substitute amplifier

If a different amplifier is used as in the calibration of the force-proving instrument, a calibration of the amplifier is needed.

$$u_{\text{bmc,amp}} = \frac{U_{\text{bmc,amp}}}{k}$$

with

$U_{\text{bmc,amp}}$ as the best measurement capability of the used amplifier

$k$ as the coverage factor

## Signal to noise ratio

In a continuous force calibration filter settings are adjusted to the need of the subsequent use of the machine. The resulting noise is dependent on the chosen filter settings and the environment in which the calibration is performed. Here now, it is recommended to calculate the standard deviation of the noise signal. In order to do this, the zero signal shall be measured after the assembly of the calibration setup right before the calibration as long as the longest sequence of the following continuous calibration.

$$u_{\text{res}_0} = \sqrt{\frac{1}{n(n-1)} \times \sum_{i=1}^{n} (X_{0_i} - \overline{X_0})^2} \times \frac{1}{X_i} \times 100\ \%$$

with

$X_0$ as the deflection during zero force
$\bar{X}_0$ as the mean deflection during zero force
$n$ as the number of samples

This uncertainty contribution needs to be added for both force measurements, force-proving instrument and MTM, into the uncertainty budget.

## Zero-point deviation

The zero-point deviation is calculated by the subtraction between the zero reading before the measurement sequence and the zero reading 30 seconds after the measurement sequence and incorporated into the measurement uncertainty budget.

$$f_0 = \frac{\bar{X}_0 - \bar{X}_f}{X_{\mathrm{Max}}} \times 100\ \%$$

$$u_{\mathrm{zero}} = f_0$$

With
$\bar{X}_0$ as the mean zero deflection before the measurement sequence
$\bar{X}_f$ as the mean zero deflection 30 seconds after the measurement sequence

## Repeatability

The repeatability $b'$ is calculated from two measurement series in the same installation position.

$$b' = \left|\frac{q_2 - q_1}{\overline{q_{\mathrm{wr}}}}\right| \times 100\ \% \ \text{ with } \ \overline{q_{\mathrm{wr}}} = \frac{q_1 + q_2}{2}$$

$$u_{\mathrm{rep}} = \frac{b'}{\sqrt{3}}$$

with

$\bar{q}_{\mathrm{wr}}$ as the mean error in the same installation position

## Resolution

A lack of resolution in the testing machine force indication is likely to manifest itself in a sawtooth pattern imposed upon the plot of error against force, as the error is determined at a large number of force values rather than a limited number, as is the case with static calibrations. However, it may be more appropriate to fit a smoother function to the error, filtering out these sawtooths – in this case, their magnitude can be compensated for by including a resolution term in the uncertainty budget.

## Reversibility (optional)

Where a machine is calibrated for decremental forces, the uncertainty interval for the decremental errors shall be calculated in the same way as that for the incremental errors. In addition, if needed, shall the deviation due to different dwell times also incorporated into the measurement uncertainty.

$$u_{dwell} = \frac{q_{r,i,\mathrm{fast}} - q_{r,i,\mathrm{slow}}}{\sqrt{3}}$$

with

$q_{r,i,\mathrm{fast}}$ relative decremental error with no dwell time

$q_{r,i,\mathrm{slow}}$ relative decremental error with long dwell time

## Synchronisation

This contribution results from both the time-base adjustment and the fine synchronisation of the two measurement traces. In order to estimate the variability associated with these two procedures, it is recommended that they be repeated at different times and/or by different operators to determine the potential spread of results, from which a standard uncertainty can be estimated

$$u_{\mathrm{syn}} = \frac{q_{r,i,\mathrm{Max}} - q_{r,i,\mathrm{Min}}}{\sqrt{3}}$$

with

$q_{r,i,\mathrm{Max}}$ Maximum relative error at a specifically chosen force

$q_{r,i,\mathrm{Min}}$ Minimum relative error at a specifically chosen force

## Error estimation (interpolation)

The errors at a specific force, which are needed for the uncertainty calculation, are calculated in two steps. In the first step the time at which the MTM reaches this specific force and in the second step the force of the force proving instrument at this previous calculated time are estimated. The uncertainty of the first step

$$u_{\mathrm{EE_{time}}} = c_i \times \sqrt{1 + \frac{1}{n} + \frac{\left(F_{\mathrm{MTM,prog}} - \overline{F_{\mathrm{MTM,int}}}\right)^2}{\sum_{i=1}^{n}\left(F_{\mathrm{MTM,int},i} - \overline{F_{\mathrm{MTM,int}}}\right)^2}} \times \sqrt{\sum_{i=1}^{n} \frac{\left(t_{\mathrm{int},i} - t_{\mathrm{int},i,\mathrm{est}}\right)^2}{(n-d-1)}} \times \frac{1}{F_i} \times 100\ \%$$

and the uncertainty of the second step

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$$u_{\mathrm{EE_{Force}}} = \sqrt{1 + \frac{1}{n} + \frac{(t_{\mathrm{prog}} - \overline{t_{\mathrm{int}}})^2}{\sum_{i=1}^{n}(t_{\mathrm{int},i} - \overline{t_{\mathrm{int}}})^2}} \times \sqrt{\sum_{i=1}^{n} \frac{(F_{\mathrm{ref,int},i} - F_{\mathrm{ref,int},i,\mathrm{est}})^2}{(n-d-1)}} \times \frac{1}{F_i} \times 100\ \%$$

with

$c_i$ Sensitivity coefficient (slope of the second step calculation)

$n$ Number of values of a chosen interval

$F_{\mathrm{MTM,prog}}$ MTM force value of interest

$\overline{F_{\mathrm{MTM,int}}}$ Mean MTM force value in the chosen interval

$F_{\mathrm{MTM,int},i}$ MTM force values in the chosen interval

$t_{\mathrm{int},i}$ Time in the chosen interval

$t_{\mathrm{int},i,\mathrm{est}}$ Estimated time in the chosen interval

$d$ Degree of the chosen fit

$F_i$ Force of interest

$t_{\mathrm{prog}}$ Time of interest

$\overline{t_{\mathrm{int}}}$ Mean time in the chosen interval

$F_{\mathrm{ref,int},i}$ Force of proving instrument in the chosen interval

$F_{\mathrm{ref,int},i,\mathrm{est}}$ Estimated force of proving instrument in the chosen interval

# Section 2

## Continuous calibration of the force-proving instrument

### Initial requirements

The force-proving instrument shall be mechanically coupled to the reference standard and located on the central axis of a machine capable of generating the required force magnitudes and application rates.

NOTE 1 This work may be better performed in a normal testing machine than in a force standard machine, as loading rates and force-time profiles may be more easily set and controlled.

The force-proving instrument and reference standard shall employ nominally-identical instrumentation and associated settings. Both instruments shall be capable of providing a post-run time v output record in digital format for subsequent data analysis. It is recommended that the data logging frequency for both instruments is fast enough to take at least one reading for every 1 % of $F_{\mathrm{max}}$ and that the filter settings are those that will subsequently be used by the force-proving instrument when calibrating testing machines.

The reference standard shall meet the performance requirements specified in section 3.

The possibility of any temperature gradients being introduced into either instrument during the calibration shall be investigated and, where appropriate, their influence should be calculated and corrected for.

NOTE 2 Due to the possible variations in oil temperature, such effects are more likely to be present in servohydraulic machines than in deadweight machines.

## Procedure

Apply incremental ramps followed by dwells of 30 s at maximum force then decremental ramps over the range of force rates of interest. Perform at least two tests at each of a minimum of four force rates, approximately evenly logarithmically spaced (e.g. 1 kN/s, 3 kN/s, 10 kN/s, and 30 kN/s). Where decremental performance is to be determined, perform an additional test at each force rate with no dwell time at maximum force.

## Data analysis

For both sets of traces, determine the deflections by subtracting the initial zero output.

Determine synchronisation between the two outputs, for example by switching the transducers and their instrumentation modules and repeating the tests, then comparing the incremental deflection ratios as a function of force for the fastest force application rate. Correct all data by the out-of-synchronisation value determined by minimising the difference between these deflection ratio plots. An alternative synchronisation determination method might be to apply the same low frequency sinusoidal input signal to both instrumentation modules then measure the phase difference between the two recorded signals.

Convert the reference standard deflections to force values, using the incremental and decremental coefficients determined during its static calibration (see section 3).

For each ramp test set of data, calculate the sensitivity of the force-proving instrument at each force by dividing its deflection by the applied force, as measured by the reference standard.

Fit separate incremental and, where required, decremental curves to these sensitivity values then determine, from these fitted curves, the force-proving instrument's sensitivity at the force values applied during its static ISO 376 calibration. At each of these forces, compare these sensitivity values determined at different loading rates with each other and calculate the percentage spread between them.

## Classification

The force-proving instrument may be classified for continuous force measurement for either incremental or incremental/decremental loading. Its classification is based on the parameters considered for its static calibration together with additional consideration of the agreement between the continuously-derived sensitivities at different loading rates. For a given classification, the spread of these sensitivities, expressed as a positive relative value, at a specific calibration force shall not exceed the value given in Table 2.

*Table 2 — Continuous calibration classification requirements*

| Class | Maximum sensitivity variation at different loading rates / % |
|---|---|
| **00** | 0,02 |
| **0,5** | 0,05 |
| **1** | 0,10 |
| **2** | 0,20 |

Determine the force-proving instrument's classification and report it in the certificate together with, for each force rate, the coefficients of the equation relating the

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instrument’s sensitivity to the applied force. The force-proving instrument may not be subsequently used to give continuous force traceability outside the range covered by this set of force rates.

## Uncertainty

For each force rate, an uncertainty associated with the force value calculated from the reported coefficients shall be estimated and included within the certificate. The estimation of this uncertainty shall take into account, as a minimum, the in figure 2 shown uncertainty contributions.

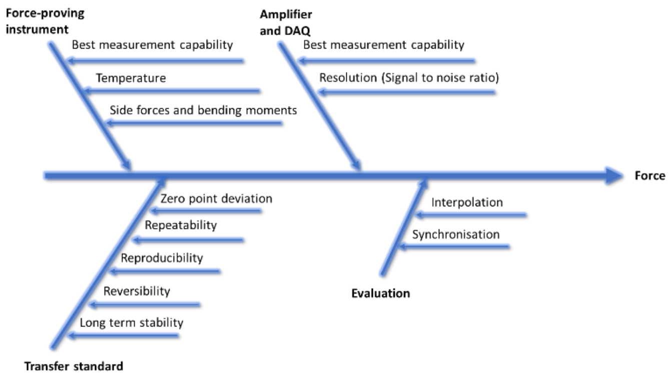


*Figure 2 Ishikawa - Influences on continuous force proving instrument calibration*

These uncertainty contributions shall be specified in the calibration certificate. Guidance on estimating the magnitude of standard uncertainty contributions associated with the above parameters, which should then be combined in quadrature and multiplied by a coverage factor $k$= 2 to give a 95 % uncertainty interval, is given in the following sections.

## Best measurement capability

Is given by the section 3 calibration of the reference standard

$$u_{\mathrm{bmc,ref}} = \frac{U_{\mathrm{bmc,ref}}}{k}$$

with

$U_{\mathrm{bmc,ref}}$ as the best measurement capability of the reference standard

$k$ as the coverage factor

## Temperature

The deviation between the temperature of the reference standard in its section 3 calibration and the section 2 calibration. The temperature coefficient can be measured by calibrating the transducer according to section 3 calibration at different temperatures. Then the error due to temperature can be corrected. Otherwise, and more likely be the case, when only the temperature coefficient given by the manufacturer is known an uncertainty due to temperature shall be calculated

$$u_{\mathrm{temp}} = K \times \Delta T \times a_{\mathrm{priori}} \times \frac{1}{\sqrt{3}} \times 100\%$$

with

$K$ as the temperature coefficient of the transducer given by the manufacturer, in $\frac{1}{°\mathrm{C}}$

$\Delta T$ as the maximum temperature difference between calibration temperature and temperature in application, in °C

$a_{\mathrm{priori}}$ as a factor relying on the trustworthiness of the given temperature coefficient (see Table 1)

If it is not possible to shield the reference standard from temperature gradients the effect of temperature gradients

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on the reference standard should then be investigated and an appropriate uncertainty due to this effect should then incorporated into the measurement uncertainty budget

## Side forces and bending moments

If side forces and bending moments are generated by the calibration machine, these influence the responses of the force transducers involved, entailing an error in the evaluation of the force-proving instrument‘s sensitivity and an increase of uncertainty due to reproducibility when rotations are performed.

$$u_{rot} = \frac{1}{\overline{X_r}} \times \sqrt{\frac{1}{n(n-1)} \times \sum_{i=1}^{n} (X_i - \overline{X_r})^2} \times 100\%$$

with

$X_i$ as the deflection at a specific installation position

$\bar{X}_r$ as the mean deflection at different installation positions

$n$ as the number of installation positions

The presence of spurious side forces and bending moments can be known a priori or can be checked and estimated according to section 1. In this case, they shall be mechanically compensated or the results mathematically corrected if sensitivity coefficients due to side forces or bending moments of the transducers involved are known. In any case, an uncertainty associated with side forces and bending moments shall be considered:

$$u_{\text{side}} = K_{\text{side}} \times a_{\text{side}} \times \frac{1}{\sqrt{3}} \times 100\ \%$$

$$u_{\text{bend}} = K_{\text{bend}} \times a_{\text{bend}} \times \frac{1}{\sqrt{3}} \times 100\ \%$$

with

$K_{\text{side}}$ is the side forces coefficient of the transducer given by the manufacturer or scientific literature, in $\frac{1}{\text{N}}$

$a_{\text{side}}$ is the half-width variability interval of spurious side forces, in N

$K_{\text{bend}}$ is the bending moments coefficient of the transducer given by the manufacturer or scientific literature, in $\frac{1}{\text{N·m}}$

$a_{\text{bend}}$ is the half-width variability interval of spurious bending moments, in N·m

## Signal to noise ratio

Here now, it is recommended to calculate the standard deviation of the noise signal. In order to do this, the zero signal shall be measured right before the calibration as long as the longest sequence of the following continuous calibration.

$$u_{\text{res}_0} = \sqrt{\frac{1}{n(n-1)} \times \sum_{i=1}^{n} (X_{0_i} - \overline{X_0})^2} \times \frac{1}{X_i} \times 100\ \%$$

with

$X_0$ as the deflection during zero force

$\bar{X}_0$ as the mean deflection during zero force

$n$ as the number of samples

This uncertainty contribution needs to be added for both force measurements, force-proving instrument and reference standard, into the uncertainty budget.

## Zero-point deviation

The zero-point deviation is calculated by subtraction between the zero reading before the loading and the zero reading 30 seconds after unloading and incorporated into the measurement uncertainty budget.

$$f_0 = \frac{\bar{X}_0 - \bar{X}_f}{X_{\text{Max}}} \times 100\%$$

$$u_{\text{zero}} = f_0$$

with

$\bar{X}_f$ as the mean zero deflection 30 seconds after the measurement sequence

## Repeatability

The repeatability $b'$ is calculated from two measurement series in the same installation position.

$$b' = \left| \frac{X_2 - X_1}{\overline{X_{\text{wr}}}} \right| \times 100\ \% \ \text{ with } \ \overline{X_{\text{wr}}} = \frac{X_1 + X_2}{2}$$

$$u_{\text{rep}} = \frac{b'}{\sqrt{3}}$$

with

$\bar{X}_{\text{wr}}$ as the mean deflection in the same installation position

## Reversibility

Two different approaches are possible:

1. An interpolation through the decremental deflections gives an alternative sensitivity which can be used for decremental forces when the exact same force time profile as in the calibration is also applied in its subsequent use. The uncertainty of the interpolation is analogously calculated as given in the section Interpolation.

2. The reversibility ν is calculated than interpolated with a suitable fit function for each force rate. For all force rates, dwell times and partial ranges the enveloping reversibility function can be used to calculate the reversibility uncertainty for any (partial) force rate covered by the calibration range in its subsequent use. For the exact same force time profile as in the calibration the reversibility function should be used for correction.

$$\nu = \frac{X_{i,\mathrm{decr}} - X_{i,\mathrm{incr}}}{X_{\mathrm{max}}}$$

   Fit error $f_\nu$ of the interpolation

$$f_\nu = (\nu - \nu_a) \times \frac{X_{\mathrm{max}}}{X_i}$$

The uncertainty of this interpolation is then calculated analogously as given in the section Interpolation.
Uncertainty calculation for the use in subsequent partial ranges

$$u_{\nu} = \frac{|\nu_a| \times \frac{F_{\max,\mathrm{app}}}{F_{i,\mathrm{app}}}}{\sqrt{3}} \times 100\%$$

with

$X_{i,\mathrm{decr}}$ as the decremental deflection

$X_{i,\mathrm{incr}}$ as the incremental deflection

$X_{\max}$ as the deflection at maximum force of the test sequence

$\nu_a$ as the balanced hysteresis

$F_{\max,\mathrm{app}}$ as the maximum force in a subsequent application sequence

$F_{i,\mathrm{app}}$ as the force in a subsequent application sequence

## Long term stability

This uncertainty contribution is calculated from the deviation of the measurement results between two adjacent calibrations.

$$u_{\mathrm{stab}} = \frac{\mathrm{MAX}\left|S_{i,\mathrm{prev}} - S_{i,\mathrm{adj}}\right|}{\sqrt{3}} \times \frac{1}{F_i} \times 100\ \%$$

with

$S_{i,\mathrm{prev}}$ as sensitivity in a previous continuous calibration

$S_{i,\mathrm{adj}}$ as sensitivity in an adjacent continuous calibration

## Synchronisation

This contribution results from the fine synchronisation of the two measurement traces. In order to estimate the variability associated with the synchronisation, the uncertainty from the phase shift calibration of the instruments modules can be used or the chosen synchronisation method shall be repeated at different times and/or by different operators to determine the potential spread of results, from which a standard uncertainty can be estimated

$$u_{\mathrm{syn}} = \frac{S_{i,\mathrm{Max}} - S_{i,\mathrm{Min}}}{\sqrt{3}}$$

With

$S_{i,\mathrm{Max}}$ Maximum sensitivity at a specifically chosen force

$S_{i,\mathrm{Min}}$ Minimum sensitivity at a specifically chosen force

## Interpolation

The uncertainty of the fit function for the sensitivity.

$$u_{\mathrm{inp}} = \sqrt{1 + \frac{1}{n} + \frac{(F_{\mathrm{prog}} - \overline{F_{\mathrm{int}}})^2}{\sum_{i=1}^{n}(F_{\mathrm{int},i} - \overline{F_{\mathrm{int}}})^2}} \times \sqrt{\sum_{i=1}^{n} \frac{(S_{\mathrm{int},i} - S_{\mathrm{int},i,\mathrm{est}})^2}{(n - d - 1)}} \times \frac{1}{S_{int,i,est}} \times 100\ \%$$

With

$n$ Number of values of a chosen interval

$F_{\mathrm{prog}}$ Force value of interest

$\overline{F_{\mathrm{int}}}$ Mean force value in the chosen interval

$F_{\mathrm{int},i}$ Force values in the chosen interval

$S_{\mathrm{int},i}$ Sensitivity in the chosen interval

$S_{\mathrm{int},i,\mathrm{est}}$ Estimated sensitivity in the chosen interval

$d$ Degree of the chosen fit

# Section 3

## Traceability requirements for the continuous calibration reference standard

### General

This section details the performance requirements for an instrument to be used as a reference standard against which a force-proving instrument is able to be continuously calibrated.

### Initial requirements

The reference standard shall be calibrated as a force-proving instrument in accordance with the ISO 376 static calibration procedure, with the results assessed for interpolation and incremental/decremental loading (Case D). The calibration results shall meet the following criteria:

Class 00 throughout the range over which the instrument is to be used, excluding reversibility criteria, although the agreement between the two decremental deflections at each calibration force shall meet the reproducibility criterion (0,05 %) specified in Table 2.

The expanded uncertainty associated with the calibration results shall not exceed 0,10 % at any calibration force

The instrumentation used with the transducer to form the reference standard shall be capable of providing a post-run time v output record in digital format for subsequent data analysis.

# Additional requirements

The additional requirements relate to the short-term creep characteristics of the reference standard. These characteristics are determined by an unloading creep test.

NOTE 1 The assumption being made is that, for a reference standard with very low creep characteristics, the force application rate will not significantly affect its output at a given calibration force. Tests performed loading two low-creep transducers in series have helped confirm this insensitivity to force application rate.

NOTE 2 Ideally, the reference standard's short-term creep characteristics would be determined by a loading creep test, but this is made impractical by the combination of the time required to smoothly apply the calibration force and the subsequent stability of this force value. Studies have shown that the loading and unloading creep characteristics of force transducers are of similar magnitudes, so a test in which the calibration force is rapidly removed offers a valid method to estimate the transducer's short-term creep performance.

When, for the reference standard's subsequent use, partial incremental and decremental calibrations are required, additional partial static incremental / decremental runs need to be performed.

# Unloading creep test

## Procedure

The reference standard shall be loaded within a force machine to the maximum calibration force applied during its ISO 376 static calibration. The expanded uncertainty of this applied force shall be no greater than 1 % and the filter frequency of the reference standard's instrumentation shall be no lower than 2 Hz.

Maintain the maximum calibration force for at least as long as the duration of the incremental run in the ISO 376 static calibration (300 s to 600 s) and then, while logging the reference standard's output at a sampling rate of at least 10 Hz, rapidly remove the applied force (the force shall reduce from 0,98 $F_{\max}$ to zero in no more than 2 s).

Continue to record the reference standard's output for at least twice as long as the loading duration (600 s to 1200 s) (after 10 s, the logging rate may be reduced to a minimum of 1 Hz).

### Analysis

From the recorded data, identify the time at which the force was fully removed from the transducer and then ignore the data from the following second (as some of this will be affected by the instrumentation's filter settings and possibly transducer vibration).

From the data recorded after this time, identify the maximum and minimum output values, then express the magnitude of their difference as a percentage of the deflection at $F_{\max}$. For certification as a continuous calibration reference standard, this difference shall not exceed 0,02 %.

## Partial reversibility test

### Procedure

This test shall be performed in the last installation position of the static ISO 376 calibration with a waiting pause of at least 10 minutes after its last measurement sequence. Partial static incremental / decremental runs covering the range from 10 % up to 30 % and 10 % up to 60 % of the maximum force with at least four evenly-distributed force steps for the incremental and decremental run with at least 30 s dwell time at each force step are to be performed.

## Analysis

For each partial run the reversibility related to its own maximum deflection is to be estimated as $v_{\mathrm{FSO}} = \frac{x_{i,\mathrm{inc}} - x_{i,\mathrm{dec}}}{x_{\max}} \times 100\ \%$. This shall also be done for the mean reversibility of the ISO 376 calibration. Then all reversibility values related to their own maximum deflections are to be plotted against deflection in % of the maximum deflection of each run. If there is a curve which envelopes all other curves this can be fitted with a 6th degree polynomial with a constant part using the least squares method.

## Uncertainty

In addition to the in ISO 376 mentioned uncertainty calculations the uncertainty for partial reversibility and creep shall be also specified in the calibration certificate. Guidance on estimating the magnitude of standard uncertainty contributions associated with these parameters, which should then be combined in quadrature and multiplied by a coverage factor $k$= 2 to give a 95 % uncertainty interval, is given in the following sections.

## Short-term creep

From the maximum span in the time dependent behaviour directly after the relieve of the maximum full load up to 600 to 1200 s after the relieve the short-term creep uncertainty is calculated with a rectangular distribution.

$$u_{\mathrm{creep,incr}} = \frac{r_{\mathrm{creep,max}} - r_{\mathrm{creep,min}}}{\sqrt{3}} \times \frac{1}{F_{Max}} \times 100\ \%$$

For decremental forces the uncertainty due to short-term creep needs to be calculated differently.

$$u_{\text{creep,decr}} = \frac{r_{\text{creep,max}} - r_{\text{creep,min}}}{\sqrt{3}} \times \frac{1}{F_{i,\text{decr}}} \times 100\ \%$$

With
$r_{\text{creep,max}}$ as the maximum reading after unloading
$r_{\text{creep,min}}$ as the minimum reading after unloading
$F_{Max}$ as the maximum applied force during creep test
$F_{i,\text{decr}}$ as the applied decremental force during application

## Reversibility

Two different approaches are possible:

1. An interpolation through the decremental deflections gives an alternative sensitivity which can be used for decremental forces when the exact same maximum force as in the calibration is also applied in its subsequent use. The uncertainty of the interpolation is analogously calculated as given in the section Interpolation.

2. The reversibility v is calculated than interpolated with a suitable fit function. When calibrations in partial ranges were performed the enveloping reversibility function can be used to calculate the reversibility uncertainty for any partial force range in its subsequent use. For the exact same reached maximum forces as in the calibration the reversibility function should be used for correction.

$$\nu = \frac{X_{i,\text{decr}} - X_{i,\text{incr}}}{X_{\max}}$$

Fit error $f_\nu$ of the interpolation

$$f_\nu = (\nu - \nu_a) \times \frac{X_{\max}}{X_i}$$

The uncertainty of this interpolation is then calculated analogously as given in the section Interpolation.
Uncertainty for the use in partial ranges

$$u_\nu = \frac{|\nu_a| \times \frac{F_{\max,\mathrm{app}}}{F_{i,\mathrm{app}}}}{\sqrt{3}} \times 100\%$$

with

$X_{i,\mathrm{decr}}$ as the decremental deflection

$X_{i,\mathrm{incr}}$ as the incremental deflection

$X_{\max}$ as the deflection at maximum force of the test sequence

$\nu_a$ as the balanced hysteresis

$F_{\max,\mathrm{app}}$ as the maximum force in a subsequent application sequence

$F_{i,\mathrm{app}}$ as the force in a subsequent application sequence

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