ComTraForce

Strategy report for offering traceable calibration for testing machines under continuous and dynamic forces

EN

Strategy Report

EUROPÄISCHE NORM
EUROPEAN STANDARD
NORME EUROPÉENNE

EN ISO 376

Juni 2011

ICS 77.040.10

Ersatz für EN ISO 376:2004

Deutsche Fassung

Metallische Werkstoffe —
Kalibrierung der Kraftmessgeräte für die Prüfung von
Prüfmaschinen mit einachsiger Beanspruchung
(ISO 376:2011)

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Strategy report – Continuous force calibration of testing machines

This part of the document delivers the strategy to amend the developed continuous force calibration procedure of testing machines, in the form of three proposed annexes to the ISO standards ISO 376 and ISO 7500-1 (see figure 1). Details of these two standards are given below, together with details of how the proposed annexes could be incorporated.

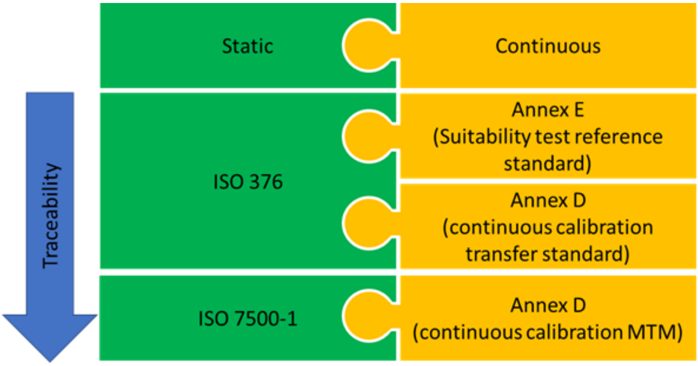

Figure 1 Proposed implementation of the new developed continuous calibration into the existing static normative traceability chain

ISO 376

This standard covers the calibration of force-proving instruments to be used for the subsequent calibration of materials testing machines. The current version defines an incremental (and, if required, decremental) staircase calibration process, applying each stable reference force for a minimum of 30 s before taking a reading from the instrument then progressing to the next force.

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To amend this standard to permit the continuous, ramp-profile calibration of force-proving instruments, two additional annexes are proposed; one (Annex D) specifying the procedure for the ramp calibration of the instrument against a reference standard, and the other (Annex E) specifying the required performance characteristics of the reference standard itself. Annex D also defines how the classification of the instrument should be assessed and the calibration uncertainty estimated.

ISO 7500-1

This standard covers the force calibration of uniaxial testing machines, using a force-proving instrument previously calibrated to ISO 376. Currently, it is permitted to carry out the calibration runs more quickly than stated in ISO 376 but, at the specified calibration points, the force should be either stable or only “slowly increasing”.

To amend this standard to permit the continuous, ramp-profile calibration of the machine’s force-measuring system, one additional annex (Annex D) is proposed in which the continuous calibration procedure as well subsequent data analysis are specified. This would form an alternative calibration methodology, called up from within Clause 6.1 of the main body of the standard. The result of the calibration would be a range of permitted loading rates, together with associated machine classifications and uncertainty information.

Strategy

Implementation

In 2023, the ISO 7500-1 standard will be reviewed. NPL, PTB, INRiM and Inmetro, which have representatives on the related standardization committee, will request a revision of this standard. Annex D, which describes the continuous calibration of material testing machines, is then submitted as a proposal for amendment. If this should be accepted, a supplement annex for ISO 376 might be necessary. Annex D and Annex E, which describe the continuous calibration of transfer standards and a suitability test of force transducers as continuous reference standards, can be proposed therefor. An enhancement of these standards, which are well established in static force metrology, will immediately attract international attention in industry and metrology. The already established classes and the traceability chain based on them can thus be retained, which creates additional understanding and acceptance in the industry. Therefore, in this case, this approach is preferable to an independent standard specifically for continuous calibrations. Many countries are involved in this decision-making process, which is why it will take some time before the first accredited laboratory can officially calibrate according to this standard.

Facilitate uptake

The uptake of these new Annexes to the relevant standards is already implemented in the actual general modernisation of PTB's 5-MN Force Standard Machine (FSM) giving the ability to realise traceable continuous force ramps up to 5 MN. The 1 MN and 200 kN FSM are also planned to be updated.

As soon as the new calibration procedure is implemented, an automated validated evaluation software could be written based on the experiences of the first users, which could be made available to other interested parties. Together with the video produced in the framework of this project, which shows the process of a continuous calibration of a testing machine, this will simplify the entry into continuous calibration for many other laboratories due to the otherwise more complex execution and evaluation ("https://www.ptb.de/empir2019/comtraforce/home/")
.

In the aim to implement continuous loadings, it will be important that the calibration laboratories take into consideration the adequate characterization a priori of their force generators‘ load profiles. This is not detailed in the proposed annexes but is crucial for the ability in applying the new methodology.

Possible impact on other standards

ISO 7500-1 is not the only ISO standard that calls up ISO 376 to give traceability to the force displayed by materials testing machines – for example, calibration standards for hardness testing machines such as ISO 6506-2 (Brinell hardness), ISO 6507-2 (Vickers hardness), and ISO 6508-2 (Rockwell hardness) all contain normative references to ISO 376. If the proposed changes to ISO 376 are accepted, it would be possible for such standards also to be modified to take advantage of the availability of a calibration procedure that is more representative of the use of the machine during its actual testwork.

Future improvements

Possible improvements that could reduce the uncertainty of the proposed traceability chain:

- Force standard machines, which can quickly and clean load force transducers abruptly to maximum load without much vibration and thus make it possible to carry out the necessary creep measurements under load.
- Further research and development of the model of the force transducer could make it possible to make more general and easier usable corrections for creep and hysteresis which are then used in an advanced developed digital twin
- A digital calibration certificate (DCC) allows to use more of the information which is gathered by a continuous calibration and thus give more specific information about the uncertainty at any point in the force time profile for the user.

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Strategy report – Dynamic force calibration of testing machines

This part of the document delivers the required strategy to implement the developed calibration procedure for the dynamic calibration of material testing machines within a new guideline document DKD-R 9-4, which uses for traceability the existing standards ISO 376, DKD-R 3-2 and DKD-R 3-10 Sheet 2 (see figure 2). Details of these existing standards are described below, together with details of how the proposed guideline shall be implemented.

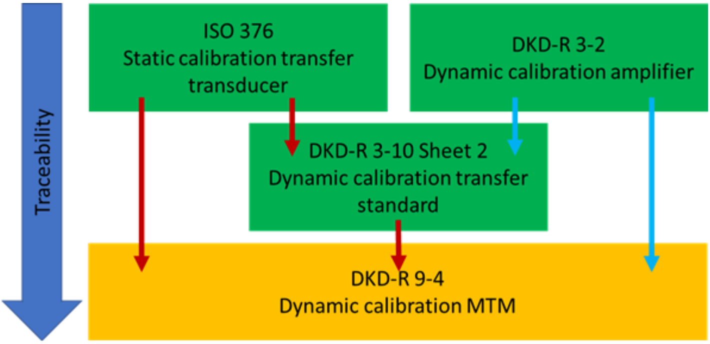

Figure 2 Proposal for extending the existing normative traceability chain to the dynamic calibration of MTM

DKD-R 3-2

This guideline describes validated methods for characterising measuring amplifiers of different types and functions for use in dynamic measurements. For this, especially the behaviour with time-varying signals is of interest, which is described by the complex transfer function depending on the frequency of the input signal.

DKD-R 3-10 Sheet 2

This guideline describes the dynamic calibration of force transducers for the use as transfer standards for the dynamic calibration of material testing machines. For this, measurements on a shaker system are performed and the frequency dependent sensitivity deviation from the statically calibrated sensitivity is estimated. Furthermore, the following properties defined by the Kelvin-Voigt model of the transducer are estimated:

- stiffness
- damping
- inner head / foot mass

Strategy

Implementation

Since the guidelines for dynamic calibration of the transducer and the amplifier are already anchored in the DKD, the consortium considered it as sensible to implement the dynamic calibration of material testing machines there as well. Because this is a national committee, but its guidelines are also internationally recognized, the decision-making process on the new guideline will progress faster than with international committees.

As a head of important standardization committees USTUTT is going to deploy the standard for dynamic calibration of material testing machines (DKD-R 9-4) by this committees, such as the DKD committee material testing machines and the DIN committee material testing

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(NMP 811). Within the DKD committee a workgroup "AG Dynamische Kalibrierung (DKD-FA WPM)" was founded, which members are of material testing institutes from different German federal states. The first meeting of this workgroup is scheduled for mid of April 2023 and is aimed to the introduction of the standard to the members. In June 2023 the whole DKD committee of material testing machines will meet in Oberaula, Germany. Members are of scientific institutes and industry. Between 70 % and 80 % of the laboratories accredited by the German Accreditation Body (DAkkS) regularly attend the meetings. This meeting will be used to introduce the standard to users and customers. Further the DIN committee DIN-Normenausschuss Materialprüfung (NMP 811) met in mid of March 2023 and was informed about the work of ComTraForce project and the dynamic calibration procedure of DKD-R 9-4 as well.

Facilitate uptake

Next steps are the accreditation of the calibration laboratory at USTUTT for the DKD-R 9-4 and offering this new service to its customers for dynamic machine calibration. Thus, the community of calibration laboratories and their customers will be informed about the new calibration procedure immediately after project's end. As part of the final workshop of the project with many representatives from industry and metrology, a video was produced which shows and explains the dynamic calibration of a material testing machine. Hosted on the ComTraForce website

https://www.ptb.de/empir2019/comtraforce/home/

this video can ease the step towards dynamic calibration of material testing machines for many laboratories.

Some NMIs, e. g. Inmetro and RISE, will continue the research activities on the proposed procedure for the use of DKD-R 9-4, which include new measurements and technical publications, but also information dissemination, e. g. inside the SIM (Inter American System of Metrology), through presentations and workshops.

Possible impact on other standards

The new DKD-R 9-4 could influence the existing DKD-R 3-10, Sheet 3, ISO 4965-1 and ASTM E467-21 which are dedicated to the dynamic verification of axial material testing machines. These standards formed the basis for the development of DKD-R 9-4 and could therefore also profit from the findings of the project in one of their future revisions.

Future improvements

This new guideline will extend the traceability chain to the dynamic calibration of material testing machines. However, this guideline is only a first step which needs to be optimised to lower the uncertainties and define valid boundary conditions with the help of future experiences and further research. With further research and experience an automated validated evaluation software could be developed, which could then be made available to all other interested laboratories to make it easier to get started with the dynamic calibration of material testing machines due to the more complex evaluation, in particular the sine approximation method.

Furthermore, the implementation of the DKD-R 9-4 could demand improvements regarding the uncertainties from calibrations according to DKD-R 3-10, Sheet 2, which is needed for traceability. To reduce these uncertainties as

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well as to facilitate access for other laboratories, initial findings from the project can be used and further improved. In the framework of the ComTraForce project, a novel approach based on the levering deep-learning method is suggested which aims to address uncertainty in the acceleration measurement arising from the rocking movement of the dynamic force calibration assembly. The approach aids in more precise modelling of force transducers under dynamic force conditions and inspires a lot of follow-up works. Besides the need to improve the performance of the trained model by fine-tuning of the hyperparameters, proper choice of data to train, test and validate the model was addressed. There is a huge potential for increasing the generalization power of the model by increasing the measurement data, generated by the scanning laser interferometer. Results will encourage the development of a validated software written in Python and packed with its dependencies using the containerization technology which is supported with a user-friendly GUI (Graphical User Interface). The software can be used by every dynamic force calibration laboratory without any need to have knowledge about the sophisticated mathematical processes to calculate model parameters that may meet the automation needs in such laboratories.

Annex

ISO 7500-1

ANNEX D
(normative)
Continuous calibration of the force-measuring system

D.1 General

Clause 6.1 of this document specifies that calibration can be carried out with either slowly increasing forces or slowly decreasing forces, using either dead-weights or force-proving instruments complying with the requirements of ISO 376. It is also permitted to carry out the calibration using faster loading and unloading rates instead, following the procedure detailed within this Annex

D.2 Initial requirements

D.2.1 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.

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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 $F_{\max}$ and the shape of the profile from $0.1F_{\max}$ to $0.98F_{\max}$ shall be virtually linear.

D.2.2 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 Annex D of ISO 376 or meet the requirements of a reference standard as detailed in Annex E of ISO 376. If calibrated in accordance with Annex D, 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.

D.3 Additional recommendations

D.3.1 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 1 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 considered.

D.3.2 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.

D.4 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 (see figure D.1).

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 $0.01F_{\mathrm{max}}$ 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 an application-oriented dwell time at maximum force.

NOTE 1 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.

NOTE 2 If the application-oriented dwell time for decremental forces is in the range between 5 and 30 s the dwell time for the first two runs can be set appropriate for it, thus making a third run obsolete.

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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.

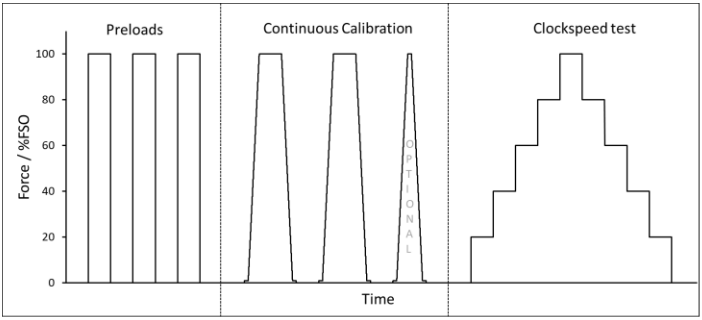

Figure D.1 Schematic force time profile of a continuous calibration of a material testing machine

D.5 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 ISO 376 Annex E 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

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.

Correct all test results for any time-scaling differences.

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

$$q_{\text{cont}} = 100\% \times \frac{F_{\text{MTM}} - F_{\text{ref}}}{F_{\text{ref}}}$$

To find the right synchronisation level different (automated) methods could be used. These could be for example:

- Setting the incremental and decremental errors to be equal close to the maximum force but at a value unaffected by inertial effects by minimising the standard deviation of all errors which are in this specific range (incremental and decremental)
- Minimising the sum of the square deviations of the first derivatives (Force rate) of the two traces
- Minimising the sum of a moving standard deviation (window 5 to 15 % F_{max}) of the relative errors in the range from 15 to 85 % F_{max} (incremental and decremental)

The plots in figure D.2 and D.3 give an example of a good visual control for synchronisation.

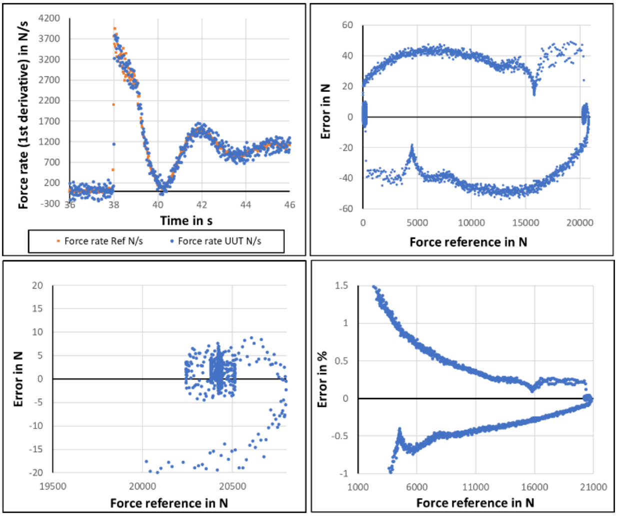

Figure D.2 Key plots to identify synchronisation of the two force time traces in a continuous force calibration: Unsynchronised behaviour

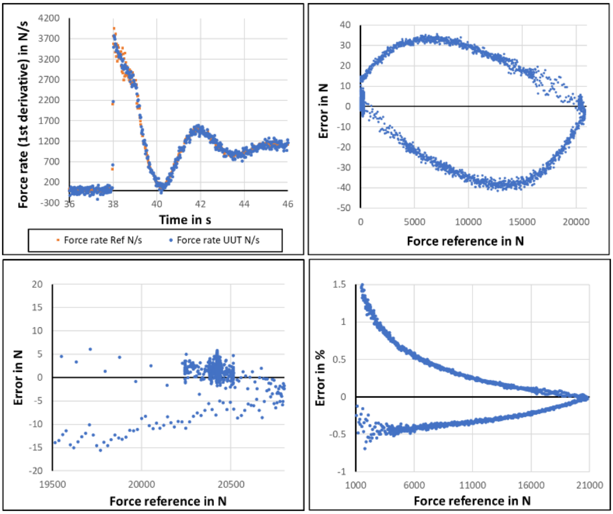

Figure D.3 Key plots to identify synchronisation of the two force time traces in a continuous force calibration: Synchronised behaviour

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

D.6 Classification

The machine classification is determined from its indicator's relative resolution (see 6.3), the proving instrument classification (see 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 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 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 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 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 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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D.7 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 consider, as a minimum, the contributions shown in figure D.4:

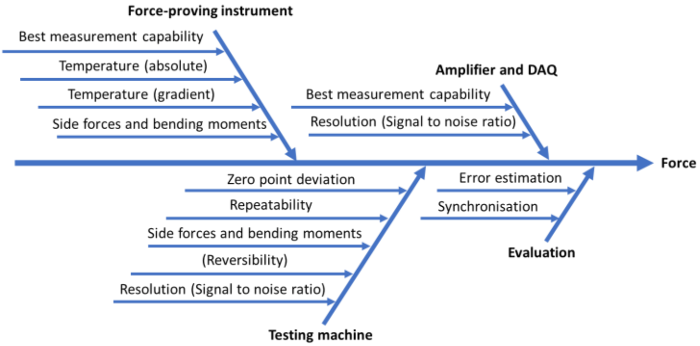

Figure D.4 Ishikawa - Influences testing machine calibration

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.

D.7.1 Uncertainty of proving instrument

Can be derived from the calibration of the force-proving instrument according to ISO 376 including Annex D or Annex E.

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

with

U_{bmc}	as the best measurement capability of the force proving instrument
k	as the coverage factor

D.7.2 Temperature

The maximum deviation between the temperature of the force-proving instrument in its ISO 376 Annex D or Annex E calibration and the subsequent use. The temperature coefficient can be measured by calibrating the force-proving instrument according to ISO 376 Annex D or Annex E 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_{temp}	as the temperature coefficient of the transducer given by the manufacturer, in $\frac{1}{°\mathrm{C}}$
ΔT	as the maximum temperature difference between calibration temperature and temperature in application, in °C
a_{priori}	as a factor (see table D.1) relying on the trustworthiness of the given temperature coefficient

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Table D.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

D.7.3 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.

D.7.4 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.

$$u_{\mathrm{rot}} = \frac{1}{\overline{q_{\mathrm{cont}}}} \times \sqrt{\frac{1}{n(n-1)} \times \sum_{i=1}^{n} \left(q_{\mathrm{cont},i} - \overline{q_{\mathrm{cont}}}\right)^2} \times 100\%$$

with

$q_{\mathrm{cont},i}$	as the error at a specific installation position
$\bar{q}_{\mathrm{cont}}$	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:

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

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

with

K_{side}	as the side forces coefficient of the transducer given by the manufacturer or scientific literature, in $\frac{1}{\mathrm{N}}$
a_{side}	as the half-width variability interval of spurious side forces, in N

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

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

D.7.5 Substitute amplifier

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

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

with

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

k as the coverage factor

D.7.6 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. 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.

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

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.

D.7.7 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 s 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

D.7.8 Repeatability

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

$$b' = \left|\frac{q_{\mathrm{cont},2} - q_{\mathrm{cont},1}}{\overline{q_{\mathrm{cont,wr}}}}\right| \times 100\ \% \ \text{ with } \ \overline{q_{\mathrm{cont,wr}}} = \frac{q_{\mathrm{cont},1} + q_{\mathrm{cont},2}}{2}$$

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

with

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

D.7.9 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 many 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.

D.7.10 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.

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

with

$q_{\text{cont},i,\text{fast}}$	relative decremental error with shortest dwell time
$q_{\text{cont},i,\text{slow}}$	relative decremental error with longest dwell time

D.7.11 Synchronisation

This contribution results from both the time-base adjustment and the fine synchronisation of the two measurement traces. To estimate the variability associated with these two procedures, it is recommended that they be repeated at different times and/or by different operators and/or by fitting the minimisation function of the used automated method and calculating the deviation near its minimum to determine the potential spread of results, from which a standard uncertainty can be estimated

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

with

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

D.7.12 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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$$u_{\mathrm{EE}_{\mathrm{Force}}} = \sqrt{1 + \frac{1}{n} + \frac{(t_{\mathrm{prog}} - \overline{t_{\mathrm{int}}})^2}{\sum_{i=1}^{n}(t_{\mathrm{int},i} - \overline{t_{\mathrm{int}}})^2}} \times \sqrt{\sum_{i=1}^{n} \frac{(F_{\mathrm{ref,int},i} - F_{\mathrm{ref,int},i,\mathrm{est}})^2}{(n-d-1)}} \times \frac{1}{F_i} \times 100\ \%$$

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_{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

ISO 376

ANNEX D
(normative)

Continuous calibration of the force-proving instrument

-

D.1 General

The main body of this document specifies the static calibration procedure for force-proving instruments. If the instrument is to be used to perform continuous calibration of testing machines, it shall also be calibrated and classified following the procedure detailed within this Annex.

D.2 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

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that the data logging frequency for both instruments is fast enough to take at least one reading for every 1 % of F_{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 Annex E.

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.

D.3 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

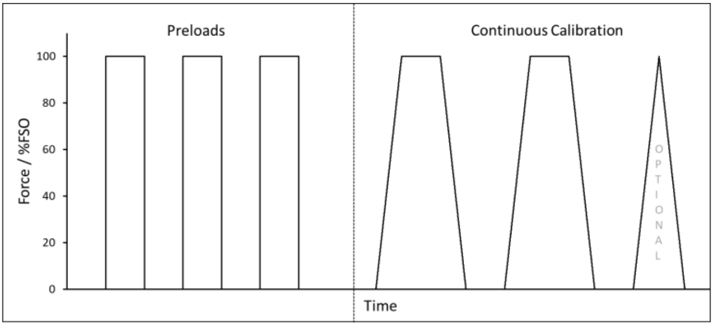

Figure D.1 Schematic force-time-profile continuous calibration of a transfer standard is to be determined, perform an additional test at each force rate with no dwell time at maximum force.

D.4 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 Annex E).

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.

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D.5 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 D.1.

Table D.1 — 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 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.

D.6 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 D.2 shown uncertainty contributions.

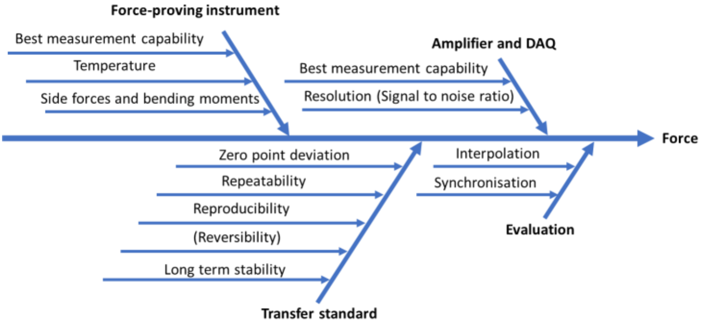

Figure D.2 Ishikawa - Influences on continuous transfer standard calibration

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.

D.6.1 Best measurement capability

Is given by the static ISO 376 including Annex E calibration of the force-proving instrument.

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

with

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

k as the coverage factor

D.6.2 Temperature

The deviation between the temperature of the force-proving instrument in its static ISO 376 including Annex E calibration and the subsequent use. The temperature coefficient can be measured by calibrating the transducer according to ISO 376 including Annex E 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 $\frac{1}{°\mathrm{C}}$

ΔT as the maximum temperature difference between calibration temperature and temperature in application, in °C

a_{priori} as a factor relying on the trustworthiness of the given temperature coefficient (see Table D.2)

Table D.2 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	

If it is not possible to shield the reference standard from temperature gradients the effect of temperature gradients on the reference standard should then be investigated and an appropriate uncertainty due to this effect should then incorporated into the measurement uncertainty budget

D.6.3 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.

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

with

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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 ISO 7500-1 Annex D. 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:

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

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

with

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

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

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

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

D.6.4 Signal to noise ratio

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

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

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.

D.6.5 Zero-point deviation

The zero-point deviation is calculated by subtraction between the zero reading before the loading and the zero reading 30 s after unloading 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

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

D.6.6 Repeatability

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

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

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

with

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

D.6.7 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 D.6.10.

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.

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

Fit error f_ν 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 D.6.10.
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
ν_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

D.6.8 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

D.6.9 Synchronisation

This contribution results from the fine synchronisation of the two measurement traces. 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

D.6.10 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_{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

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ISO 376

ANNEX E
(normative)

Traceability requirements for the continuous calibration reference standard

E.1 General

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

E.2 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.

E.3 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 as detailed in E.4.

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 as detailed in E.5.

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E.4 Unloading creep test

E.4.1 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).

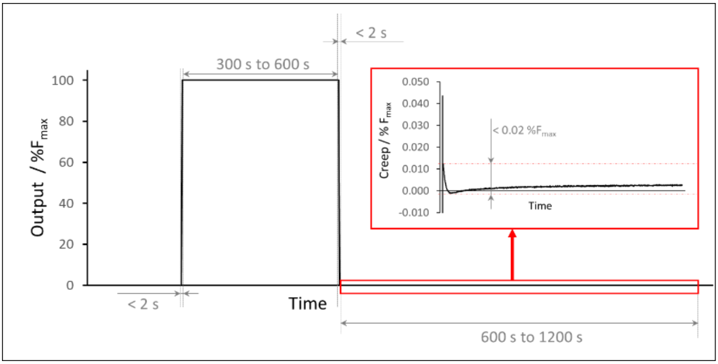

Figure E.1 Schematic procedure and analysis of the creep test

E.4.2 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 %.

E.5 Partial reversibility test

E.5.1 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.

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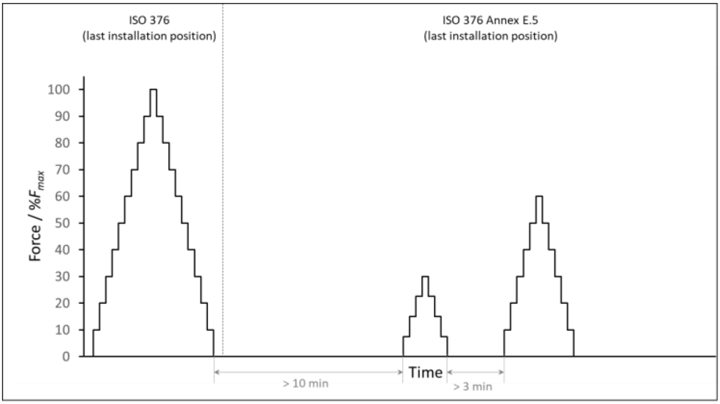

Figure E.2 Schematic force-time-profile for the partial reversibility test

E.5.2 Analysis

For each partial run the reversibility related to its own maximum deflection is to be estimated as $v_{F\max} = \frac{x_{i,\text{inc}} - x_{i,\text{dec}}}{x_{\max}} \times 100\ \%$. This shall also be done for the mean reversibility of the ISO 376 calibration. Then all reversibility values related to their own maximum

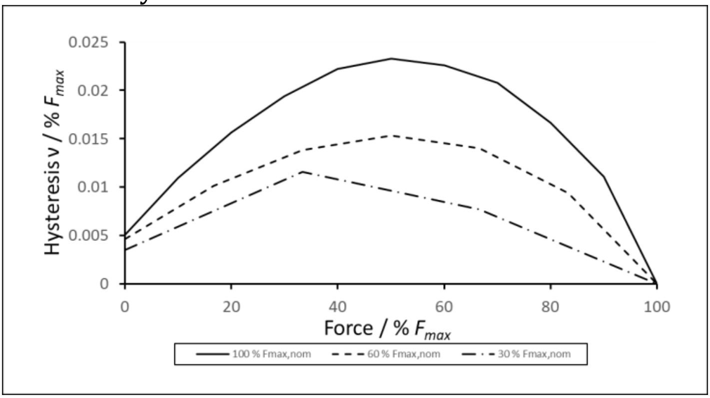

Figure E.3 Plot of the normalised hysteresis against the normalised force deflections are to be plotted against deflection in % of the maximum deflection of each run (see figure E.3). If there is a curve which envelopes all other curves this can be fitted with a suitable function $v_{\mathrm{a}}(\%F_{Max})$, for example a 6th degree polynomial with a constant part, using the least squares method.

E.6 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.

E.6.1 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.

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

With

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$r_{\text{creep,max}}$	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

E.6.2 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 D.6.10.

2. The reversibility ν 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.

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

Fit error f_ν of the interpolation

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

The uncertainty of this interpolation is then calculated analogously as given in D.6.10.
Uncertainty for the use in partial ranges

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

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
ν_a	as the balanced hysteresis
$F_{\mathrm{max,app}}$	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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Literature

1. J. Sander, D. Mirian, F. Hauschild, S. Hassan, R. Kumme, A. Prato et al. Validation report which details the advanced models developed to describe a) static and continuous and b) dynamic force transfer standards taking into account sensitivity stability, temperature and other parasitic influences on the measurement uncertainty (target uncertainty is 1 % up to 100 Hz and 2 % between 100 – 1000 Hz) Zenodo. https://doi.org/10.5281/zenodo.7113187, 2022
2. A. Knott, J. Sander, R. S. Oliveira, M. Hiti et al. Calibration procedure for testing machines to extend the traceability chain from static to continuous forces which can be used for forces in the range of 1 N to 1 MN, Zenodo. https://doi.org/10.5281/zenodo.7680252, 2023
3. J. Sander, A. Knott, A. Prato, R. S. Oliveira et al Guidelines detailing recommendations and standards for force calibration of testing machines under continuous applications taking into account parasitic influences from multi-component forces and temperature effects Zenodo. https://doi.org/10.5281/zenodo.7684089, 2023
4. DKD-R 3-2:2019, Calibration of amplifiers for dynamic applications, https://doi.org/10.7795/550.20190425
5. DKD-R 3-3:2018, Calibration of force measuring devices, https://doi.org/10.7795/550.20180823F
6. DKD-R 3-9:2018, Continuous calibration of forces transducers according to the comparison method, https://doi.org/10.7795/550.20180823J

7. A. Knott, R. S. Oliveira, Effects of force application rate on transducer performance, IMEKO 2022 TC3 Proceedings, https://www.imeko.info/publications/tc3-2022/IMEKO-TC3-2022-020.pdf
8. A. Prato, E. Giacardi, A. Facello, F. Mazzoleni, A. Germak, Influence of parasitic components in the static calibration of uniaxial force transducers, IMEKO 2022 TC3 Proceedings. https://www.imeko.info/publications/tc3-2022/IMEKO-TC3-2022-095.pdf
9. J. Sander, R. Kumme, F. Tegtmeier, Creep correction method for force applications, IMEKO 2022 TC3 Proceedings, https://www.imeko.info/publications/tc3-2022/IMEKO-TC3-2022-082.pdf
10. M. Hiti, Comparison of two 1 kN force transducers at continuous calibration, IMEKO 2022 TC3 Proceedings, https://www.imeko.info/publications/tc3-2022/IMEKO-TC3-2022-053.pdf
11. ISO 376:2011, Calibration of force-proving instruments for the verification of uniaxial testing machines
12. ISO 7500-1:2018, Calibration and verification of static uniaxial testing machines – Part 1: Tension/compression testing machines – Calibration and verification of the force-measuring system
13. JCGM 100:2008, Evaluation of measurement data – Guide to the expression of uncertainty in measurement

DOI 10.5281/zenodo.7866831

14. Dizdar, H., Aydemir, B., Vatan, C. "Establishment of Continuous Force Calibration System at TUBITAK UME Force Laboratory in Türkiye", MEASUREMENT: SENSORS,18: https://doi.org/10.1016/j.measen.2021.100216 (2021): Article number 100216
15. Dizdar, H., Aydemir, B., Vatan, C. "Investigation of the Effect of Load Rate on Creep and Hysteresis Errors in Strain Gauge and Piezoelectric Force Transducer ", MEASUREMENT: SENSORS, 22: https://doi.org/10.1016/j.measen.2022.100374 August (2022): Article number 100374

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“https://doi.org/10.5281/zenodo.7866847”

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