ComTraForce

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

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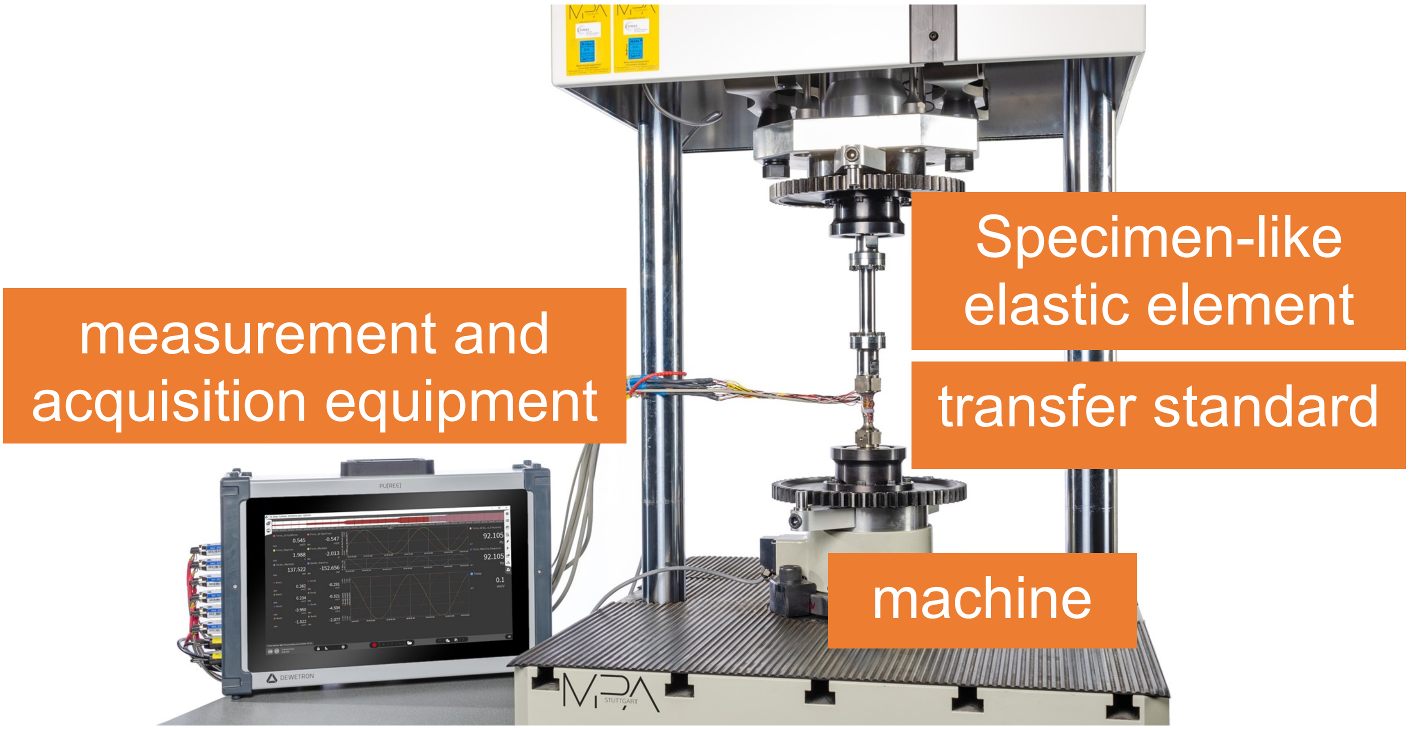
Guidelines



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Dynamic Calibration of Material Testing Machines

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Deutscher Kalibrierdienst (DKD)

Since its foundation in 1977, the DKD has brought together calibration laboratories of industrial enterprises, research institutes, technical authorities, inspection and testing institutes. On 3 May 2011, the DKD was re-established as a technical body of PTB and the accredited laboratories.

This body is known as Deutscher Kalibrierdienst (DKD – German Calibration Service) and is under the direction of PTB. The guidelines and guides elaborated by DKD represent the state of the art in the respective technical areas of expertise and can be used by the Deutsche Akkreditierungsstelle GmbH (the German accreditation body – DAkkS) for the accreditation of calibration laboratories.

The accredited calibration laboratories are now accredited and supervised by DAkkS as legal successor of the DKD. They carry out calibrations of measuring instruments and measuring standards for the measurands and measuring ranges defined during accreditation. The calibration certificates issued by these laboratories prove the traceability to national standards as required by the family of standards DIN EN ISO 9000 and DIN EN ISO/IEC 17025.

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Foreword

DKD guidelines are application documents regarding the DIN EN ISO/IEC 17025 requirements. The guidelines contain a description of the technical, process-related and the organizational procedures which accredited calibration laboratories use as a model for defining internal processes and regulations. DKD guidelines may become an essential component of the quality management manuals of calibration laboratories. By implementing the guidelines, it is ensured that the devices to be calibrated are all treated equally in the various calibration laboratories and that the continuity and verifiability of the work of the calibration laboratories are improved.

The DKD guidelines should not impede the further development of calibration procedures and processes. Deviations from guidelines as well as new procedures are allowed in agreement with the accreditation body if there are technical reasons to support this action.
Calibrations by accredited laboratories provide the user with the security of reliable measuring results, increase the confidence of customers, enhance competitiveness in the national and international markets, and serve as metrological basis for the monitoring of measuring and test equipment within the framework of quality assurance measures.

This guideline is the first official working draft (WD23-04) which has been developed within the 18SIB08 COMTRAFORCE project [1] coordinated by PTB Braunschweig. The project has received funding from the EMPIR programme co-financed by the participating states and from the European Union's Horizon 2020 research and innovation programme.

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1 Introduction

1.1 Definition of Dynamic Forces and Dynamic Calibration

Supported by DKD-R 3-10, Sheet 1-3, forces, considered as dynamic forces are periodic forces, where the product of mass and acceleration varies periodically over time. The calibration of this forces applied by a material testing machine will be called dynamic calibration.

1.2 Definition of Transfer Standard

A single device which was designed as a high precision sensing element of forces is called transfer standard in this document. This device can be equipped with more high precision sensing elements, such as temperature sensors.

1.3 Purpose and Scope of Application

This document is a guideline for the dynamic calibration of material testing machines, such as machines for fatigue testing, using dynamically calibrated force transfer standards equipped with special adapters. The adapters are necessary to apply defined elastic elements and additional uncompensated, accelerated masses to meet the configurations of materials testing as close as possible.

1.4 Basic Principle of the Calibration Process

The dynamic calibration consists of two parts: the preliminary work and the machine calibration itself. Both parts are fundamental to provide a full traceability chain for dynamic machine calibration.

Amongst other things, the preliminary work part consists of static calibrations of machine according to ISO 7500-1 as well as transfer standard's static calibration according to ISO 376 and dynamic calibration according to DKD-R 3-10, Sheet 2. The second part is dedicated to the dynamic calibration of the machine using this dynamically calibrated transfer standard. Both parts are described in chapters 3 and 4 and were supported by ASTM E467 and ISO 4965-1.

It is not necessary to use the same transfer standard for static and dynamic calibration of the machine. It is possible to do this with different transfer standards and with different assemblies.

1.5 Setup of Dynamic Machine Calibration

An example of a calibration setup is shown in Figure 1, where A is the mechanical test frame and its components, including machine's force transducer, B is the dynamic force transfer standard, C is the specimen-like elastic element, called stiffness adapter and D is the measurement and acquisition equipment of machine and transfer standard. It is based on [2, [3, 4].

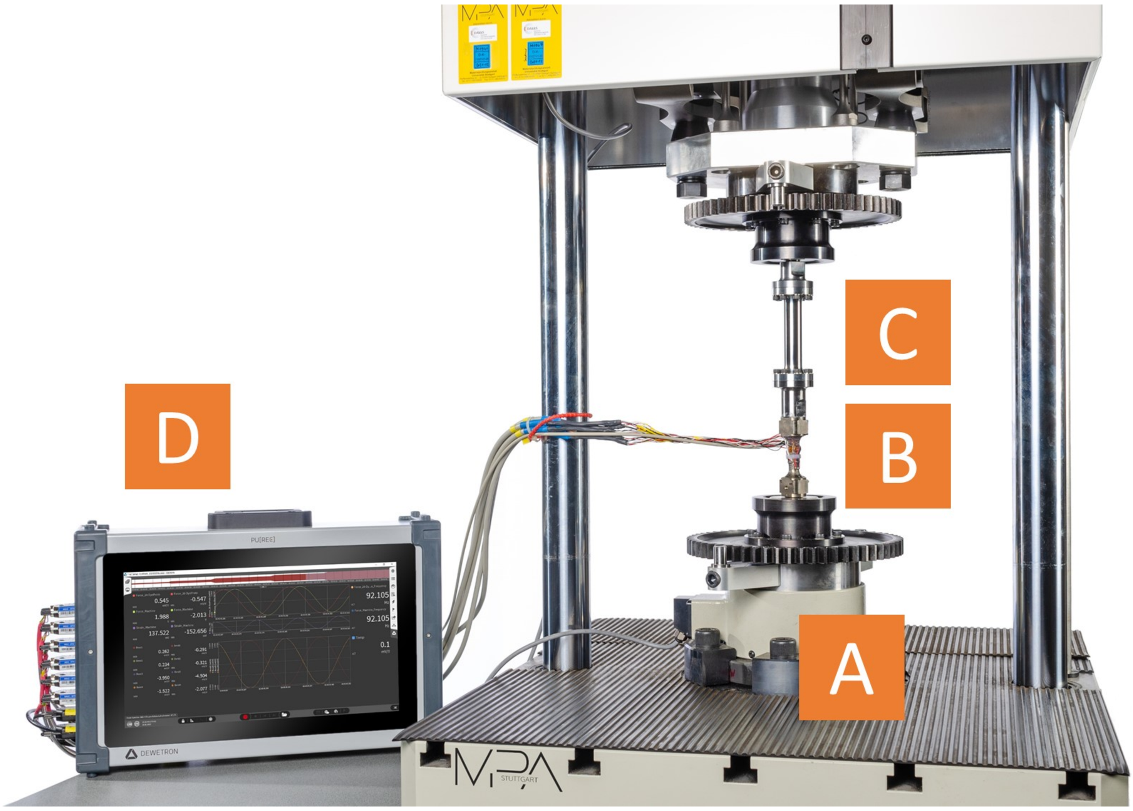


Figure 1: Setup of a dynamic calibration of a material testing system, A: Machine and its force transducer, B: Dynamic force transfer standard, C: Specimen-like elastic element, D: Measurement and acquisition equipment of machine and transfer standard, based on [2, 3]

2 Symbols

α	Machine's force transducer temperature coefficient
Δf	Difference in frequency
$\Delta F_i(t)$	Difference between force of fit function and measurement at runtime t
$\Delta F_{\max}(c)$	Differences between the max. force of machine and transfer standard at cycle c
$\Delta F_{\min}(c)$	Differences between the min. force of machine and transfer standard at cycle c
$\Delta FSMS(c)$	Difference of the force span of machine and transfer standard at cycle c
$\Delta FSMS(c)_{\mathrm{rel}}$	Relative difference of the force span of machine and transfer standard at cycle c
$\Delta FSMS_{\mathrm{mean}}$	Mean difference between force spans of machine and transfer standard
$\Delta FSVF_i(c)$	Difference of forces spans of the in-situ peak-valley detected min. and max. forces and the force span calculated by amplitude of the fit function

ΔMFS	Difference of mean force spans of forces due to additional masses and the mean difference between spans of machine and transfer standard
Δp	Difference in phase
ΔT	Temperature range during calibration, including uncertainty in the measurement of the temperature
$a_{m_{\text{add}}}$	Measured acceleration of additional masses
b_i	Force amplitude of the fit function
$b_{\text{M}} + u_M$	Sum of mean force and amplitude measured by the machine
c	Cycle number
F	Nominal force level corresponding to the error q (acc. to ISO 7500-1)
$\bar{F}$	Mean of recorded force values F_j
f_i	Frequency of the fit function
$F_i(t)$	Measured force at runtime t
F_j	Recorded force value in force unit
f_{M}	Frequency of machine
$F_{\max,i}$	In-situ detected max. force
$F_{\max,\text{M}}(c)$	Peak-valley detected max. force of machine at cycle c
$F_{\max,\text{S}}(c)$	Peak-valley detected max. force of transfer standard at cycle c
$F_{\min,i}$	In-situ detected min. force
$F_{\min,\text{M}}(c)$	Peak-valley detected min. force of machine at cycle c
$F_{\min,\text{S}}(c)$	Peak-valley detected min. force of transfer standard at cycle c
f_{S}	Frequency of transfer standard
$FF_i(t)$	Force calculated by sine fit function at runtime t
$FMAD$	Force due to additional, uncompensated masses
$FMAD_{\max}(c)$	Maximum force due to additional masses at cycle c
$FMAD_{\min}(c)$	Minimum force due to additional masses at cycle c
$FSMAD_{\text{mean}}$	Mean force span of forces due to additional masses
$FSMAD(c)$	Span of force due to additional masses at cycle c
$FSV_i(c)$	Force span by in-situ peak-valley detected min. and max. forces at cycle c
$FSV_{\text{M}}(c)$	Force span of the machine at cycle c

$FSV_\mathrm{S}(c)$	Force span of the transfer standard at cycle c
i	Equipment index: M for machine, S for transfer standard
j	Number of measurement series
m_add	Measured or estimated additional masses
n	Number of analysed samples
N_c	Number of cycles to be evaluated
p_i	Phase of the fit function
p_M	Phase of machine
p_S	Phase of transfer standard
q_drift	Difference in force errors of the machine determined in previous calibrations
t	Runtime of measurement
u_i	Mean force of the fit function
$w(\Delta FSMS_\mathrm{mean})$	Relative standard uncertainty for mean difference between force spans of machine and transfer standard
$w(a_{m_\mathrm{add}})$	Relative standard uncertainty due to determination of acceleration of uncompensated masses
$w(b_i)$	Relative standard uncertainty due to determination of force amplitude from the fit function
$w(f_i)$	Relative standard uncertainty due to determination of frequency from the fit function
$w(F_\mathrm{M})$	Force measured by the machine
$w(F_\mathrm{M,stat})$	Relative standard uncertainty of static calibration of the machine
$w(F_\mathrm{S})$	Relative standard uncertainty of force measured by the transfer standard
$w(F_\mathrm{S,dyn})$	Relative standard uncertainty of dynamic calibration of the transfer standard; frequency dependant
$w(F_\mathrm{S,stat})$	Relative standard uncertainty of static calibration of the transfer standard
$w(FF_i)$	Relative standard uncertainty of fitted force as a function of time
$w(FMAD)$	Relative standard uncertainty of force due to uncompensated masses
$w(FSMAD_\mathrm{mean})$	Relative standard uncertainty associated with the repeatability
$w(m_\mathrm{add})$	Relative standard uncertainty of the value of the uncompensated masses
$w(p_i)$	Relative standard uncertainty due to determination of phase from the fit function

$w(u_i)$	Relative standard uncertainty due to determination of mean force from the fit function
$w_{\mathrm{M,align}}$	Relative standard uncertainty due to misalignment
$w_{\mathrm{M,ctr}}$	Relative standard uncertainty due to machine's controller; frequency dependant
$w_{\mathrm{M,drift}}$	Relative standard uncertainty due to long-term stability of the machine
$w_{\mathrm{M,noise}}$	Relative standard uncertainty due to fluctuation of readings (noise)
$w_{\mathrm{M,T}}$	Relative standard uncertainty due to temperature gradients affecting the machine during calibration
$w_{\mathrm{M,zer}}$	Relative standard uncertainty due to effect of zero signal drift of the machine
$w_{\mathrm{S,amp}}$	Relative standard uncertainty due to amplifier; frequency dependant
$w_{\mathrm{S,drift}}$	Relative standard uncertainty due to drift of the transfer standard
$w_{\mathrm{S,end}}$	Relative standard uncertainty due to end-loading effect of the transfer standard
$w_{\mathrm{S,par}}$	Relative standard uncertainty due to effect of parasitic components
$w_{\mathrm{S,res}}$	Relative standard uncertainty due to resolution of the transfer standard
$w_{\mathrm{S,T}}$	Relative standard uncertainty due to temperature effect on sensitivity of the transfer standard
$w_{\mathrm{S,use}}$	Relative standard uncertainty due to subsequent use of the transfer standard, composed of several contributions
$\bar{X}$	Mean value of recorded values X_j
X_j	Recorded force values in electrical unit
X_{N}	Deflection corresponding to the force value $b_{\mathrm{M}} + u_{\mathrm{M}}$

3 Preliminary Work

3.1 Machine's Controller

To ensure precise working it is recommended to calibrate the controller according to DKD-R 3-2. It is a dynamic calibration of all input and output channels of the controller. The outputs are necessary for a signal transfer from the controller to a data acquisition system which is used for the acquisition and evaluation of all channels needed for dynamic calibration of the material testing system.

3.2 Machine's Static Calibration

One important part of a safe and proper working of the machine is its static calibration according to ISO 7500-1 (note: a similar verification procedure can be done acc. to ASTM E4). Therefore, static calibration is essential and class according to ISO 7500-1 is recommended for the force ranges to be calibrated dynamically.

3.3 Machine's Verified Alignment

The alignment of the machine has to be checked and bending strains has to be minimized. It has to fulfil the requirements of class 5 of ISO 23788 (note: a similar verification procedure can be done acc. to ASTM E1012).

3.4 Machine's Parameter Matrix

Supported by ISO 4965-1 and in order to reduce and optimize the work applied to the dynamic calibration, it is applicable to derive a parameter matrix consisting of the machine configurations used around a calibration period first and to carry out (at least) two parameter sets which covers the full parameter matrix as best as possible. Otherwise, a dynamic calibration for each parameter set of the matrix should be performed.

The full matrix should contain the main parameters of the machine configurations used around a calibration period, such as uncompensated masses of mounting equipment, kind of the test specimen, stiffness of the test specimen and temperature ranges of the specimen. Furthermore, compensation methods and compensation parameters provided and used by machine's software should be documented in the matrix.

The stiffness of a calibration reference device should emulate the stiffness of the specimens used by the machine. The information of the stiffness range of the load train configuration (test specimen) shall be provided (by previous test measurements) by the user of the machine. Up to now the shape of the specimen is neglected.

If these stiffness values are not available a priori, some calculation must be done based on the specimen's geometry. In the case of cylindrical standard specimen Annex B.4 contains several diagrams Figure 5 to assist the estimation of stiffness's.

An example for a parameter matrix is given in Table 1. The matrix and both chosen parameter sets are parts of the calibration certificate.

Table 1: Example of a parameter matrix, containing arbitrary values, in practice all values have to be derived and specified by the user from the testing applied around a year to the machine to be calibrated.

Parameter	Value (Machine's capacities)		Parameter Set A	Parameter Set B
Mode of periodic force	Tension only or compression only or tension-compression		Compression	Compression
Compensation method provided by machine's software	Mass, Temp., Bending, …		Mass Compensation	Mass Compensation
Value used with the compensation method			20 kg	150 kg
Parameter	**Min. Value**	**Max. Value**	**-**	**-**
Force amplitude [kN]	2	50	50	50
Mean force [kN]	-20	200	-20	200
Frequency [s^{-1}]	50	250	250	250
Mounting equipment's uncompensated masses [kg]	20	150	20	150
Specimen's uncompensated masses [kg]	3	10	3	10
Stiffness [$kN \cdot mm^{-1}$]	400	1000	400	1000
Temperature [°C]	20	25	25	25

3.5 Transfer Standard's Static Calibration

Select one or more transfer standards appropriate for parameter sets derived in the step before and to be used during dynamic calibration. The chosen transfer standards need to be calibrated statically according to ISO 376 considering the following aspects:

- The force range statically calibrated has to cover the proposed dynamic force range.
- The condition of load direction (tension and/or compression).
- Class 1 or better is required.

3.6 Transfer Standard's Dynamic Calibration

Beside the static calibration of the transfer standards a dynamic calibration according to DKD-R 3-10, Sheet 2 is needed too.

Annotation: A tolerance classification of the transfer standard required for machine's calibration is not available now and has to be developed and added here in the future. The impact of structure-borne noise, especially for the piezoelectric acceleration transducer and others might be considered in the dynamic calibration of the transfer standard.

3.7 Transfer Standard's Amplifier

The amplifier used to measure the channels of the transfer standard, e.g. force, acceleration, temperature should be calibrated according to DKD-R 3-2. There is no need for it, if the transducer is calibrated in measurement chain with the amplifier.

3.8 Data Acquisition System

The acquisition system should be able to acquire all channels needed for dynamic calibration at once, from the machine and from the transfer standard.

If there is no acquisition system available which is able to acquire all needed channels at once, machine's data can be acquired by the machine and data of transfer standard by a separate system. For evaluation, both data sets have to be synchronized using common test points generated during the calibration process as stated in chapter 4.2.

4 Dynamic Calibration of the Machine

4.1 Prepare for Cyclic Loading

In accordance with ISO 7500-1 calibration shall be performed at temperatures between 10 °C and 35 °C. All equipment shall be installed and electronics should be wired and switched on a sufficient period of time before calibration to ensure stable temperature and signal conditions. The temperature of sensors and calibration parts shall not exceed a difference of 2 K during calibration. Temperature has to be documented in the calibration certificate.

Mass, stiffness adapter and transfer standard appropriate to the parameter set to be calibrated should be assembled following the instructions in Annex B.2 to B.4.

Sensors of the Machine should be connected to machine's controller and the transfer standard to its signal conditioner and amplifier. It is recommended that all channels will be transferred to a multi-channel acquisition system.

Primary channels to be acquired and recorded are:

- runtime□,

- force of the machine□, ±,

- force of the transfer standard□, ±,

- bending strains□, ±,

- acceleration of the additional masses□, ±,

- temperature□.

- Crosshead displacement, measured by machine's displacement sensor, or derived from accelerometer measurements □, ±, #

Channels marked with □ should be acquired and recorded as full streams in one file. One more file should contain the min. and max. values of all channels marked with ± as well as the corresponding values of runtime and temperature. # Helpful for evaluation steps (to be defined) e.g. explaining bending influence with regard to the frequency. Channels not listed can be added to the files optionally.

Supported by DKD-R 3-10, Sheet 3 and ASTM E1942 signal conditioning and amplifying should be done without any filters or by the use of an anti-aliasing and a low-pass filter. Whereby the cut-off frequency of the low-pass filter is about 10 % to 15 % of the sampling rate. Data acquisition should be done using a sampling rate of at least 80 samples/cycle in case of a sinusoidal and 400 samples/cycle in case of a triangular wave form. For example, a test frequency of a sinusoidal wave of 70 Hz leads to a minimum sampling rate of (70 cycles/s * 80 samples/cycles =) 5600 samples/s. Thus, the cut-off frequency of the low-pass filter should not lower than (5600 samples/s * 10 % / 100 % =) 560 samples/s which corresponds to 560 Hz.

All acquired bridges and signals have to be balanced and zeroed when electronics reached a steady state and the parts of the load train are fully disassembled.

Finally, compensation parameters denoted in the parameter set of interest has to be applied to the machine.

4.2 Apply Cyclic Loading

Preload the machine with the mean force of cycling, then start cycling and adjust machine controls so that the machine achieves the calibration force end levels defined by the parameter set currently of interest. Be aware of overloads of the calibration equipment. Refer to the technical documentation of the transfer standard and stiffness adapter to ensure that limits are known and methods are available and applied to prevent overloads.

Wait for stabilization of the system (min. cycles = 10 * frequency). Start the recording of the measurement channels and set-up to the calibration force again. After at least 3 * frequency cycles (for frequencies greater-equal 1 Hz) reduce the force amplitude significantly and stop data recording finally. Repeat that start-stop procedure fully two more times. Thus, three calibration series were performed each recorded in two files (file 1: full streams, file 2: min. and max. values as well as corresponding runtime and temperature).

Ensure that the requirements for data acquisition and recording mentioned in section 4.1 were fulfilled.

4.3 Evaluation of Measured Data

Three series of dynamic calibration for a parameter set of interest were performed. Each of the series has been recorded in two files, one contains the full data stream, the other one the min. and max. values as well as the corresponding runtime and temperature. Annex B.1 gives an overview of the analysis possibilities depending on the measurement capabilities of the calibration setup.

Evaluation starts with the analysis of the full data streams. Force streams of machine and transfer standard have to be fitted at first. Fitting should be applied to the main part of the dataset, where constant cyclic loading at the level of the calibration force has been achieved. Amplitude, mean force, frequency and phase are elements of the fit function and will be derived due to the fitting of each force stream. Afterwards differences between the fit function forces and the measured forces have to be calculated as well as differences in frequency and phases of both streams.

Annotation: Three measurement series have been acquired. Each of the series has to be evaluated for itself using the following equations. Therefore, the equation parameters should have an additional index which represents the number of the measurement series. To keep the equations as simple as possible, the series index is not written here, but the calibration certificate shall point out the parameters for each measurement series.

Fit function and its parameters:

$$FF_i(t) = u_i + b_i \cdot \sin(2\pi \cdot f_i \cdot t + p_i) \tag{1}$$

where:

i Equipment index: M for machine, S for transfer standard

t Runtime of measurement

$FF_i(t)$ Force calculated by sine fit function at runtime t

u_i Mean force of the fit function

b_i Force amplitude of the fit function

f_i Frequency of the fit function

p_i Phase of the fit function

Differences between forces of fit function and measurement:

$$\Delta F_i(t) = FF_i(t) - F_i(t) \quad (2)$$

where:

i Equipment index: M for machine, S for transfer standard

t Runtime of measurement

$FF_i(t)$ Force calculated by sine fit function at runtime t (Equation 1)

$F_i(t)$ Measured force at runtime t

Differences in frequency and phase:

$$\Delta f = f_M - f_S \quad (3)$$

$$\Delta p = p_M - p_S \quad (4)$$

where:

$f_\mathrm{M}, p_\mathrm{M}$ Frequency and phase of machine (from Equation 1)

$f_\mathrm{S}, p_\mathrm{S}$ Frequency and phase of transfer standard (from Equation 1)

Annotation: The method of frequency and phase difference needs to be revised, e.g. to get time dependent differences and to consider effects such as dither amplitudes or harmonic disturbances.

The evaluation will be continued with the analysis of the min. and max. forces detected by the in-situ peak-valley detection of both force channels. Each min.-max. pair is used for a calculation of the force span introduced by the machine. These calculated force spans will be used for a calculation of the difference between each force span and the double of the amplitude of the fit function. This has to be done for the machine as well as for the transfer standard.

Force span by in-situ peak-valley detected min. and max. forces:

$$FSV_i(c) = F_{\mathrm{max},i}(c) - F_{\mathrm{min},i}(c) \quad (5)$$

where:

i Equipment index: M for machine, S for transfer standard

c	Cycle number
$F_{\max,i}$	In-situ detected max. force
$F_{\min,i}$	In-situ detected min. force

Difference of forces spans of the in-situ peak-valley detected min. and max. forces and the force span calculated by amplitude of the fit function:

$$\Delta FSVF_i(c) = FSV_i(c) - 2b_i \tag{6}$$

where:

i	Equipment index: M for machine, S for transfer standard
c	Cycle number
$FSV_i(c)$	Force span at cycle c (from Equation 5)
$2b_i$	Force span calculated by amplitude of the fit function
b_i	Force amplitude of the fit function (from Equation 1)

Further, differences of the force spans of machine and transfer standard $\Delta FSMS(c)$ have to be calculated followed by the differences between the min. forces of both channels as well as their max. forces for each cycle c and its relative value $\Delta FSMS(c)_{\mathrm{rel}}$.

$$\Delta FSMS(c) = FSV_{\mathrm{M}}(c) - FSV_{\mathrm{S}}(c) \tag{7}$$

$$\Delta FSMS(c)_{\mathrm{rel}} = \frac{\Delta FSMS(c)}{FSV_{\mathrm{S}}(c)} \cdot 100 \tag{8}$$

where:

c	Cycle number
$FSV_{\mathrm{M}}(c)$	Force span of the machine at cycle c (Equation 5)
$FSV_{\mathrm{S}}(c)$	Force span of the transfer standard at cycle c (Equation 5)

$$\Delta F_{\min}(c) = F_{\min,\mathrm{M}}(c) - F_{\min,\mathrm{S}}(c) \tag{9}$$

$$\Delta F_{\max}(c) = F_{\max,\mathrm{M}}(c) - F_{\max,\mathrm{S}}(c) \tag{10}$$

where:

c	Cycle number
$F_{\min,\mathrm{M}}(c), F_{\min,\mathrm{S}}(c)$	Peak-valley detected min. force of machine and transfer standard at cycle c
$F_{\max,\mathrm{M}}(c), F_{\max,\mathrm{S}}(c)$	Peak-valley detected max. force of machine and transfer standard at cycle c

If $\Delta FSMS(c)_{\mathrm{rel}}$ is significantly high, then the evaluation of inertial forces caused by uncompensated additional masses $FMAD$ should be performed. Therefore, the product of additional mass m_{add} and measured acceleration $a_{m_{\mathrm{add}}}$ should be calculated followed by a peak-valley analysis and a calculation of the force spans. Further, the difference between the mean span of $FMAD$ and the mean of the force span difference $\Delta FSMS_{\mathrm{mean}}$ should be calculated.

$$FMAD = m_{\mathrm{add}} \cdot a_{m_{\mathrm{add}}} \tag{11}$$

where:

$FMAD$ Force due to additional, uncompensated masses

m_{add} Measured or estimated additional masses

$a_{m_{\mathrm{add}}}$ Measured acceleration of additional masses

$$FSMAD(c) = FMAD_{\max}(c) - FMAD_{\min}(c) \tag{12}$$

where:

c Cycle number

$FSMAD(c)$ Span of force due to additional masses at cycle c

$FMAD_{\max}(c)$ Maximum force due to additional masses at cycle c

$FMAD_{\min}(c)$ Minimum force due to additional masses at cycle c

$$FSMAD_{\mathrm{mean}} = \frac{\sum_{i=1}^{N_c} FSMAD_i(c)}{N_c} \tag{13}$$

where:

c Cycle number

N_c Number of cycles to be evaluated

$FSMAD_{\mathrm{mean}}$ Mean of span of force due to additional masses

$$\Delta FSMS_{\mathrm{mean}} = \frac{\sum_{i=1}^{N_c} \Delta FSMS_i(c)}{N_c} \tag{14}$$

where:

c Cycle number

N_c Number of cycles to be evaluated

$\Delta FSMS_{\mathrm{mean}}$ Mean difference between force spans of machine and transfer standard

$$\Delta MFS = FSMAD_{\mathrm{mean}} - \Delta FSMS_{\mathrm{mean}} \tag{15}$$

where:

ΔMFS	Difference of mean force spans of forces due to additional masses and the mean difference between spans of machine and transfer standard
$FSMAD_{\mathrm{mean}}$	Mean force span of forces due to additional masses
$\Delta FSMS_{\mathrm{mean}}$	Mean difference between force spans of machine and transfer standard

4.4 Next Parameter Set

Repeat sections 4.1 to 4.3 for the next parameter set of interest. Each combination of frequency, stiffness and load range must have its own tare value and preferably be stored in separate files (see Annex B.3 for how to do).

In order to minimize the operator’s efforts and maintain a certain repeatable mechanical condition, it is suggested that a variation of force ranges be carried out for each mechanical assembly (same additional mass and same stiffness adapter), and for each force range, a variation for frequency values should be carried out. In the selection of frequencies, resonance regions must be identified and avoided.

5 Measurement Uncertainty

This chapter provides a guide for the estimation of the uncertainty budget of dynamic calibration of materials testing systems. Depending on the application of this standard it is possible that more uncertainty sources might be relevant which have to be considered additionally.

Measurement uncertainty shall be evaluated separately for every parameter set.

Uncertainty sources can be divided into four groups related to the transfer standard, the machine, uncompensated masses and the procedure, according to Figure 2.

The models of the evaluation of force calibrations are formulated as linear product models using relative measurement uncertainties.

Some of the components are frequency dependant (e.g uncertainty corresponding to the dynamic sensitivity of the transfer standard) which makes the necessity to derive the uncertainty value for the specific frequency level at which the calibration was performed.

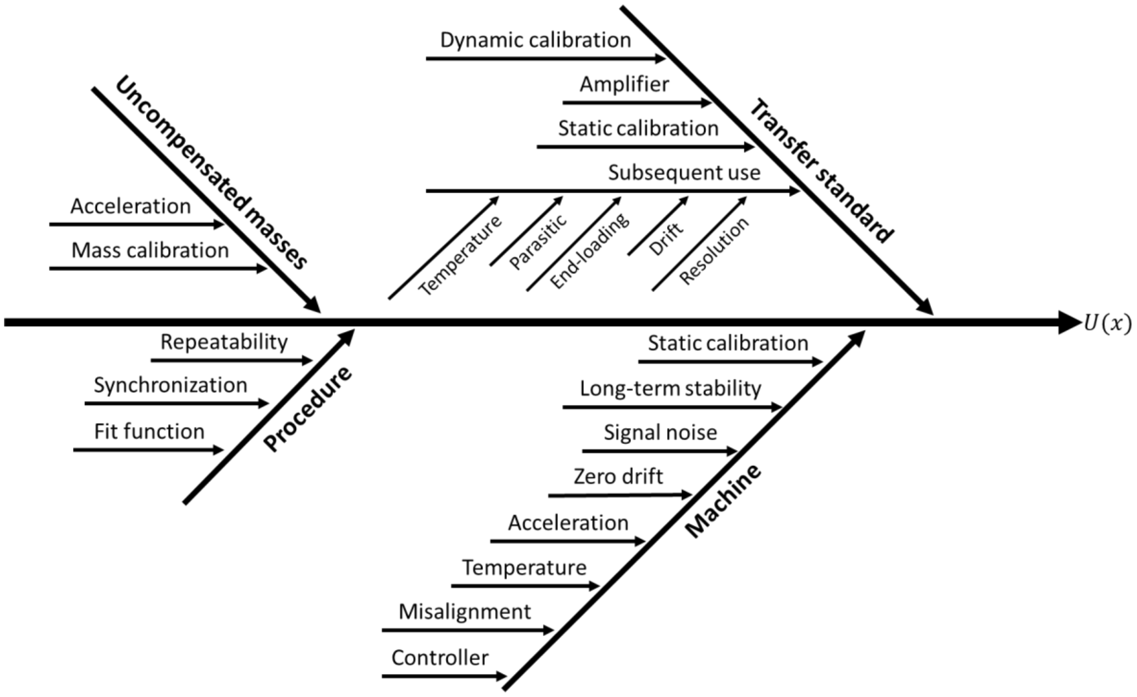


Figure 2: Sources of uncertainty attributed to the parameters determined during the evaluation of measurement data.

5.1 Transfer Standard

The relative standard uncertainty of force measured by the transfer standard $w(F_{\mathrm{S}})$, for chosen linear model and the sensitivity coefficients equal to ± 1, can be expressed as follows:

$$w(F_{\mathrm{S}}) = \sqrt{w^2(F_{\mathrm{S,dyn}}) + w^2(F_{\mathrm{S,stat}}) + w_{\mathrm{S,use}}^2 + w_{\mathrm{S,amp}}^2} \qquad (16)$$

where:

$w(F_{\mathrm{S,dyn}})$ Relative standard uncertainty of dynamic calibration of the transfer standard; frequency dependant

$w(F_{\mathrm{S,stat}})$ Relative standard uncertainty of static calibration of the transfer standard

$w_{\mathrm{S,use}}$ Relative standard uncertainty due to subsequent use of the transfer standard, composed of several contributions

$w_{\mathrm{S,amp}}$ Relative standard uncertainty due to amplifier; frequency dependant

5.1.1 Uncertainty of Dynamic Calibration of the Transfer Standard

The relative standard uncertainty $w(F_{\mathrm{S,dyn}})$ shall be derived from the certificate of dynamic calibration of the transfer standard.

During dynamic calibration of the transfer standard the dynamic sensitivity and corresponding measurement uncertainty are evaluated. Both these parameters generally depend on the frequency of periodic loading. Thus, the frequency of chosen parameter set determines the value of force sensitivity and uncertainty derived from the calibration certificate.

5.1.2 Uncertainty of Static Calibration of the Transfer Standard

The relative standard uncertainty of static calibration $w(F_{\mathrm{S,stat}})$ according to ISO 376 shall be considered in this evaluation if it is not included in the dynamic calibration of the transfer standard. Although it does not cover effects of dynamic loading, it provides information about the general performance of the transfer standard. Moreover, the value of $w(F_{\mathrm{S,stat}})$ is usually significantly lower than $w(F_{\mathrm{S,dyn}})$ and it could be ignored, however taking this uncertainty into account gives proof of traceability.

5.1.3 Uncertainty Contributions Due to the Subsequent Use of the Transfer Standard

The relative standard uncertainty contributions due to the subsequent use of the transfer standard $w_{\mathrm{S,use}}$, for chosen linear model and the sensitivity coefficients equal to ± 1, can be expressed as follows:

$$w_{\mathrm{S,use}} = \sqrt{w_{\mathrm{S,res}}^2 + w_{\mathrm{S,drift}}^2 + w_{\mathrm{S,T}}^2 + w_{\mathrm{S,end}}^2 + w_{\mathrm{S,par}}^2} \tag{17}$$

where:

$w_{\mathrm{S,res}}$	Relative standard uncertainty due to resolution of the transfer standard
$w_{\mathrm{S,drift}}$	Relative standard uncertainty due to drift of the transfer standard
$w_{\mathrm{S,T}}$	Relative standard uncertainty due to temperature effect on sensitivity of the transfer standard
$w_{\mathrm{S,end}}$	Relative standard uncertainty due to end-loading effect of the transfer standard
$w_{\mathrm{S,par}}$	Relative standard uncertainty due to effect of parasitic components

5.1.3.1 Resolution

The readings of the transfer standard usually fluctuate (can be seen as noise) due to use of high frequency filter of not applying any filter. The noise signal of the unloaded transfer standard can be considered as the resolution contribution.

Record relatively high number of samples of unloaded transfer standard (e.g. 50 * frequency). Calculate relative standard deviation of recorded samples, which can be considered as the uncertainty component due to resolution.

5.1.3.2 Drift

According to ISO 376.

5.1.3.3 Temperature

According to ISO 376.

5.1.3.4 End-loading effect

According to ISO 376.

5.1.3.5 Effect of parasitic components

According to ISO 376.

5.1.4 Amplifier of the Transfer Standard

If the force transfer standard is calibrated in measurement chain with the amplifier, the relative uncertainty contribution of the amplifier $w_{\mathrm{S,amp}}$ is included in the uncertainty of the force transfer standard. Otherwise, it is recommended to calibrate the amplifier according to DKD-R 3-10, Sheet 2, where uncertainty contributions will be quantified in the calibration certificate.

5.2 Machine

The relative standard uncertainty of force measured by the machine $w(F_{\mathrm{M}})$, for chosen linear model and the sensitivity coefficients equal to ± 1, can be expressed as follows:

$$w(F_{\mathrm{M}}) = \sqrt{w^2(F_{\mathrm{M,stat}}) + w_{\mathrm{M,drift}}^2 + w_{\mathrm{M,T}}^2 + w_{\mathrm{M,noise}}^2 + w_{\mathrm{M,zer}}^2 + w_{\mathrm{M,align}}^2 + w_{\mathrm{M,ctr}}^2} \qquad (18)$$

where:

$w(F_{\mathrm{M,stat}})$ Relative standard uncertainty of static calibration of the machine

$w_{\mathrm{M,drift}}$ Relative standard uncertainty due to long-term stability of the machine

$w_{\mathrm{M,T}}$ Relative standard uncertainty due to temperature gradients affecting the machine during calibration

$w_{\mathrm{M,noise}}$ Relative standard uncertainty due to fluctuation of readings (noise)

$w_{\mathrm{M,zer}}$ Relative standard uncertainty due to effect of zero signal drift of the machine

$w_{\mathrm{M,align}}$ Relative standard uncertainty due to misalignment; frequency dependant

$w_{\mathrm{M,ctr}}$ Relative standard uncertainty due to machine's controller; frequency dependant

5.2.1 Static calibration

The relative standard uncertainty value declared in the certificate of the calibration process performed according to the ISO 7500-1 standard is taken.

If applicable, force measured by the machine can be corrected by force errors determined during static calibration of the machine. In this case the relative standard uncertainty of static calibration $w(F_{\mathrm{M,stat}})$ shall be considered.

5.2.2 Long-term stability

This contribution $w_{\mathrm{M,drift}}$ should be estimated by the user of machine, based on information from the history of the results obtained in previous calibrations. If results of previous dynamic calibrations are not available, then results of static calibration can be used.

For dynamic calibration results:

$$w_{\mathrm{M,drift}} = \frac{1}{|b_{\mathrm{M}} + u_{\mathrm{M}}|} \cdot \frac{|q_{\mathrm{drift}}|}{\sqrt{3}} \qquad (19)$$

For static calibration results:

$$w_{\mathrm{M,drift}} = \frac{1}{|F|} \cdot \frac{|q_{\mathrm{drift}}|}{\sqrt{3}} \tag{20}$$

where:

q_{drift}	Difference in force errors of the machine determined in previous calibrations
$b_{\mathrm{M}} + u_{\mathrm{M}}$	Sum of mean force and amplitude measured by the machine
F	Nominal force level corresponding to the error q (acc. to ISO 7500-1)

5.2.3 Temperature

The temperature fluctuations during dynamic calibration of the machine can significantly influence the results. The desired method to estimate this influence would be to measure temperature of the machine's force transducer. If it is not the case the ambient temperature shall be measured as close as possible to the mechanical set-up.

$$w_{\mathrm{M,T}} = \alpha \cdot \frac{\Delta T}{2} \cdot \frac{1}{\sqrt{3}} \tag{21}$$

where:

α	Machine's force transducer temperature coefficient (in $°\mathrm{C}^{-1}$)
ΔT	Temperature range during calibration, including uncertainty in the measurement of the temperature

5.2.4 Signal noise

The readings of the machine usually fluctuate (can be seen as noise). The noise signal of the unloaded machine can be considered also as the resolution contribution.

In order to estimate the uncertainty component record relatively high number of samples of unloaded machine (e.g. 50 * frequency, see chapter B for further instructions). Calculate standard deviation of recorded samples. Relative standard uncertainty related to resolution is given by the following equations.

For readings in electrical units:

$$w_{\mathrm{M,noise}} = \frac{1}{|X_{\mathrm{N}}|} \cdot \sqrt{\frac{1}{n(n-1)} \sum_{j=1}^{n} \left(X_j - \bar{X}\right)^2} \tag{22}$$

For readings in units of force:

$$w_{\mathrm{M,noise}} = \frac{1}{|b_{\mathrm{M}} + u_{\mathrm{M}}|} \cdot \sqrt{\frac{1}{n(n-1)} \sum_{j=1}^{n} \left(F_j - \bar{F}\right)^2} \tag{23}$$

where:

n	Number of analysed samples
X_j, F_j	Recorded values, expressed in electrical units and units of force respectively

$\bar{X}$, $\bar{F}$ Mean value of recorded values X_j, F_j

X_N Deflection (in the same unit as X_j) corresponding to the force value $b_\mathrm{M} + u_\mathrm{M}$, determined from the calibration series

5.2.5 Zero drift

In order to estimate the effect of zero signal drift of the machine record relatively high number of samples of unloaded machine (e.g. 50 * frequency) before and after each measurement series. Calculate maximum difference between mean values of determined for samples before and after the series, $\bar{X}_\mathrm{before}$, $\bar{F}_\mathrm{before}$ and $\bar{X}_\mathrm{after}$, $\bar{F}_\mathrm{after}$ respectively. Relative standard uncertainty due to zero drift of the machine is given by the following equations.

For readings in electrical units:

$$w_\mathrm{M,zer} = \frac{1}{|X_\mathrm{N}|} \cdot \frac{\max\{|\bar{X}_\mathrm{after,j} - \bar{X}_\mathrm{before,j}|\}}{\sqrt{3}} \tag{24}$$

For readings in units of force:

$$w_\mathrm{M,zer} = \frac{1}{|b_\mathrm{M} + u_\mathrm{M}|} \cdot \frac{\max\{|\bar{F}_\mathrm{after,j} - \bar{F}_\mathrm{before,j}|\}}{\sqrt{3}} \tag{25}$$

where:

j Number of measurement series

X_N Deflection corresponding to the force value $b_\mathrm{M} + u_\mathrm{M}$

$\bar{X}_\mathrm{before}$, $\bar{F}_\mathrm{before}$ Mean value of recorded values before the measurement series, expressed in electrical units and units of force respectively

$\bar{X}_\mathrm{after}$, $\bar{F}_\mathrm{after}$ Mean value of recorded values after the measurement series, expressed in electrical units and units of force respectively

5.2.6 Misalignment

If it is possible to measure the misalignment the force deviation as a function of bending strains due to misalignment should be determined for the used calibration set-ups. Afterwards a relative standard uncertainty contribution $w_\mathrm{M,align}$ can be derived from the function.

5.2.7 Controller

If it is possible to calibrate the machine's controller according to DKD-R 3-2, then the relative standard uncertainty contribution $w_\mathrm{M,ctr}$ can be derived from the calibration certificate and applied to the uncertainty budget.

5.3 Uncompensated masses

If the inertial forces generated by uncompensated masses $FMAD$ are determined according to (11), the relative standard uncertainty of this force $w(FMAD)$, for chosen linear model and the sensitivity coefficients equal to m_add and a_{m_add},can be expressed as follows:

$$w(FMAD) = \sqrt{m_\mathrm{add} \cdot w^2(a_{m_\mathrm{add}}) + a_{m_\mathrm{add}} \cdot w^2(m_\mathrm{add})} \tag{26}$$

where:

$w\left(a_{m_{\text{add}}}\right)$ Relative standard uncertainty due to determination of acceleration of uncompensated masses; may be frequency dependant

$w(m_{\text{add}})$ Relative standard uncertainty of the value of the uncompensated masses

5.3.1 Acceleration (of uncompensated masses)

The acceleration of uncompensated masses can be determined by measuring the acceleration directly, or the speed or the displacement.

This model can be easily applied for the case of direct measurement of acceleration. The relative uncertainty contribution due to acceleration measurement shall be evaluated, including the calibration uncertainty of the acceleration measuring device.

For other cases the relative uncertainty contribution of the acceleration shall be determined.

5.3.2 Uncompensated masses

The relative standard uncertainty contribution of the additional masses can be taken from the calibration certificates of the masses.

5.4 Procedure

The evaluation of the measured data includes the calculation of mean values of $FSMAD_{\text{mean}}$ (mean of span of force due to additional masses) and $\Delta FSMS_{\text{mean}}$ (mean difference between force spans of machine and transfer standard) and the fitting procedure.

Therefore, the relative standard uncertainty components associated with repeatability of $FSMAD_{\text{mean}}$ and $\Delta FSMS_{\text{mean}}$ as well as parameters of the fit function, respectively, should be determined.

Furthermore, the user of this procedure shall analyse and consider other possible uncertainty components that can be identified. This can be for example effect of not fully synchronized channels of the data acquisition system used during the calibration of the machine.

5.4.1 Repeatability

The relative standard uncertainty associated with the repeatability is the standard deviation of the estimated mean value given by the formulas below.

For mean of span of force due to additional masses (if determined):

$$w(FSMAD_{\text{mean}}) = \frac{1}{|FSMAD_{\text{mean}}|} \cdot \sqrt{\frac{1}{N_c(N_c-1)} \sum_{i=1}^{N_c} (FSMAD_i(c) - FSMAD_{\text{mean}})^2} \tag{27}$$

For mean difference between force spans of machine and transfer standard:

$$w(\Delta FSMS_{\text{mean}}) = \frac{1}{|\Delta FSMS_{\text{mean}}|} \cdot \sqrt{\frac{1}{N_c(N_c-1)} \sum_{i=1}^{N_c} (\Delta FSMS_i(c) - \Delta FSMS_{\text{mean}})^2} \tag{28}$$

where:

c Cycle number

N_c Number of cycles to be evaluated

$FSMAD_{\text{mean}}$ Mean of span of force due to additional masses

$\Delta FSMS_{\text{mean}}$ Mean difference between force spans of machine and transfer standard

5.4.2 *Fit function*

The relative standard uncertainty of fitted force as a function of time determined according to (1), can be expressed as follows:

$$w(FF_i) = \sqrt{\left(\frac{\partial FF_i}{\partial u_i}\right)^2 \cdot w^2(u_i) + \left(\frac{\partial FF_i}{\partial b_i}\right)^2 \cdot w^2(b_i) + \left(\frac{\partial FF_i}{\partial f_i}\right)^2 \cdot w^2(f_i) + \left(\frac{\partial FF_i}{\partial p_i}\right)^2 \cdot w^2(p_i)} \tag{29}$$

where:

i Equipment index: M for machine, S for transfer standard

$w(u_i)$ Relative standard uncertainty due to determination of mean force from the fit function

$w(b_i)$ Relative standard uncertainty due to determination of force amplitude from the fit function

$w(f_i)$ Relative standard uncertainty due to determination of frequency from the fit function

$w(p_i)$ Relative standard uncertainty due to determination of phase from the fit function

The values of standard uncertainties shall be derived from the statistical data used for the fitting procedure.

5.4.3 *Synchronization*

The relative uncertainty contribution associated with the effect of not fully synchronized channels of the data acquisition system shall be included in the uncertainty contribution of the amplifier $w_{\text{S,amp}}$, given in chapter 5.1.4.

Note: The result of the synchronisation procedure can affect the determined values of f_i and p_i from the fit function and their uncertainties $w(f_i)$ and $w(p_i)$ respectively.

6 Literature

[1] PTB Braunschweig, 18SIB08 – ComTraForce – Comprehensive Traceablility for Force Metrology Services, https://www.ptb.de/empir2019/comtraforce/home/, visited on March 24th 2023

[2] M.J. Dixon: Dynamic Force Measurement, in Materials Metrology and Standards for Structural Performance, B.F. Dyson, M.S. Loveday, M.G. Gee [Editors], Chapman & Hall, 1st Edition, London, 1995

[3] A. Nitschke, et al.: Entwicklung eines Kraft-Transfernormals für die Kalibrierung periodischer Kräfte in Werkstoffprüfmaschinen mit Quantifizierung parasitärer Einflussgrößen, ITG-Fachbericht 303 – Sensoren und Messsysteme, Beiträge der 21. ITG/GMA-Fachtagung, 10.-11. Mai 2022 in Nürnberg, VDE Verlag, 2022, ISBN 978-3-8007-5835-7, S.63-73

[4] R. S. Oliveira, et al: DYNAMIC CALIBRATION OF FATIGUE TEST MACHINES USING A DYNAMIC CALIBRATION DEVICE, IMEKO 23rdTC3, 13thTC5 and 4thTC22 International Conference 30 May to 1 June, 2017, Helsinki, Finland.

[5] H. Dizdar; B. Aydemir; C. Vatan, EVALUATION OF THE EFFECT OF DYNAMIC VERIFICATION ON DIFFERENT TYPES OF FORCE SENSORS, IMEKO 24rdTC3, International Conference 11 – 13 October 2022, Cavtat-Dubrovnik, Croatia. DOI: 10.21014/tc3-2022.012

Annex

A Generally

A.1 Necessity of Calibration

Material and mechanical tests are very important as they ensure the quality and safety of the products produced in today's industry in daily use. In material and mechanical tests, accurate force measurement is one of the most significant parameters to obtain reliable test results. Force measuring devices in materials testing machines are most often calibrated statically by comparison to transfer standards traceable to the National Metrology Institutes of that country. Therefore, the traceability of force measurement is needed for all applications under static, continuous, and dynamic loads. Systems used in testing machines are designed to operate dynamically as well as statically. Under certain conditions, the static calibration may be inadequate or in error for some domains of dynamic testing. The dynamic calibration of the material testing machine helps us to learn about the dynamic behaviour of the machine during use. This information validates the results obtained by testing the materials.

A.2 Dynamic Calibration Compared to Others

The force standard machines and the force calibration methods described in standards (ISO 376, ISO 7500-1) are optimized to calibrate force sensors with minimal measurement uncertainty. In these procedures the load is applied stepwise (Figure 3a) with time intervals of typically 60 s per step. Therefore, a duration of the order of $t_{\mathrm{c}} = 1000\ \mathrm{s}$ results for a load cycle.

For the calibration of some force sensors (piezoelectric), where the drift is present in the signal, the duration of a load cycle should be shorter in order to reduce the measurement uncertainty. Therefore, continuous calibration procedures have been developed and established (Figure 3b), where the time interval for a load cycle is typically $t_{\mathrm{c}} = 10\ \mathrm{s}$

For dynamic calibrations, where the dynamic properties of the sensors are measured, much faster load cycles with cycle times in the range of $t_{\mathrm{c}} = 1 \text{ to } 0.0001\ \mathrm{s}$ are needed (Figure 3c). For the sake of comparison, the load cycle frequency f_{c} is defined as $f_{\mathrm{c}} = \frac{1}{t_{\mathrm{c}}}$. For the standard stepwise load cycle this yields $f_{\mathrm{c,s}} = 1\ \mathrm{mHz}$, for the continuous cycle $f_{\mathrm{c,c}} = 100\ \mathrm{mHz}$ and for the dynamic calibration typically $f_{\mathrm{c,d}} = 1 \text{ to } 10\ \mathrm{kHz}$.

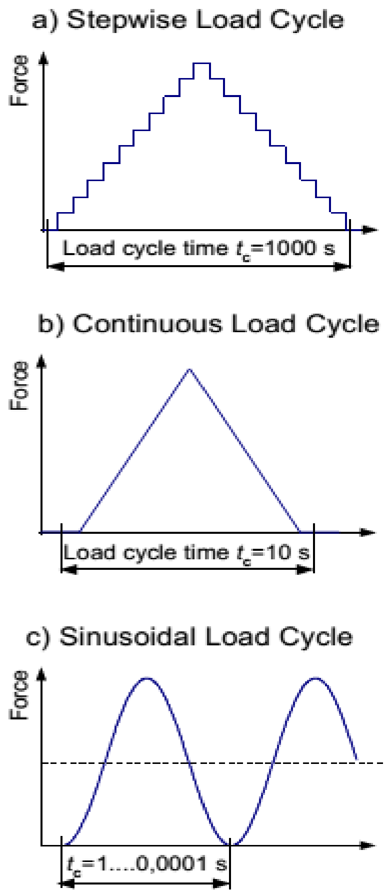


Figure 3: Load-time dependence diagrams for stepwise, continuous and sinusoidal load cycles

B Practical and Auxiliary Procedures (Annotations)

The measurement procedure for the dynamic calibration of a testing machine requires attention to some details that may impact the proposed metrological analysis, once some parameters may be sensitive to the assembly method and the load application sequence. Below there is a compilation of guidelines for best practice on this measurement, derived from experiences of e.g. [4, 5].

B.1 Paths for the Analysis of Characteristic Parameters

The viability of the paths for the analysis of characteristic parameters of the measured sinusoidal curves (see Section 4.3) will depend on the way and capacity that these systems have to generate and store these values. The table 2 below shows an example of analysing the viability of certain curve parameters in different measurement systems.

Table 2: Evaluation paths

Legend: Evaluation possible = Y; Evaluation not possible = N									
		Machine						Transfer Standard	
	Machine's Type	Servo-hydraulic		Resonance Young		Resonance Old			
	Information of Interest	Wave	Extremes	Wave	Extremes	Wave	Extremes	Wave	Extremes
Acquired by	Machine	internal to an ASCII file	internal to an ASCII file	not stored	internal to an ASCII file	not stored	not stored	-	-
	External Multi-channel System	from machine's analog output to an ASCII file	Can be derived from wave file	from machine's analog output to an ASCII file	Can be derived from wave file	from machine's analog output to an ASCII file	Can be derived from wave file	from signal conditioner to an ASCII file	from signal conditioner to an ASCII file
	Considered Channels	t; F	t; F	t; F	t; F	t; F	t; F	t; F; a	t; F; a
Evaluation	Fit Function	Y	N	N	N	Y	Y	Y	N
	Delta Fit to Meas	Y	N	N	N	Y	Y	Y	N
	Delta Frequ.	Y	N	N	N	Y	Y	Y	N
	Delta Phase	Y	N	N	N	Y	Y	Y	N
	Fspan (peva)	Y	Y	Y	Y	Y	Y	Y	Y
	Delta Fspan (peva) to 2*ampl(FitFunc)	Y	Y	Y	Y	Y	Y	Y	Y
	Delta Fspan (pevaMc) to Fspan (pevaTStd)	Y	Y	Y	Y	Y	Y	Y	Y
	Delta Min(Mc) to Min(TStd)	Y	Y	Y	Y	Y	Y	Y	Y
	Delta Max(Mc) to Max(TStd)	Y	Y	Y	Y	Y	Y	Y	Y
	Fmadd	N	N	N	N	N	N	Y	Y
	Fspan (pevaz,madd)	N	N	N	N	N	N	Y	Y
	MeanFspan (pevaz,madd)	N	N	N	N	N	N	Y	Y
	MeanFspandeltaMcTStd (Delta Fspan (pevaMc) to Fspan (pevaTStd))	N	N	N	N	N	N	Y	Y
	Delta MeanFpanmadd to MeanFspandeltaMcTStd	N	N	N	N	N	N	Y	Y

B.2 Factors Relevant to the Mounting of the Transfer Standard to the Machine

Some factors are relevant to the mounting of the transfer standard to the machine. For example, we can cite:

The stiffness adapter (G in Figure 4) must not be coupled between the machine force transducer (B) and the force transfer standard (E).

Both force sensors must be directly connected through a rigid coupling (C). The mass of the coupling must be known, and its value can be used to compensate its inertia contribution to the readings. In the same way, it is desirable that this coupling should be able to receive coupling of the additional masses and the acceleration instrumentation (D), so it can work in both load train configurations with and without additional parts.

It is important to register the assembly sequence (photos, videos), with the position of each part of the load train identified (e.g. axles, screw-nut assemblies, masses, stiffness adapter parts, applied tightening torques), and there is the need for (visual) identification of each of these parts in order to ensure that during disassembly and reassembly, it is possible to reproduce the same original set.

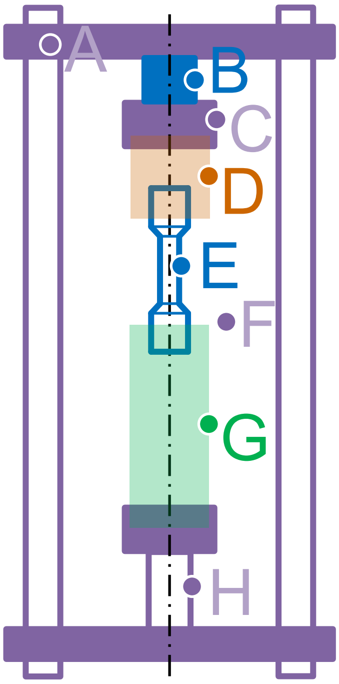


Figure 4: Simplified scheme of the mechanical set-up for dynamic force calibration: A Load frame, B Machine's force transducer, C Mounting equipment, D Mounting zone for additional masses and accelerometers, E Force transfer standard, F Environment, G Stiffness adapter, H Force introducing element

B.3 Specific Procedures for the Correct Load Series Application

Some specific procedures are important for the correct load series application:

Best balancing and zeroing practice have to be observed in test runs on different material testing systems, e.g. using machines with force transducer on the top vs. on the bottom. However, in both cases a minimum approximation force should be applied to the load train in order to carry out a first mechanical accommodation of parts. This force applied value will be the zero reference piston position for the machine;

The Zero Value (or the Tare Value) must be calculated from the data recorded continuously in the unload static condition before applying the offset force value.

The noise in both sensors, adopted as the resolution parameter, must be measured with the force sensors decoupled.

When applying an offset force value, it is interesting to apply a low rate ramp loading from zero force value up to the offset target and keep that for some seconds before starting cycling. In the same way, after ending the cycling period, the force should be brought to the offset again, and then unloaded through a low rate ramp up to zero value.

B.4 Stiffness Adapter (Design and Validation)

The Stiffness adapter is the element responsible for suiting the stiffness of the mechanical set up. The design of this part will be mostly depending on the demanded characteristics of the calibration. In a first approach, the adapters can be divided into two groups: one of high stiffness (tubular or cylindrical shafts coupled in line in the load train [1, 2]) and one of low stiffness (sets of bending beams [1, 3]).

For example, to estimate stiffness's of cylindrical specimens, Figure 5 could be helpful. Young’s modulus, the diameter and the unsupported cylindrical length of a specimen are needed to estimate the stiffness. For that purpose, go to the x-axis which is closely related to the Young’s Modulus of specimen’s material. There are different x-axis for different Young’s Modulus. At the appropriate x-axis look for the position of the diameter of the specimen of interest. If you find the position of the diameter, go straight upwards until you reached the length of the unsupported column of your specimen on the y-axis. The blue line closed to the point where your diameter and your unsupported length are intersecting marks roughly the stiffness of your specimen.

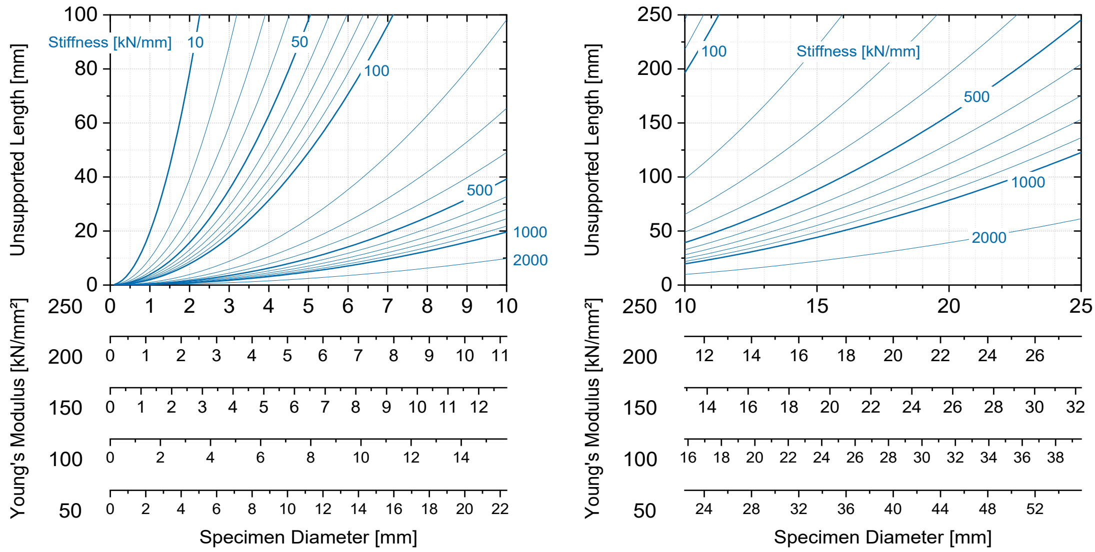
For other types of adapters, different from the shape aforementioned and more complex, the mechanical structures might be designed through some specific mechanical analysis tools (such as FEA).

In all cases, the stiffness of the built structure can be verified through measurements. This can be done during the static calibration of the sensor (see section 3.5) when already coupled to the machine using as reference the measured values of force and displacement recorded by the machine's sensors (cross beam movement, LVDT). For each measured force value F there will be a measured deflection δ and a calculated stiffness S, according to equation A1.

$$S = \frac{F}{\delta} \tag{A1}$$

These stiffness values should not vary too much from point to point. If this happens, check whether there is any kind of mechanical accommodation, looseness, or misalignment. Ultimately, it should be checked whether the stiffness design is adequate.

This stiffness calculation method should be repeated at the end of the last dynamic cycles (before unmounting the setup) and the value should be compared to the one calculated at the beginning.



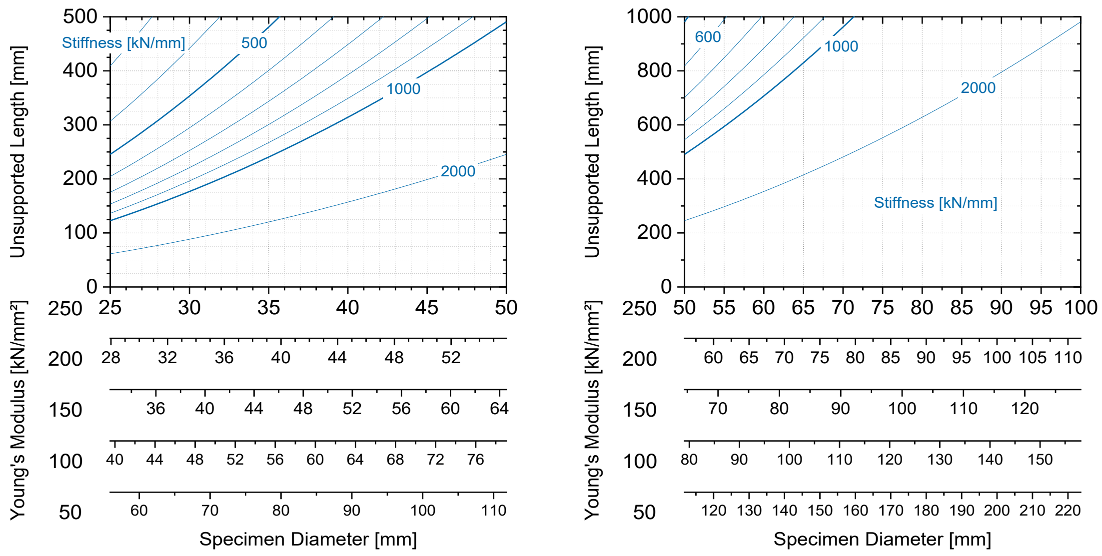


Figure 5: Stiffness as a function of specimen's diameter, unsupported cylindrical length and Young's modulus

B.5 Temperature

When a significant heat transfer on the machine and/or force-proving instrument is suspected, it is recommended to acquire the temperature near the transducer and the machine as well as directly on the machine and on the force-proving instrument as close as possible to the sensing element, e.g. to the strain gauge bridges when using strain gauge transducers. Temperature spots could be introduced due to radiation, e.g. sunlight; conduction, e.g. oil of a servo-hydraulic machine; convection, e.g. stream of air condition or due to a hot-cold gradient air circulation near the machine.

Before collecting the data for calibration, it should be taken care for the temperature fluctuation on the machine which shall be stable within 2 K during the whole calibration (see Figure 6) and that there are no significant temperature gradients across the force proving instrument (see Figure 7).

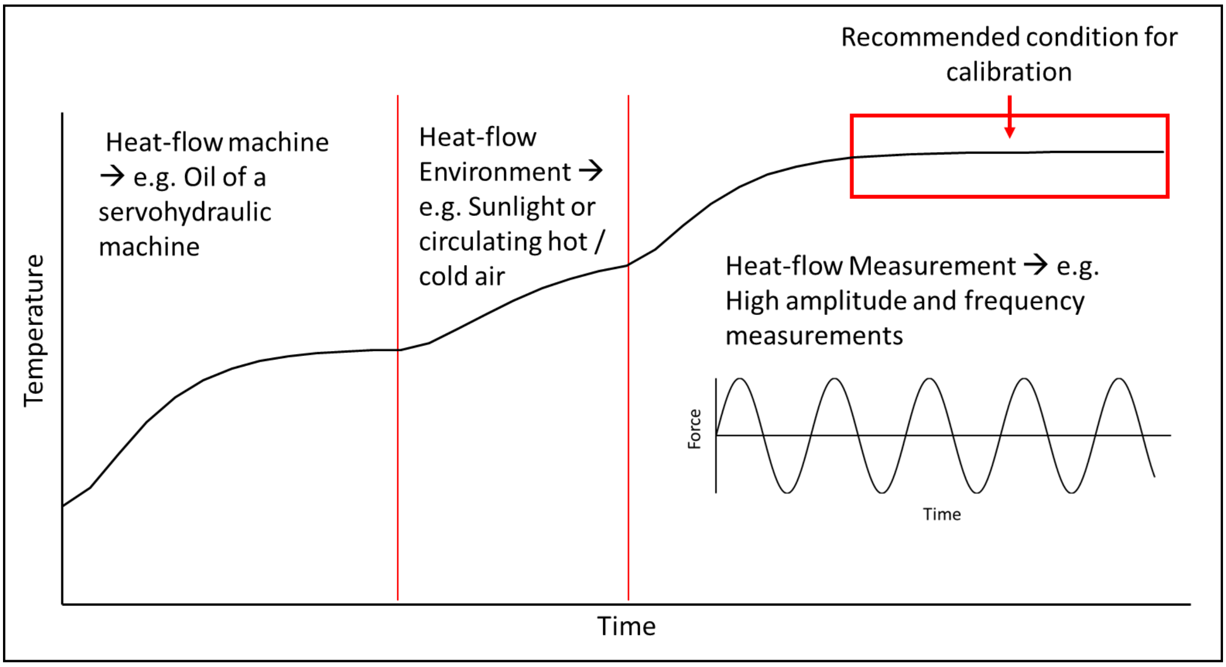


Figure 6: Schematic temperature time profile of a testing machine and /or the force proving instrument during a measurement day

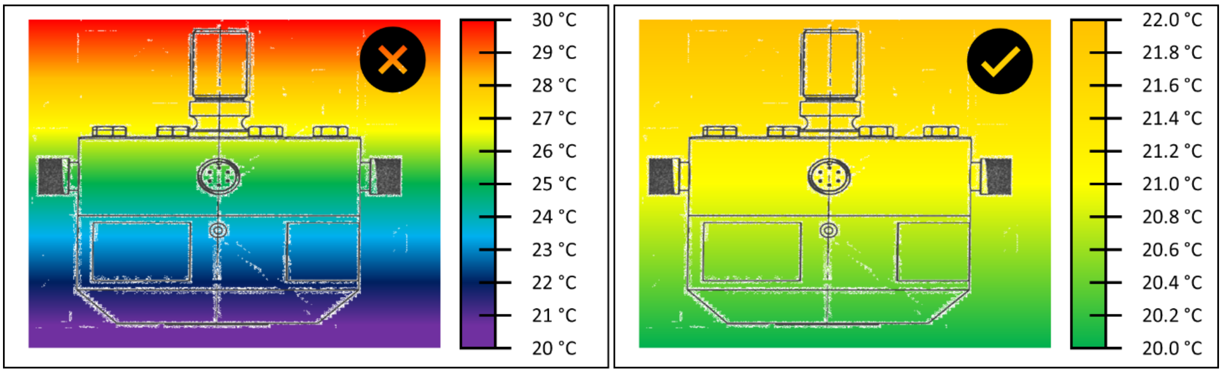


Figure 7 Schematic non-acceptable (left hand side) and acceptable (right hand side) temperature gradient across the force proving instrument

B.6 Non-linear effects

Real measurements show a relevant impact of harmonics which are caused by different sources. Harmonics and non-linearities are interrelated. Sources for those non-linearities can be for example bending, torsion, side forces, deformation and movement of the adaptions, influences of the piston damping, mass and acceleration, machine frame dynamics, modal oscillations, and misalignments.

Non-linearities and harmonics causes, in interactions with other system behaviours as e.g. dithering signal or the control loop, several effects. Effects in compression, tension or both can get weaker and disappear while other effects appear and get stronger with frequency. Therefore, non-linearities should be minimized as far as possible. The recommendation is to apply, additional to force measurements, time series measurements of the displacement and the two-dimensional bending moment. For hydraulic machines these measurements should be done at least at the lowest, the middle and the highest frequency. The time series measurements can be used to generate Lissajous figures of a force signal and the calculated geometric sum of the x and y bending moments. The goal is to reduce the non-symmetric-bludgeon-like or intersecting non-linearities. Examples for those at 0.1 Hz, 45 Hz and 100 Hz are shown in Figure 8.

Beside the regular efforts to reduce side effects, as an alignment procedure and bolting under pre-load, two further approaches are suitable. First reduce the static values for both bending moments as good as possible during the assembling. Second reduce the starting force value,

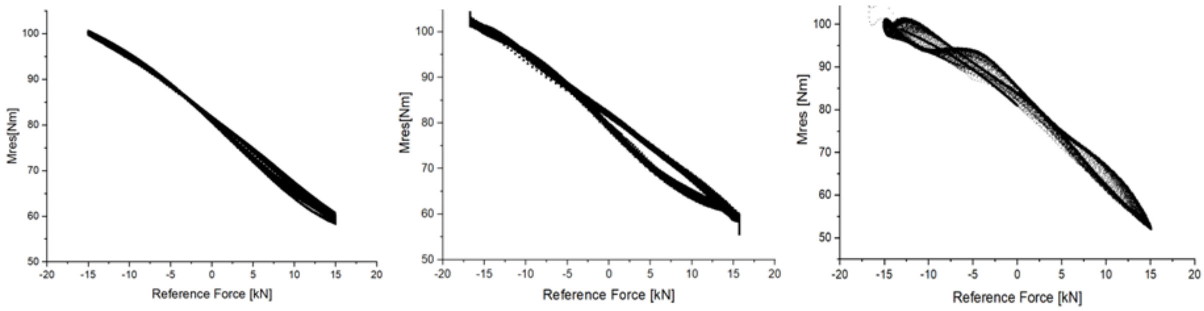


Figure 8: Resulting bending moment over force of the reference force transducer: left hand side at 0.1 Hz; middle at 45 Hz; right hand side at 100 Hz

caused by the pre-load-process, by adjusting the frame height. The starting value of the force and displacement signal should be as close to zero as possible.

A way to distinguish between linear and non-linear effects in a numerical way is to use the difference of the used sinus fit and the original time series data. As the fit is per definition linear the difference must contain all non-linear impacts (see Figure 9).

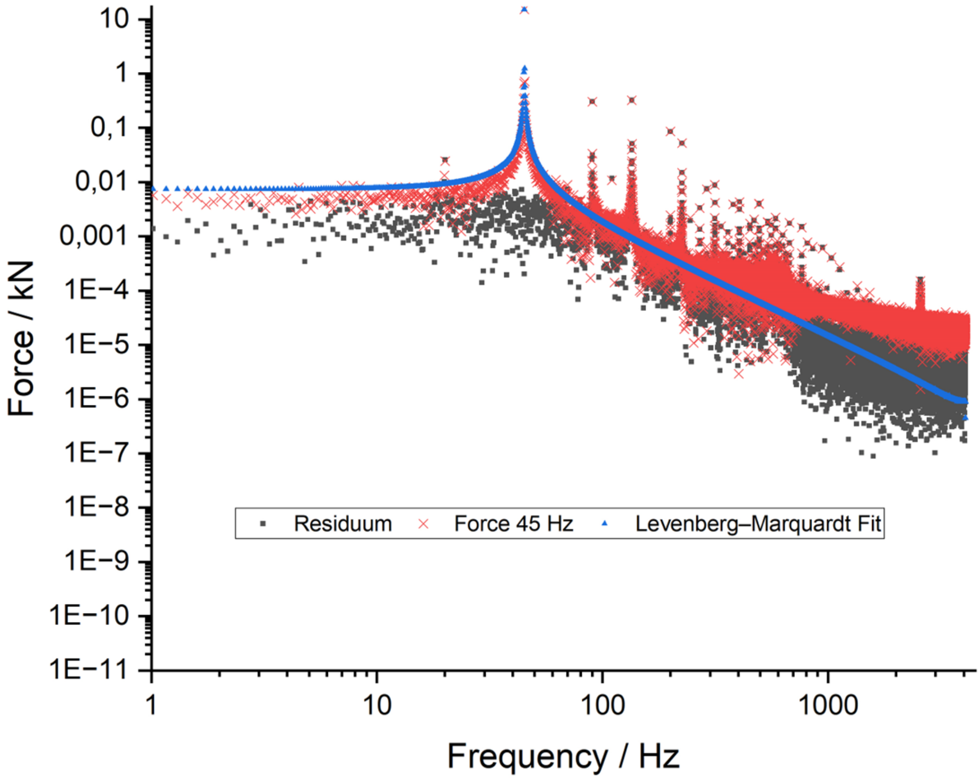


Figure 9: FFT of a control looped force signal at 45 Hz: with original time series data, sine approximation (with Levenberg-Marquardt algorithm) and Residuum

For a hydraulic machine this difference contains all kind of harmonics as the harmonics of the applied force, the dithering signal, other interferences and their intermodulations. The ratio of the maximum amplitude of the fit and the 95 % scattering interval of the difference, also called residuum, is an indicator for the non-linear content of the time series (see Figure 10).

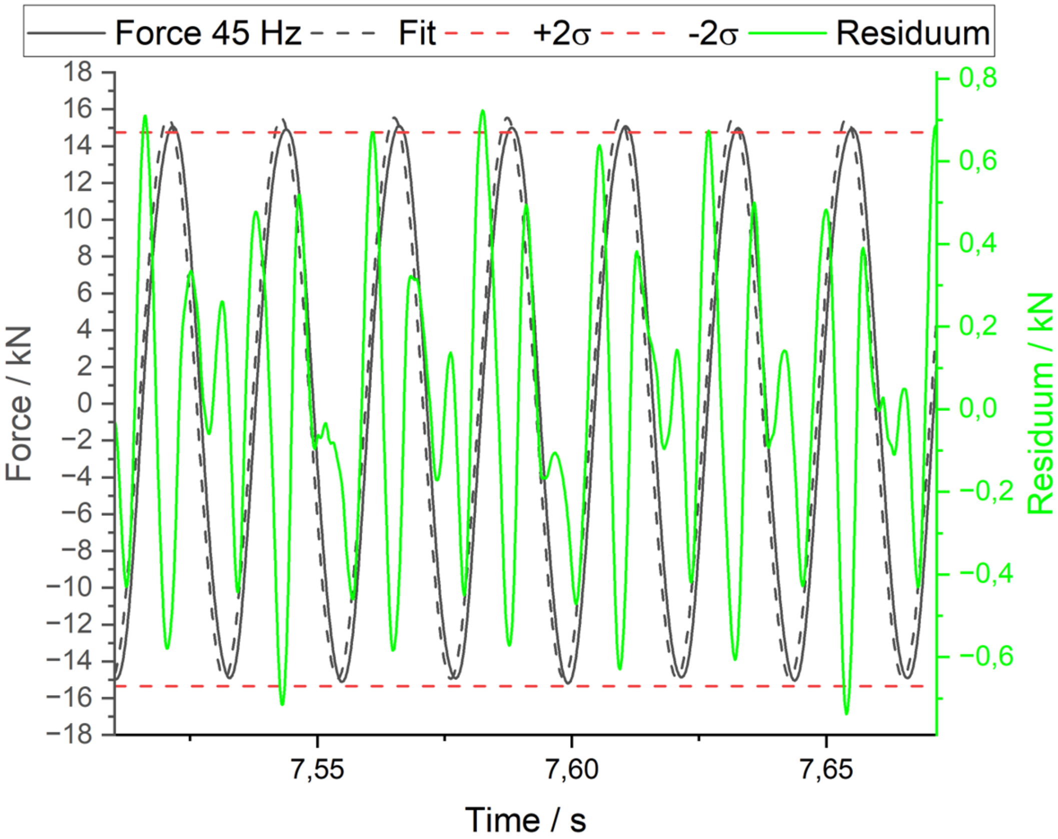


Figure 10 Real time series data, sine approximation, residuum and scattering interval of the residuum of a control looped force signal at 45 Hz

The residuum contains harmonics from all possible sources of non-linearities. The scattering interval is a better choice for the residuum as just the maximum value because that residuum usually contain high discrete-local deviations respectively spikes. As the scattering level delivers two thresholds the indicator can be defined separately for tension and compression.

Nevertheless, if the goal is e.g. to ensure that the bending moment does not impact the control looped force signal by more than 5 % the indicator could be used to ensure that the whole non-linear content is below 5 %. As the non-linear content rises with frequency this approach might only work till a specific frequency. If the threshold is exceeded at a frequency the above-mentioned procedure can be applied to reduce those non-linear impacts.

C Certificate

C.1 Contents

The certificate must contain the following information:

a) Identification of the testing machine: (manufacturer, type, year of manufacture if known, serial number) and, if applicable, specific identification of the force indicator (manufacturer, type, serial number);

b) the class of each range calibrated according to ISO 7500-1;

c) Machine parameters: Mode of periodic force, Machine compensation method and its parameters, force range, frequency range, stiffness range;

d) Calibration parameters (for each set): force amplitude, mode of calibration (tension, compression, tension/compression), mean force, frequency, , compensation method and its values, mounting parts (with mass value identified if necessary);

e) Transfer standard arrangement: type, class and reference number of the force-proving instrument used, calibration certificate number, indicator, stiffness adapter used and expiration date of the certificate;

f) Inertial Forces: information about additional masses, mounting parts (with mass value identified if necessary), accelerometers, indicator

g) the calibration temperature;

Results of verification

h) Dataset for Waves and Peak-Valleys (graphics are recommended)

i) Fitting curve analysis: Parameters of the fitting curve, Phase analysis, force spans differences;

j) Peak-to-peak analysis: Differences between peaks; Differences between valleys;

k) any anomaly found during the general inspection;

l) Portion measured of the inertia forces (additional masses and acceleration);

m) Uncertainty evaluation

C.2 Example Certificate

The following pages showing an example of the calibration certificate structure.

Certificate of Dynamic Calibration of a Material Testing System

Object:			
Manufacturer:			
Type:			
Serial No.:			
Customer:			
Number of pages:			
Reference No.:			
Calibration mark:			
Location of calibration:			
Date of Calibration:			
Date of Certificate			
On behalf of	Institute and Seal	Head of calibration lab.	Person in charge

Page 2 of calibration certificate of DATE, calibration mark: 123 456 789

Calibration procedure DKD-R 9-4

Calibration parameters

Parameter	**Value**		**Parameter Set A**	**Parameter Set B**
Mode of periodic force				
Compensation method provided by machine's software				
Numeric value used with the compensation method				
Parameter	**Min. Value**	**Max. Value**	**-**	**-**
Force amplitude [kN]				
Mean force [kN]				
Frequency [s^{-1}]				
Mounting equipment's uncompensated masses [kg]				
Specimen's uncompensated masses [kg]				
Stiffness [$kN \cdot mm^{-1}$]				
Temperature [°C]				

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Calibration arrangement

		Parameter set A		Parameter Set B	
		Machine	Transfer Standard	Machine	Transfer Standard
Force transducer	Type				
	Serial				
	Manufacturer				
	Cable length				
Force Indicator	Type				
	Serial				
	Manufacturer				
	Measuring range				
	Measuring channel				
	Sampling Rate				
	Filter				
	Excitation voltage				
Stiffness Adapter	Type	-		-	
	Serial	-		-	
	Manufacturer	-		-	
	Stiffness	-		-	
Additional Mass	Type	-		-	
	Serial	-		-	
	Manufacturer	-		-	
	Mass	-		-	
Accelerometer	Type	-		-	
	Serial	-		-	
	Manufacturer	-		-	
	Cable length	-		-	
Accel. Indicator	Type	-		-	
	Serial	-		-	
	Manufacturer	-		-	
	Measuring range	-		-	
	Measuring channel	-		-	
	Sampling Rate	-		-	
	Filter	-		-	
	Excitation	-		-	

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Measurement Results

Parameter Set A

Dataset "Wave" (Table length depends on number of measured values)

	Machine		Transfer Standard						
Runtime	Force	Displacement	Force	Bending 1	Bending 2	Bending 3	Bending 4	Acceleration of additional mass	Temperature
Series 1									
Series 2									
Series 3									

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Measurement Results

Parameter Set A
Dataset "Peak-Valley" (Table length depends on number of measured values)

	Machine				Transfer Standard													
Runtime	Force		Displacement		Force		Bending 1		Bending 2		Bending 3		Bending 4		Acceleration of additional mass		Temperature	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max
Series 1																		
Series 2																		
Series 3																		

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Evaluation

Parameter Set A

Parameters of the sine fit $FF_i(t) = u_i + b_i \cdot \sin(2\pi \cdot f_i \cdot t + p_i)$

Parameter	Machine			Transfer Standard		
	Series 1	Series 2	Series 3	Series 1	Series 2	Series 3
Mean force u_i						
Force amplitude b_i						
Frequency f_i						
Phase p_i						
$\Delta f = f_M - f_S$						
$\Delta p = p_M - p_S$						

Differences between forces of fit function and measurement $\Delta F_i(t) = FF_i(t) - F_i(t)$

Runtime	Cycle	Machine	Transfer Standard
Series 1			
Series 2			
Series 3			

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Evaluation

Parameter Set A

Force span by in-situ peak-valley detected min. and max. forces

$$FSV_i(c) = F_{\max,i}(c) - F_{\min,i}(c)$$

Difference of forces spans of the in-situ peak-valley detected min. and max. forces and the force span calculated by amplitude of the fit function

$$\Delta FSVF_i(c) = FSV_i(c) - 2b_i$$

differences of the force spans of machine and transfer standard

$$\Delta FSMS(c) = FSV_{\mathrm{M}}(c) - FSV_{\mathrm{S}}(c)$$

relative differences of the force spans of machine and transfer standard

$$\Delta FSMS(c)_{\mathrm{rel}} = \frac{\Delta FSMS(c)}{FSV_{\mathrm{S}}(c)} \cdot 100$$

Differences between the min. forces of Machine and Transfer Standard

$$\Delta F_{\min}(c) = F_{\min,\mathrm{M}}(c) - F_{\min,\mathrm{S}}(c)$$

$$\Delta F_{\max}(c) = F_{\max,\mathrm{M}}(c) - F_{\max,\mathrm{S}}(c)$$

Differences between the max. forces of Machine and Transfer Standard

Runtime	Cycle	FSV		ΔFSVF		ΔFSMS				ΔFmin	ΔFmax
		Machine	Transfer Standard	Machine	Transfer Standard	Machine		Transfer Standard			
		N	N	N	N	N	[%]	N	[%]	N	N
Series 1											
Series 2											
Series 3											

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Evaluation

Parameter Set A

Forces caused by uncompensated, additional masses FMAD

$$FMAD = m_{add} \cdot a_{madd}$$

Runtime	Cycle	Force due to uncompensated masses
Series 1		
Series 2		
Series 3		

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Evaluation

Parameter Set A

Span of force due to additional masses FSMAD(c) = FMADmax(c) – FMADmin(c)

Runtime	Cycle	Force due to uncompensated masses		FSMAD(c)
		min	max	
Series 1				
Series 2				
Series 3				

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Evaluation

Parameter Set A

Span of force due to additional masses FSMAD(c) = FMADma(c) – FMADmin(c)

		Series 1	Series 2	Series 3
Mean of span of force due to additional masses	$FSMAD_{mean} = \frac{\sum_{i=1}^{N_c} FSMAD_i(c)}{N_c}$			
Mean of differences of the force spans of machine	$\Delta FSMS_{mean} = \frac{\sum_{i=1}^{N_c} \Delta FSMS_i(c)}{N_c}$			
Difference of mean force spans of forces due to additional masses and the mean difference between spans of machine and transfer standard	$\Delta MFS = FSMAD_{mean} - \Delta FSMS_{mean}$			

Uncertainty

Parameter Set A

Transfer Standard		Machine	
$w(F_S)$		$w(F_M)$	
$w_{S,use}$		$w_{M,ctr}$	
$w_{S,amp}$			

Parasitic Components	
$w(a_{m_{add}})$	
$w(m_{add})$	
$w(FMAD)$	

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Measurement Results

Parameter Set B

Dataset "Wave" (Table length depends on number of measured values)

	Machine		Transfer Standard						
Runtime	Force	Displacement	Force	Bending 1	Bending 2	Bending 3	Bending 4	Acceleration of additional mass	Temperature
Series 1									
Series 2									
Series 3									

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Measurement Results

Parameter Set B

Dataset "Peak-Valley" (Table length depends on number of measured values)

	Machine				Transfer Standard															
Runtime	Force		Displacement		Force		Bending 1		Bending 2		Bending 3		Bending 4		Acceleration of additional mass		Temperature	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max
Series 1																				
Series 2																				
Series 3																				

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Evaluation

Parameter Set B

Parameters of the sine fit $FF_i(t) = u_i + b_i \cdot \sin(2\pi \cdot f_i \cdot t + p_i)$

Parameter	Machine			Transfer Standard		
	Series 1	Series 2	Series 3	Series 1	Series 2	Series 3
Mean force u_i						
Force amplitude b_i						
Frequency f_i						
Phase p_i						
$\Delta f = f_M - f_S$						
$\Delta p = p_M - p_S$						

Differences between forces of fit function and measurement $\Delta F_i(t) = FF_i(t) - F_i(t)$

Runtime	Cycle	Machine	Transfer Standard
Series 1			
Series 2			
Series 3			

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Evaluation

Parameter Set B

Force span by in-situ peak-valley detected min. and max. forces

$$FSV_i(c) = F_{\mathrm{max},i}(c) - F_{\mathrm{min},i}(c)$$

Difference of forces spans of the in-situ peak-valley detected min. and max. forces and the force span calculated by amplitude of the fit function

$$\Delta FSVF_i(c) = FSV_i(c) - 2b_i$$

differences of the force spans of machine and transfer standard

$$\Delta FSMS(c) = FSV_{\mathrm{M}}(c) - FSV_{\mathrm{S}}(c)$$

relative differences of the force spans of machine and transfer standard

$$\Delta FSMS(c)_{\mathrm{rel}} = \frac{\Delta FSMS(c)}{FSV_{\mathrm{S}}(c)} \cdot 100$$

Differences between the min. forces of Machine and Transfer Standard

$$\Delta F_{\mathrm{min}}(c) = F_{\mathrm{min,M}}(c) - F_{\mathrm{min,S}}(c)$$

Differences between the max. forces of Machine and Transfer Standard

$$\Delta F_{\mathrm{max}}(c) = F_{\mathrm{max,M}}(c) - F_{\mathrm{max,S}}(c)$$

Runtime	Cycle	FSV		ΔFSVF		ΔFSMS				ΔFmin	ΔFmax
		Machine	Transfer Standard	Machine	Transfer Standard	Machine		Transfer Standard			
		N	N	N	N	N	[%]	N	[%]	N	N
Series 1											
Series 2											
Series 3											

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Evaluation

Parameter Set B

Forces caused by uncompensated, additional masses FMAD

$$FMAD = m_{add} \cdot a_{madd}$$

Runtime	Cycle	Force due to uncompensated masses
Series 1		
Series 2		
Series 3		

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Evaluation

Parameter Set B

Span of force due to additional masses FSMAD(c) = FMADmax(c) – FMADmin(c)

Runtime	Cycle	Force due to uncompensated masses		FSMAD(c)
		min	max	
Series 1				
Series 2				
Series 3				

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Evaluation

Parameter Set B

Span of force due to additional masses FSMAD(c) = FMADma(c) – FMADmin(c)

		Series 1	Series 2	Series 3
Mean of span of force due to additional masses	$FSMAD_{mean} = \frac{\sum_{i=1}^{N_c} FSMAD_i(c)}{N_c}$			
Mean of differences of the force spans of machine	$\Delta FSMS_{mean} = \frac{\sum_{i=1}^{N_c} \Delta FSMS_i(c)}{N_c}$			
Difference of mean force spans of forces due to additional masses and the mean difference between spans of machine and transfer standard	$\Delta MFS = FSMAD_{\mathrm{mean}} - \Delta FSMS_{\mathrm{mean}}$			

Uncertainty

Parameter Set A

Transfer Standard		Machine	
$w(F_S)$		$w(F_{\mathrm{M}})$	
$w_{\mathrm{S,use}}$		$w_{\mathrm{M,ctr}}$	
$w_{\mathrm{S,amp}}$			

Parasitic Components	
$w(a_{m_{\mathrm{add}}})$	
$w(m_{\mathrm{add}})$	
$w(FMAD)$	

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