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Guideline DKD-R 3-10 Sheet 1

Dynamic calibration of uniaxial force measuring devices and testing machines (basic principles)

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Deutscher Kalibrierdienst (DKD)

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

This body is called *Deutscher Kalibrierdienst* (DKD – *German Calibration Service*) and is under the direction of the PTB. The guidelines and guides elaborated by the 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 monitored by the DAkkS as legal successor of the DKD. They carry out calibrations of measuring devices and measuring standards for the measured values 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 was drawn up by the Technical Committees *Force and Acceleration* and *Materials Testing Machines* and approved by the Board of the DKD.

Table of contents

1 Introduction

1.1 Definition of dynamic forces

A dynamic force is the product of mass and acceleration, with the mass or acceleration being temporally variable. The calibration of dynamic forces makes it possible to determine the frequency-dependent properties of the force measuring application.

1.2 Purpose and scope of application

This guideline seeks to sustain the efforts to trace back applications with dynamic forces that are frequently used in industry to national standards. This document and its supplements only consider uniaxial loads. Due to their frequency-dependent contributions, parasitic forces and parasitic moments play an important role in dynamic force measurement; however, the scientific and technical prerequisites for multiaxial dynamic force calibrations do not yet exist.

This guideline is to be understood as a supplement to other standards and guidelines. The multitude of dynamic force applications calls for a large number of specific standards and guidelines for calibration, most of which are still to be elaborated in the future. This guideline is intended to assist the elaboration of future standards and guidelines.

The scope of application has been kept deliberately wide by referring to force measuring devices as well as materials testing machines. Accordingly, the guideline should also be applied, for example, for temporary test benches commonly used in many branches of industry for assembly inspection or in crash measurement technology.

This guideline does by no means compromise the validity of existing calibration instructions and the necessity of their implementation. Even in case of a dynamic calibration, force measuring devices and materials testing machines should also be statically calibrated (e.g. ISO 376 or ISO 7500) to prove their metrological traceability.

1.3 Rules for the calibration of force measuring devices

Figure 1 lists the existing regulations for the calibration of force measuring devices as well as the calibration procedures for the dynamic calibration to be newly described, such as periodic methods, step or shock methods. If a dynamic calibration is desired, it must be additionally backed up by a static calibration with a significantly lower measurement uncertainty.

The main differences between the calibration methods shown in Figure 1 are described below.

Calibration of force measuring devices

Static

- DIN EN ISO 376: Calibration of force-proving instruments used for the verification of uniaxial testing machines
- DKD-R 3-3: Calibration of force measuring devices

Continuous

- DKD-R 3-9: Continuous calibration of force transducers according to the comparison method

Dynamic

- *Periodic methods*
- *Step methods*
- *Shock methods*

Figure 1: Existing regulations for the calibration of force measuring devices. Corresponding regulations are to be developed for the applications shown in italics.

1.3.1 Static calibration according to DIN EN ISO 376

DIN EN ISO 376 [1] describes the static calibration of force measuring devices as required for the static calibration of materials testing machines. Table 1 shows the schematic calibration sequence. The duration of calibration for each measurement series with increasing and decreasing measurement values takes about ten minutes. At least eight measuring points are required per measurement series and the calibration is carried out in three different mounting positions. In the first mounting position, two rising measurement series are run; in the second and third mounting position, one rising and one falling measurement series is run.

1.3.2 Static calibration according to DKD-R 3-3

DKD-R 3-3 [2] also deals with the static calibration of force measuring devices – however, these devices may then not be used for the calibration of materials testing machines. This is a simplified procedure which leads to a higher measurement uncertainty. Depending on the calibration sequence, fewer measuring points per measurement series (up to at least three measuring points) are approached, if necessary only one mounting position is used and, if necessary, fewer measurement series or no downward measurement series are run. Table 1 shows a schematic calibration sequence of a measurement series with increasing and decreasing measurement values. This usually takes about three minutes.

1.3.3 Continuous calibration according to DKD-R 3-9

In the guideline DKD-R 3-9 [3] the continuous calibration process is understood as a continuous change of the measurement quantity, e.g. with a ramp-shaped time behaviour. However, the sequence is to be regarded as quasi-static (in contrast to the dynamic load with, for example, a sinusoidal or shock-shaped course of time). The duration of the load time from zero to the highest value of the calibration range is assumed to be at least one minute. Table 1 shows a schematic calibration sequence of a measurement series with increasing and decreasing measurement values.

1.3.4 Dynamic calibration according to this guideline

This guideline deals with the dynamic calibration of force measuring devices. Here, significantly greater measurement uncertainties are to be expected. To additionally secure the calibration, it is recommended to carry out a static calibration according to DIN EN ISO 376 in addition to the dynamic calibration. The dynamic force excitation can be carried out periodically (e.g. sinusoidally), with a step or shock-shaped excitation. Table 1 schematically shows a sinusoidal force amplitude which must be kept constant over a certain period of time

For the selection and evaluation of dynamically used force transducers, knowledge of the basic resonance frequency is usually the first step. As relevant parameter for dynamics, the basic resonance frequency is accordingly mentioned in the guideline VDI/VDE 2638 [4] on characteristics of force transducers. Additional indications for the dynamic suitability of a force transducer are provided by data on stiffness and mass.

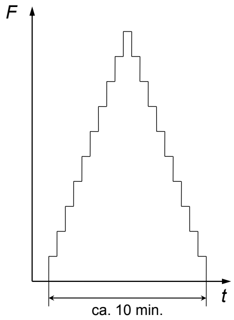
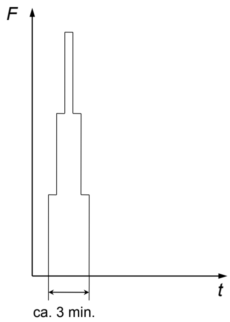
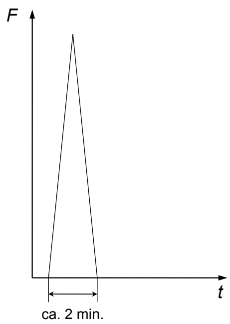
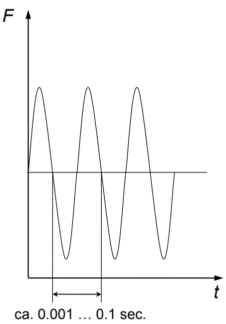
Procedure	**Schematic sequence of the calibration**	**Expected measurement uncertainty**
DIN EN ISO 376	 	Class 1: > 0.12 % Class 0.5: > 0.06 % Class 00: > 0.01 %
DKD-R 3-3	 	~ 0.1 % to ~1 %
DKD-R 3-9	 	> 0.1 % to >1 %
Dynamic calibration	 	Approx. > 1 %

Table 1: Schematic calibration procedures for the calibration of force measuring devices according to the various methods

1.4 Regulations for the calibration of materials testing machines

Figure 2 lists the existing regulations for the calibration of tensile and compression testing machines as well as the calibration procedures for dynamic calibration to be newly described, e.g. periodic methods, step or shock methods. If a dynamic calibration is desired, it is necessary to additionally support this by a static calibration with a significantly lower measurement uncertainty.

Calibration of materials testing machines

Static

- DIN EN ISO 7500-1: Calibration and verification of static uniaxial testing machines. Part 1: Tension/compression testing machines. Calibration and verification of the force-measuring system

Continuous

- Currently not provided.

Dynamic

- *Periodic methods*
- *Step methods*
- *Shock methods*

Figure 2: Existing regulations for the calibration of materials testing machines. Appropriate regulations must be developed for the applications shown in italics.

1.4.1 Static calibration according to DIN EN ISO 7500-1

The static calibration of tensile and compression testing machines is carried out according to DIN EN ISO 7500-1 [5]. The schematic calibration procedure is shown in Table 2. The calibration is usually carried out at the measuring points 10 %, 20 %, 40 %, 60 %, 80 % and 100 %. If finer graduations are required, the measurement series is supplemented by additional measuring points, for example 0.1 %, 0.2 %, 0.4 %, 0.7 %, 1 %, 2 %, 4 % and 7 %. Usually, the time frame for a rising and falling measurement series is approximately five minutes. For the start-up of the respective force step, either the force value must be kept constant for several seconds or, if this is not possible, it is also permitted to run the calibration with a slowly increasing force in the desired measuring point.

1.4.2 Dynamic calibration according to this guideline

This guideline addresses the dynamic calibration of materials testing machines. Here, significantly greater measurement uncertainties are to be expected than in static calibration. To additionally secure the calibration, it is necessary to carry out a static calibration according to DIN EN ISO 7500-1, complementary to the dynamic calibration. Table 2 schematically shows a sinusoidal force amplitude which must be kept constant over a certain period of time.

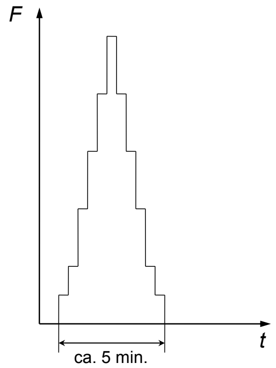
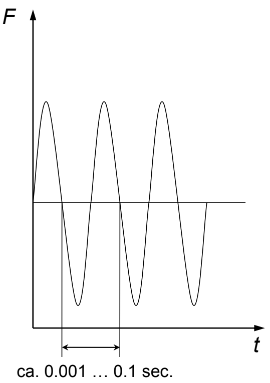
Procedure	**Schematic sequence of the calibration**	**Expected measurement uncertainty**
DIN EN ISO 7500-1		Class 1: 0.24 % Class 0.5: 0.12 %
Dynamic calibration		Approx. > 2 %

Table 2: Schematic calibration procedures for the calibration of materials testing machines according to the different procedures

2 Terms, definitions

The following table is of informative character and lists terms and definitions taken from current standards and guidelines. This list is not intended to be exhaustive.

Table 3: Terms and definitions

Term	Reference	Definition
Amplitude	*ASTM E467*	*One-half the peak-to-peak measurement of the cyclic waveform*
Indicated force *Indicated force* F_i	*ASTM E467* *ISO 4965-01*	*The force value provided by the force transducer or the dynamometer's readout (for example, a numeric or graphical output for reading by a human including a peak picking capability); these values are typically obtained from a digital voltmeter (DVM), or files generated by a computerized data acquisition* *Force measured and indicated by the dynamic testing system's statically calibrated load cell under both static and dynamic conditions*
Dynamic indicated forces *Indicated force* F_i	*ASTM E467* *ISO 4965-01*	*The maximum and minimum forces reported by the test machine during a portion of a dynamic test. These values are typically obtained using an oscilloscope, peak-valley meter, or files generated by computerized data acquisition.* *Force measured and indicated by the dynamic testing system's statically calibrated load cell under both static and dynamic conditions*
Display deviation *Indication error* e_i	-- *ISO 4965-01*	*Relative accuracy error of the indicated dynamic force of the testing machine* *Difference in the force ranges indicated by the testing system and the dynamic calibration device (DCD), expressed as a percentage of the DCD force range*
Transducer	*ASTM E467*	*A measuring device which has an output signal proportional to the engineering quantity being measured*
Cal factor *Correction factor* C	*ASTM E467* *ISO 4965-01*	*The conversion factor between the dynamometer force and the indicated force* *Ratio between the dynamic force range determined by a DCD* (ΔF_{DCD}) *and the dynamic force range indicated by the testing system* (ΔF_i)*, at the same testing frequency*
Conversion function	*BS 7935-1*	*Ratio between the dynamic force range determined by a replica test-piece and the dynamic force range indicated by a given testing system, at a given frequency*
Data acquisition equipment	*ASTM E467*	*The equipment used to convert a conditioned force to an indicated force*

Term	Reference	Definition
Dynamic errors	*ASTM E467*	*Errors in the force transducer's corrected force output that occur due to dynamic operation (with specimen bending errors intentionally corrected out)*
Indication error e_i	*ISO 4965-01*	*Difference in the force ranges indicated by the testing system and the DCD, expressed as a percentage of the DCD force range*
Dynamic dynamometer forces	*ASTM E467*	*The maximum and minimum forces produced in the dynamometer during a portion of a dynamic test*
Endlevel	*ASTM E467*	*Either a maximum or minimum level for a cyclic waveform*
Dynamometer force	*ASTM E467*	*The force value provided by the dynamometer's readout*
Conditioned force	*ASTM E467*	*The high level voltage or digital data available from the dynamometer or force transducer's signal conditioning instrumentation; it is frequently of value during dynamic verification as it can be more conveniently monitored by stand-alone measurement instrumentation*
Corrected force	*ASTM E467*	*The force obtained after applying a dynamic correction factor to the force transducer's indicated force*
Force command	*ASTM E467*	*The desired force to be applied to the specimen or dynamometer by the testing machine*
Force transducer	*ASTM E467*	*The test machine transducer which indicates the applied force by means of an electrical voltage which can be measured* *Discussion: the electrical voltage typically increases linearly with applied force. The testing system may use this voltage for control.*
Instrumentation	*ASTM E467*	*The electronics used with a transducer providing excitation for the transducer, conditioning of the measured signal, and readout of that signal; typically, the conditioned signal is a voltage and the readout is a numerical display or printout.*
Valley	*ASTM E467*	*The minimum endlevel of a cycle*
Dynamometer	*ASTM E467*	*An elastic calibration device used to indicate the forces applied by a fatigue testing system during dynamic operation. A strain-gauged specimen is often used as the dynamometer. Suitable transducer instrumentation is also required to provide accurate readings over the intended frequency and force range.*
Dynamic calibration device DCD	*ISO 4965-01*	*For method A, a strain-gauged replica test-piece that has the same mass and compliance as the specimens to be tested. For method B, a strain-gauged replica test-piece or proving device, of known compliance*

Term	Reference	Definition
Calibration device	*BS 7935-1+2*	*Replica test-piece or proving device*
Peak	*ASTM E467*	*The maximum endlevel of a cycle*
Span *Dynamic force range* ΔF *Force range*	*ASTM E467* *ISO 4965-1* *BS 7935-1*	*The absolute value of the peak minus the valley for a cyclic waveform* *Difference between the maximum (peak) and minimum (valley) values of force under cyclic conditions* *Difference between the maximum and minimum peak values of force under cyclic conditions*
Fatigue testing system	*ASTM E467*	*A device for applying repeated force cycles to a specimen or component, which applies repeated force cycles of the same span, frequency, wave shape, mean level, and end levels*
Peak picking	*ASTM E467*	*The process of determining the peak or valley of a cyclic waveform*
True force	*ASTM E467*	*The actual force applied to the specimen or dynamometer*
Repeatibility	*ASTM E467*	*The closeness of agreement among repeated measurements of the dynamic forces under the same conditions*

3 Classification of dynamic forces

3.1 Application of dynamic forces for calibration and test purposes

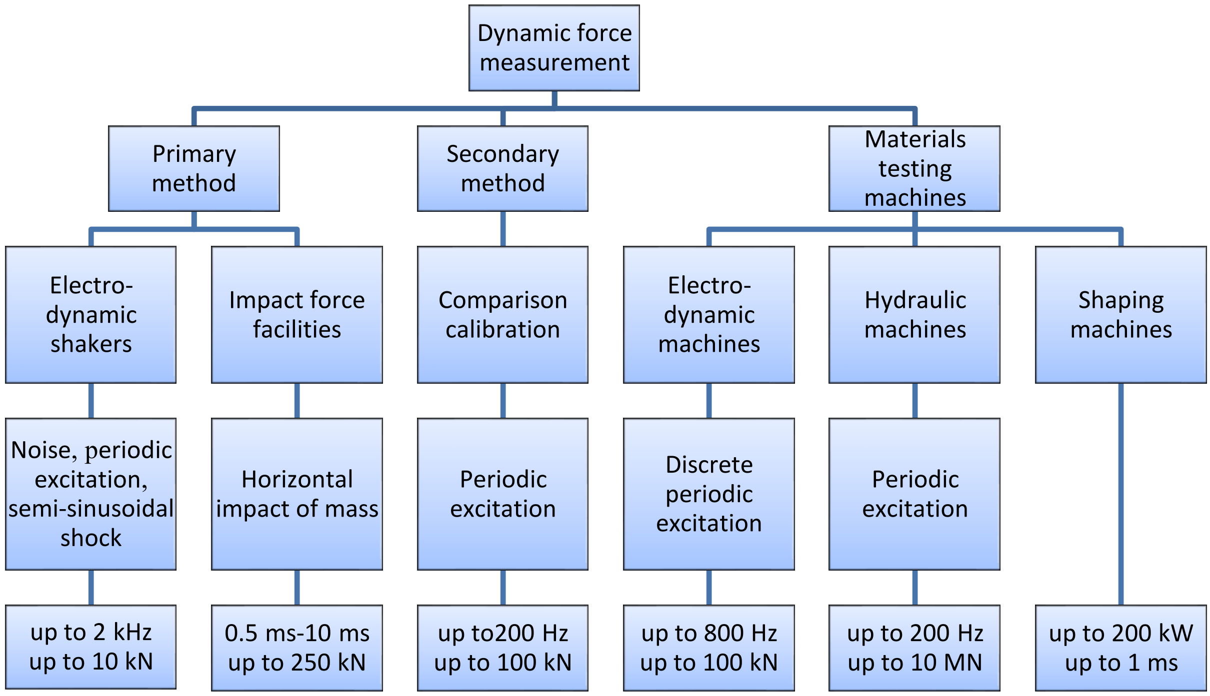
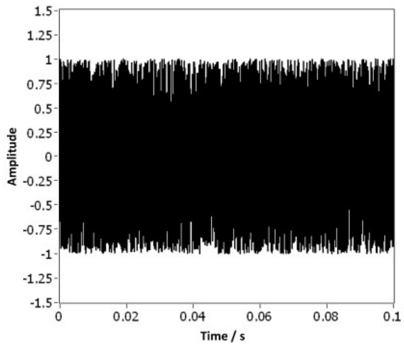
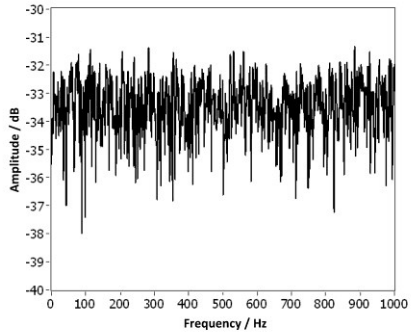
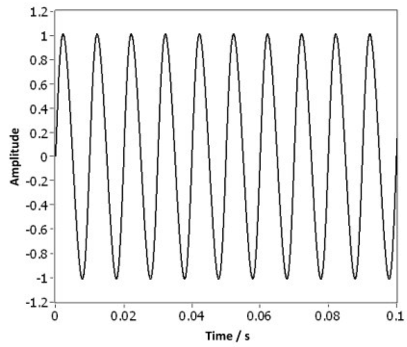
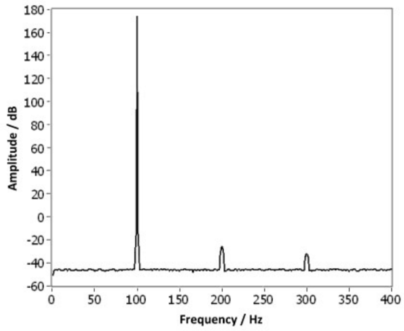
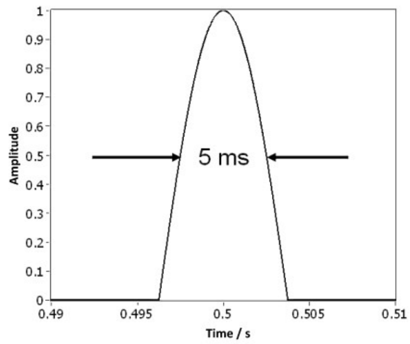
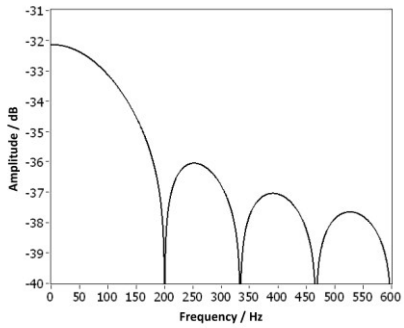
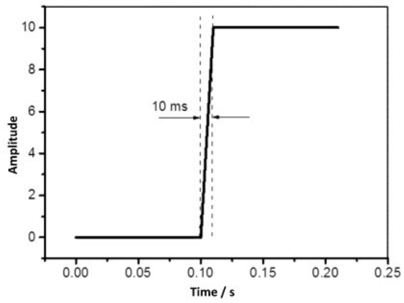
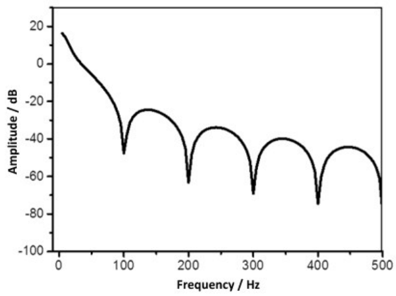


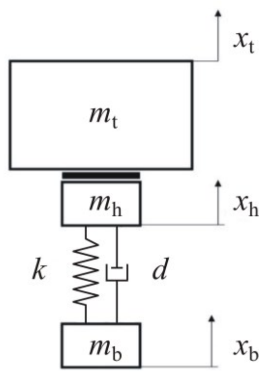
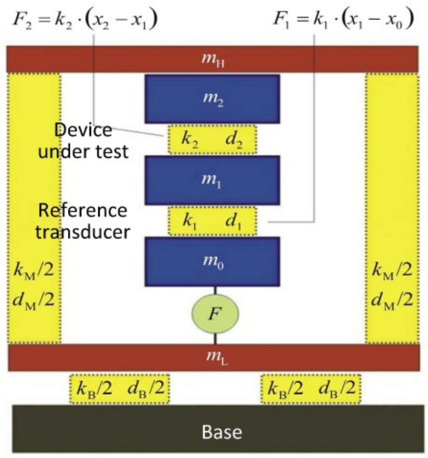
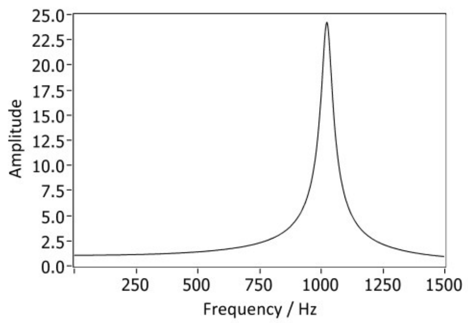
Figure 3: Classification of dynamic force measurement according to the current state of technology

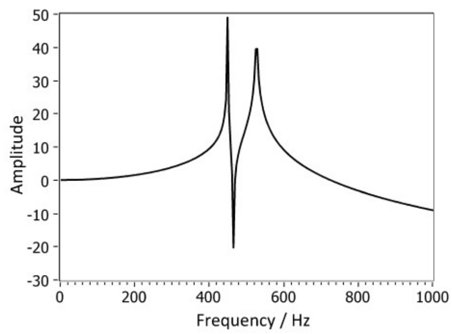
3.2 *Overview of dynamic force excitations (examples)*

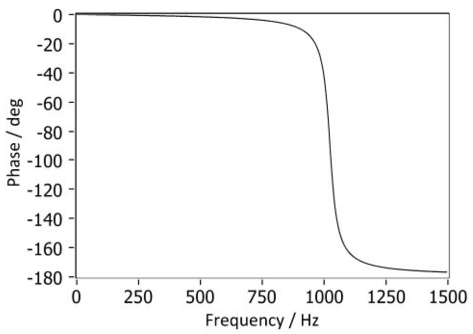
Table 4: Overview of dynamic force excitations

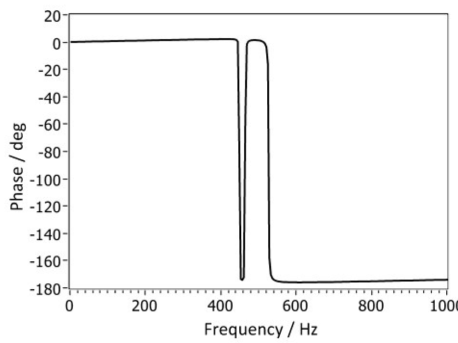
<table>
<tr><th>Type of excitation</th><th>Time domain</th><th>Frequency domain</th></tr>
<tr><td>Noise</td><td>
</td><td>
</td></tr>
<tr><td>Sine</td><td>
</td><td>
</td></tr>
<tr><td>Shock</td><td>
</td><td>
</td></tr>
<tr><td>Step</td><td>
</td><td>
</td></tr>
</table>

3.3 Classification according to primary and secondary method

<table>
<tr><td></td><td>Primary method</td><td>Secondary method</td></tr>
<tr><td></td><td>Traceable force measurement by primary methods
(unilateral force introduction, e.g. sine, shock)</td><td>Traceability by means of a reference force transducer
(clamped, dynamically loaded transducer, (e.g. with reference transducer in materials testing machine))</td></tr>
<tr><td>Model</td><td>
</td><td>
</td></tr>
<tr><td>Amplitude response of the transfer function</td><td>

Ratio of the acceleration amplitudes
$$S_{bt} = \frac{\ddot{x}_b}{\ddot{x}_t}$$</td><td>

Force amplitude of the device under test (damping neglected):
$$F_2 = k_2 \cdot (x_2 - x_1) = F_1 + m_1 \cdot \ddot{x}_1$$</td></tr>
<tr><td>Phase response of the transfer function</td><td>

$$\phi = \varphi(\ddot{x}_b) - \varphi(\ddot{x}_t)$$</td><td>

$$\phi = \varphi(F_2)$$</td></tr>
</table>

4 Technical equipment

4.1 Standards

For dynamic calibration, sinusoidal and pulsed forces have the greatest practical significance. These very different excitations in the time and frequency domain make it possible to cover the variety of dynamic force measurement tasks in a relatively application-oriented manner.

During the sine force calibration, sinusoidal forces act on the force transducer to be calibrated. The amplitudes and phases related to a reference signal are evaluated as dynamic calibration result. During the calibration, sine excitations of different frequencies are performed sequentially to characterize the behaviour of the transducer over the widest possible frequency range.

In shock calibration, force pulses of a defined amplitude, duration and shape act on the force transducer to be calibrated. The ratio of the pulse heights of the output signal and input force is a typical calibration result, but on closer inspection it depends on the duration and shape of the force pulse.

4.1.1 Primary calibration

Especially those methods in which the measuring force is generated in a defined manner by means of accelerated masses are suitable for dynamic primary calibration. According to Newton's second law, the inertial force F of an accelerated mass is calculated from the product of mass and acceleration, $F(t) = m \cdot a(t)$, the mass m being constant and the acceleration a being dependent on the time t. The traceability of the dynamic force therefore requires the determination of the mass value m (by weighing) and the time-dependent acceleration curve $a(t)$ (by means of acceleration sensors). The acceleration measurement can be carried out using optical methods (e. g. by means of laser vibrometers) as well as mechanically contacting sensors.

Methods for the dynamic primary calibration of sinusoidal and shock forces are the subject of current research activities [6], [7] of national metrology institutes such as the PTB. In accordance with the calibration of accelerometers [8], [9], [10], the aim here is to make the measurement results of different methods and measuring devices transferable into each other by means of parametric modelling. The model parameters of the force transducer determined, for example, through calibration by means of regression will make it possible to describe the dynamic measurement behaviour of a force transducer in any application.

4.1.1.1 Sinusoidal load

The basic principle of a method for primary calibration with sinusoidal forces is illustrated in Figure 4. A shaker generates a periodic base displacement of the force transducer to be calibrated which is attached to the shaker armature. The load mass M attached to the top side of the transducer generates an inertia force which represents the desired dynamic input quantity.

Further information on dynamic force calibration with sinusoidal forces can be found in [6], [7], [11], [12].

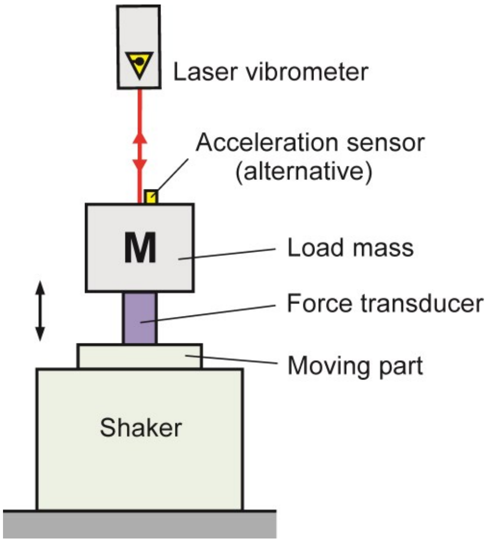


Figure 4: Basic principle of the primary calibration with sinusoidal forces

4.1.1.2 Shock load

The basic principle of a method for primary calibration with shock forces is illustrated in Figure 5. Two mass bodies are brought to collision, with the force transducer to be calibrated mounted between them. The mass body M1, which is accelerated to the desired impact velocity by a linear drive, impacts on the force transducer fastened on mass body M2 which is initially at rest with it. During the impact, the impulse is transmitted to the pushed body and the occurring inertia forces are measured by means of sensors. The traceability of the dynamic force is established by an acceleration measurement, e.g. by means of laser vibrometers or acceleration sensors.

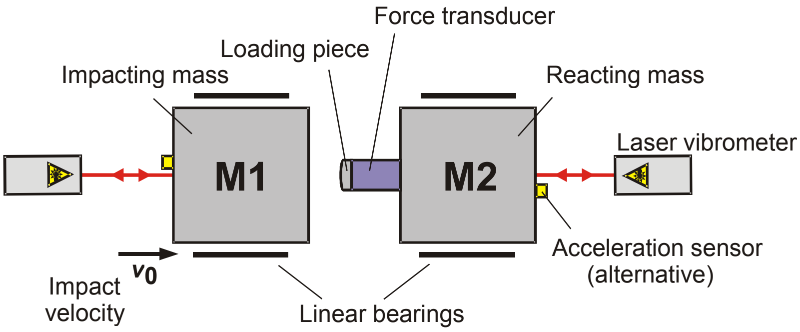


Figure 5: Basic principle of the primary calibration with shock forces

When comparing sinusoidal and shock calibration, it remains to be said that shock methods are very well suited for high force amplitudes which in the case of sinusoidal excitation would require unrealizably large load masses or displacements.

Further information on dynamic force calibration with shock-shaped forces can be found in [6] - [8], [14], [15].

4.1.2 Secondary calibration

In contrast to the primary calibration, the calibration signals are represented by measurements using dynamically and traceably calibrated reference force transducers.

4.1.2.1 Sinusoidal load

In the case of a sine calibration with higher forces and low frequencies, a primary calibration method based on the generation of inertia forces is less suitable since this may require disproportionately large and heavy load masses or the vibration amplitudes would become inadmissibly large. For these requirements it would therefore be better to use a method in which the forces are generated by corresponding elastic deformations in a pre-stressed load frame. The set-up of such a procedure operating according to the comparison procedure is illustrated in Figure 6. The force transducer to be calibrated, a reference force transducer and a shaker are mechanically clamped in series in a load frame. The installation height can be adapted to the respective requirements by means of a vertically adjustable traverse.

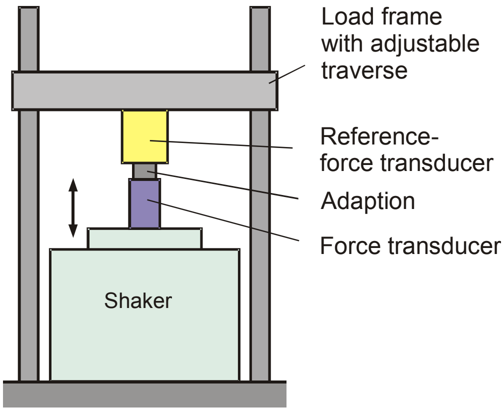


Figure 6: Basic principle of the secondary calibration with sinusoidal forces

4.1.2.2 Shock load

For example, a secondary calibration with impact forces can be performed on impact pendulum devices (see Figure 7). In this case, the force transducer to be calibrated and a reference force transducer are mechanically arranged in row and brought to collision. For example, both transducers can be mounted on the stationary anvil (Figure 7a), or the test specimen and reference force transducer are each mounted on the anvil and the impact pendulum (Figure 7b). Due to the inertia forces of the transducers and attachment parts (load buttons, adapters) generated during impact, different forces generally act on both force transducers. Depending on the mass and stiffness distribution of the components within the force flow, the occurring measurement deviations can become very large, particularly in the case of short force pulses, so that this kind of comparison method would no longer provide a usable calibration.

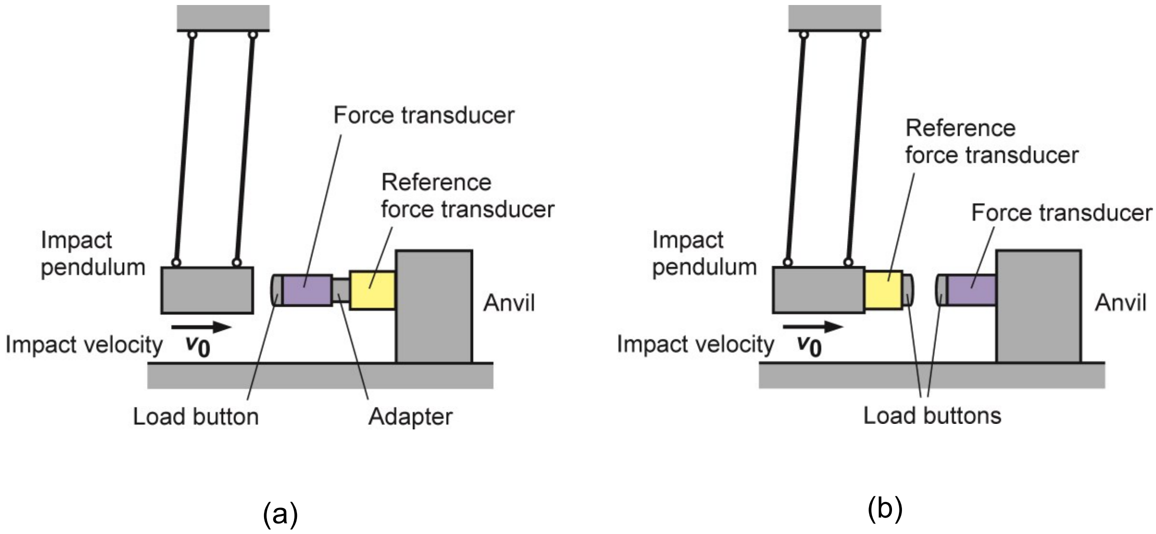


Figure 7: Basic principle of the secondary calibration with shock forces using an impact pendulum, joint fastening of both transducers on the anvil (a), separate fastening to impact pendulum and anvil (b)

4.2 Exciters

4.2.1 Vibration exciters

To generate a sine or multi-sine oscillation, mainly electrodynamic vibration exciters are used in which a (in most cases cylindrical) coil connected to the shaker armature is moving within a magnetic field. The axial guidance of this system is provided by means of air bearings, diaphragm springs or rolling bearings. There is no vibration exciter that is equally suitable for all frequencies, masses and force amplitudes. Among the many types of vibration exciters that have been developed primarily for vibration testing, only a few have gained acceptance for calibration purposes; these have the following features:

1. transverse vibrations or armature resonances as low as possible
2. magnetic field at the coupling surface of the vibrating part as low as possible
3. sufficient force for calibration
4. operation of the vibration exciter preferably without cooling (if possible)
5. preferably vertical direction of the vibration

As to the installation of the vibration exciters, the following requirements apply:

1. preferably vibration isolation of the vibration exciter from the installation site by means of insulators
2. low tuning of the insulators: the highest natural frequency of the vibration-isolated system (vibration exciter, calibration set-up with calibration item) must be much smaller than the lowest exciter frequency.
3. the displacement practically limits the force amplitude at low frequencies, so that the following applies for most vibration exciters: the lower frequency at which the full force amplitude of the exciter is available, is much greater than the highest natural frequency of the vibration-isolated system.

There is no vibration exciter whose moving part moves exclusively in the axial direction (z-direction). Depending on the design of the vibration exciter, tilting and/or rocking movements of the moving part occur depending on frequency and load; these movements generate transverse components of the force transversally to the nominal vibration direction (x-, y-direction).

Parasitic signal components are generated due to the cross-directional sensitivity of an acceleration standard working with seismic mass and the cross-directional sensitivity of the device under test. With such calibration set-ups, calibrations can only be performed with increased measurement uncertainty.

In primary calibrations with laser vibrometers, this effect is reduced because a laser vibrometer has no transverse direction sensitivity.

4.2.2 *Shock exciters*

In the case of shock excitation, the following conditions apply:

1. the hammer-anvil principle generates shocks,
2. the impact must be linear,
3. the force shunt caused by the bearing must be negligible.

4.2.2.1 *Shock device with linearly guided impact mass*

The impact mass accelerated by a drive can hit either a freely mounted target (see Figure 5) or a fixed-mounted target (hammer-anvil principle, similar to Figure 7). A free, low-friction and linear guidance of the impact mass can be achieved by using air bearings. The acceleration of the impacting mass body is achieved by means of a suitable drive. Possible drive mechanisms are:

1. spring drive
2. hydraulic drive
3. electrodynamic drive
4. impact pendulum

4.2.2.2 *Impact pendulum, e.g. with multifilar suspension*

The displacement and release of the pendulum can be realized through various mechanisms. The impact can be applied to a fixed target (hammer-anvil principle, as in Figure 7) or, if designed as a double pendulum, to a freely mounted target.

4.2.2.3 *Drop weight shock device*

To generate the impact, this device uses a drop mass that falls vertically in the gravity field (hammer-anvil principle). One way of doing this is to use spheres which are dropped from a predetermined height. If necessary, an air bearing can be used for the vertical guidance of the falling mass. In the case of magnetic drop masses, electromagnets can be used to lift and release the falling mass.

4.2.2.4 *Electrodynamic and electrohydraulic shock exciters*

The calibration set-up for shock excitation is analogous to Figure 4 (primary calibration) or Figure 6 (secondary calibration).

The shock excitations with seismic force generation of the primary calibration (see Figure 4) allow only comparatively small shock forces compared to shock devices that use impacting mass bodies.

4.3 Force transducers

4.3.1 Components of the force measuring chain – calibration item

The complete force measuring chain consists of a force transducer, a signal conditioner (e.g. amplifier) and an output device (e.g. display device, software). Any combinations in the arrangement of force transducer, amplifier, indicator, housed in one unit, are possible. In the case of force gauges with digital output, the measurement value can also be transferred to a data terminal – printer, recording device or computer – via a standardized interface, instead of being indicated on the device display. The display of measured values during calibration is recommended. It must be ensured that the read-in data are unambiguously interpreted and processed.

If the calibration item does only consist of the force transducer, a measuring chain with dynamically and traceably calibrated amplifiers and indicating devices must be put together. Among other things, this entails differences regarding the measurement uncertainty consideration. Given that only the measurement uncertainty of a single calibration and not the sum of several individual calibrations is to be considered here, a complete measuring chain is preferable.

Figure 8 shows the different cases with the items to be calibrated.

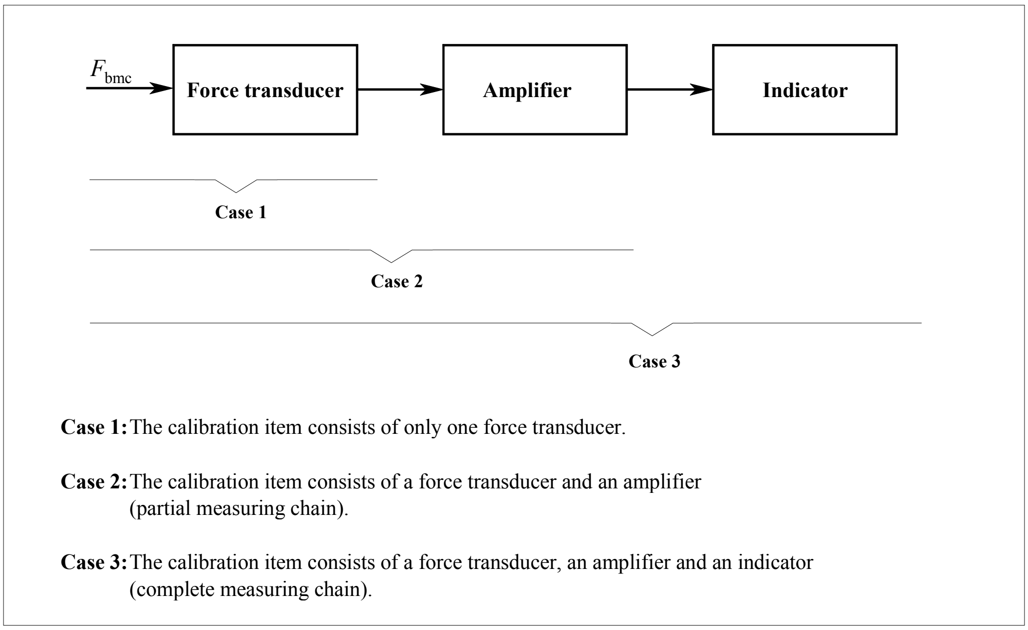


Figure 8: Case distinction calibration item

Calibrations can be performed over the entire nominal measurement range or over a partial measurement range (if a larger safety range is required for dynamic peak loads).

The resolution of the individual components of the calibration item (transducer, amplifier, indicator) is to be chosen in such a way that the desired measurement uncertainty can be achieved.

4.3.2 *Force transducers based on strain gauges (SGs)*

In the following, uniaxial force transducers are described in more detail. These are suited for the measurement in a defined loading direction. In addition, there are multi-component force transducers which measure forces in several directions, also in combination with torques. The basic physical principles correspond to those of the following paragraphs; however, for a crosstalk-free measurement of the forces, a complex structure of the measuring body is necessary.

A deformation body is subjected to the force to be measured, thus causing mechanical stress. According to Hooke's Law, this stress produces strain.

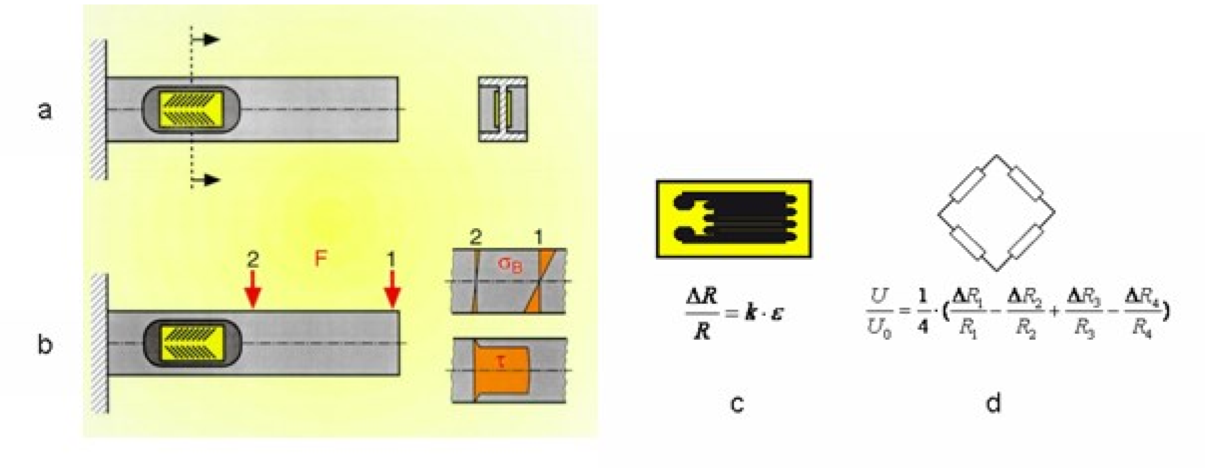


Figure 9: Operating principle of a force transducer based on SGs

Figure 9 shows the functioning of a strain gauge force transducer: A spring body (a) is loaded with a force (b) and deforms accordingly. The installed strain gauges convert the resulting strain into a resistance change (c). The use of the Wheatstone bridge circuit produces an output voltage that is proportional to the applied supply voltage U_0 and the resistance change (d), and thus proportional to the applied force. In a very good approximation, all correlations are described by a linear dependence [16].

The design, the carrier material and the metal of the measuring grid of the SG are each adapted to the material and the dimensions of the measuring body. Temperature behaviour and creep are thereby optimized. By using strain gauges with adjusted temperature coefficients, the influence of the thermal expansion of the spring body material is minimized.

There are many different types of strain gauge force transducers; they can be designed solely for pressure loads or for tensile and pressure loads. For example, central threads or flange geometries are used for mechanical coupling.

SGs themselves are ideal for measuring dynamic forces [17]. Because of their very low mass, the influence on the vibration behaviour of the measuring body can be neglected. However, in dynamic applications the natural frequency of the force transducer and the influence of the coupled spring-mass systems should be taken into account.

4.3.3 Piezoelectric force transducers

Under mechanical stress, piezoelectric materials generate electrical charges which are converted into proportional electrical voltages by means of charge amplifiers. Most force transducers use a measuring element that mainly consists of thin quartz plates, disks or rods. Due to the high rigidity of the crystal, the measurement displacements are correspondingly small, usually in the range of a few micrometers. The finite insulation resistance makes purely static measurements with piezoelectric transducers impossible. However, the piezoelectric transducers have good quasi-static and dynamic measurement properties when using suitable signal conditioners.

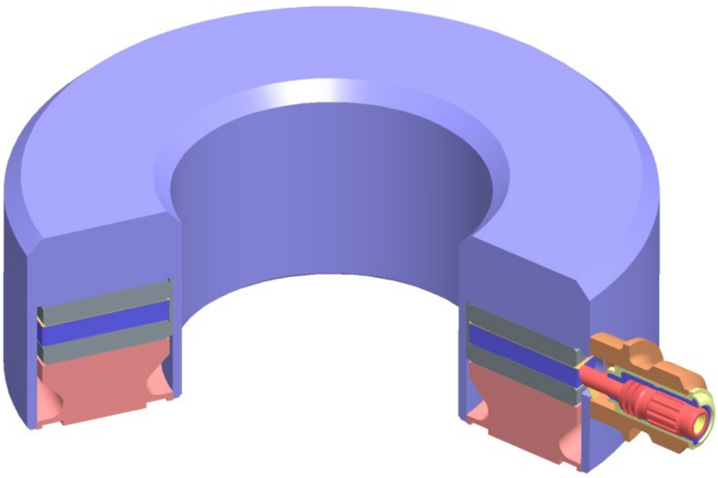


Figure 10: Schematic illustration of a piezoelectric force transducer

Single-component force transducers are used to measure forces in a defined spatial direction. They are available in various designs. Basically, a base and a cover plate hold two quartz disks in a tightly welded housing under slight preload. The electrode located between the quartz plates picks up the measuring signal which is proportional to the applied force and feeds it to the connector.

For the measurement of tensile and compressive forces, the ring-shaped force transducers are clamped between two special nuts which creates a force-measuring element. The surfaces of the coupling must meet the requirements for a high surface quality so that the forces are transmitted homogeneously.

Transducers for smaller forces have a fundamentally different design. Slender rods are clamped between the force-transmitting parts. The piezoelectric transversal effect in the rods results in a significantly higher sensitivity compared to the quartz discs.

4.4 Accelerometers

Accelerometers are used to measure the vector quantity "acceleration". It is periodic or shock-shaped. By means of a suitable mathematical treatment of the measured acceleration signal, the quantities "velocity" and "displacement" can be described.

Each accelerometer contains an electromechanical transducer or measuring element (several elements in the case of multiaxial transducers) which converts the acceleration acting on the transducer into a proportional electrical signal. The measuring element is placed in a housing whose mounting surface allows the transducer to be attached to the structure to be examined. The electrical signal is available at a plug connection, at solder connections or an integrated cable.

4.4.1 Piezoelectric accelerometers

The measuring element of the piezoelectric accelerometer contains piezoelectric material (quartz, other piezoelectric crystals, tourmaline, ferroelectric ceramics) which provides electrical charge on its prism surfaces during mechanical deformation. The mechanical deformation is caused by the application of force, in that the acceleration acting on the transducer acts on the piezoelectric material via the seismic mass of the measuring element.

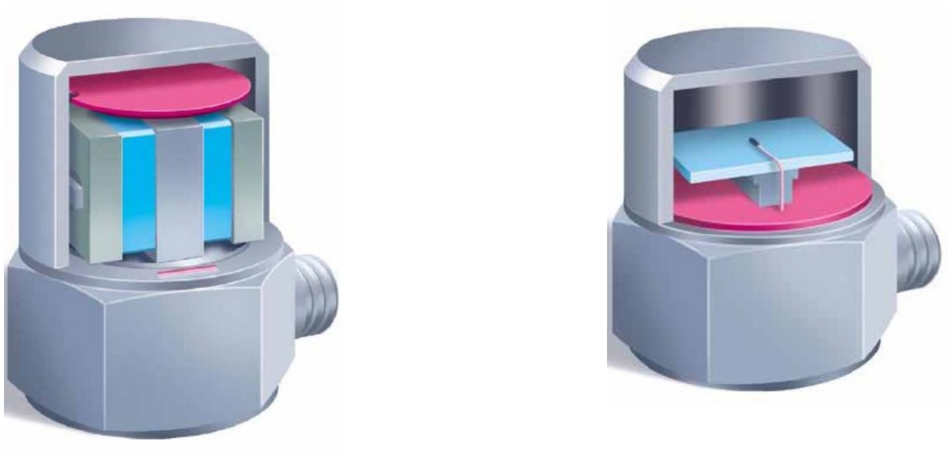


Figure 11: Schematic view of a piezoelectric accelerometer (left K-Shear ®, right K-Beam ®)

Piezoelectric accelerometers mainly operate according to the compression or shear principle. In case of the compression principle, the piezoelectric material is deformed by compressive forces; in case of the shear principle, transverse or shear forces act on the piezoelectric material. Due to their design, accelerometers based on the compression principle can exhibit a considerable sensitivity to temperature changes and basic strain. Shear type accelerometers exhibit a much lower sensitivity to temperature changes and base strain.

Transducers with charge output are operated with an external signal conditioner. In this case, a highly insulating and low-noise connection cable must be used. They have a very high dynamic range and a very low background noise. The threshold frequency can be in the range of a few millihertz; however, a real static measurement (f = 0 Hz) is not possible. In case of transducers with voltage output, the signal conditioner is integrated in the transducer. Therefore, the use of highly insulating and low-noise connection cables is not necessary.

These transducers are operated with a power supply unit for the electronics integrated in the transducer. Compared to the transducers with charge output, transducers with voltage output have a limited dynamic range. The threshold frequency is usually in the range of approximately 0.5 Hz to 1 Hz.

4.4.2 Piezoresistive accelerometers

The transducer or measuring element of a piezoresistive accelerometer consists of a silicon monocrystal into which a half or full bridge is diffused. The acceleration acting on the seismic mass of the measuring element deforms the silicon monocrystal and detunes the measuring bridge. A voltage signal proportional to the acting acceleration is available at the output of the bridge amplifier. The output signal behaves ratiometrically, which means that it depends on the bridge supply voltage.

Piezoresistive accelerometers have the highest usable frequency ranges. However, their complete utilisation is only possible if the transducer is attached to the structure to be examined as rigidly as possible in accordance with the manufacturer's instructions. Piezoresistive accelerometers are often gas-damped and therefore have no resonance step-up. Piezoresistive accelerometers can be used for true static measurements (f = 0 Hz).

4.4.3 Capacitive accelerometers

The transducer or measuring element of a capacitive accelerometer usually consists of a micromechanically manufactured differential capacitor with two fixed electrodes and a spring-mass system located between them. The acceleration acting on the transducer deflects this spring-mass system and thus detunes the capacitive measuring bridge. The ASIC (application-specific integrated circuit) integrated in the transducer provides a voltage signal proportional to the acting acceleration. Usually, there is no need for a signal conditioning device to operate a capacitive accelerometer. The transducer just needs to be fed with a supply voltage according to the manufacturer’s instructions.

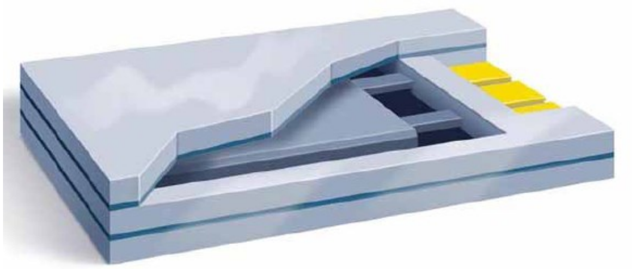


Figure 12: Schematic view of a capacitive accelerometer

Capacitive accelerometers are usually gas-damped and therefore have no resonance step-up. The lower cut-off frequency is f = 0 Hz which allows true static measurements. Due to the design, the usable frequency range is about 1 kHz. Some of them are equipped with mechanical stops to protect them against overload.

4.4.4 Servo accelerometers

Servo accelerometers are the most sensitive and accurate accelerometers. They contain a seismically suspended mass with a displacement transducer. If the accelerometer is subjected to motion, the mass shifts by a very small amount relative to the housing. This small deflection generates an error signal in a control circuit from which a control variable is generated which is supplied to the mass in such a way that the initial error signal tends to zero. The acceleration is proportional to this control variable. It is measured by the voltage drop at a resistor connected in series with the coil; the coil generates the force to correct the position of the seismic mass.

Servo accelerometers can be made very sensitive for measuring particularly small vibration amplitudes. The typical frequency range is 0 Hz to 50 Hz. The disadvantages of servo accelerometers are their small frequency range, their size and mass as well as their fragility.

4.4.5 Laser vibrometers

Laser vibrometers enable a contact-free acceleration measurement in which the measurement object is not influenced by the additional mass of an accelerometer. A laser beam is focused on a reflective surface on the accelerated mass to be measured. The reflected beam is superimposed with the original laser beam and the velocity of the measurement object can be determined from the analysis of the frequency of the reflected beam by means of the Doppler effect.

Depending on the design of the laser vibrometer, single-point measurements, differential measurements or even 3-D measurements of the accelerations can be carried out.

Laser vibrometers can be used up to the kilohertz range, measurement uncertainties of < 0.1 % can be achieved.

4.5 Force introduction

In dynamic force measurement, it should be considered that force introduction effects, which are also known from static force measurement, are generally significantly increased by the time-dependent change in force. This results in the following requirements:

1. *Installation and contact surfaces* must be flat and clean and free from contaminants and damage. Details regarding the correct mechanical adaptation are to be taken from the respective mounting instructions of the manufacturers.
2. *Low mass inertia* of the force introduction parts. Coupled masses have an influence on the measurement result; particularly, the effects on the frequency response are to be considered.
3. *Low eccentricities*, since these cause time-varying bending moments.
4. *Low introduction of parasitic loads* such as bending moments, torques and shear forces, as these also change over time.
5. *Backlash-free introduction of force*. Special attention must be paid to a fixed mounting and coupling. If the force is applied via threads, it must be ensured during mounting that the torques specified by the manufacturer and any necessary preloads are met.
6. *Reproducible contact stiffness.* To achieve reproducible conditions when attaching mechanical components, screw connections should be tightened in a controlled manner (e.g. by means of a torque wrench).

4.6 Electronics

4.6.1 Measuring amplifiers for SG force transducers

Measuring amplifiers for strain gauge force transducers amplify the bridge output voltage of the Wheatstone bridge, which lies within the millivolt range, to a level in the volt range.

The Wheatstone bridge circuit can be supplied both with DC voltage and with AC voltage (so-called carrier frequency measuring amplifier). Carrier frequency amplifiers have the advantage of a lower sensitivity to disturbing influences (e.g. thermal voltages, glitches) since only a narrow frequency band is amplified. However, they are less suitable for dynamic applications, given that the highest signal frequency should typically be < 10 % of the carrier frequency.

DC amplifiers are also used for dynamic signals up to high frequencies. There is no limitation of the frequency response by a carrier frequency.

In case of dynamic events, it is necessary to ensure a sufficiently high cut-off frequency for all amplifier types in the filter settings (low-pass filter) (recommendation: approx. 20 % higher than the signal frequency).

The measuring bridge can be connected to the amplifier in a 4-wire or 6-wire circuit (with regulated bridge supply voltage). With the 6-wire circuit, influences on the supply voltage due to resistance changes of the cable (e.g. by temperature changes) are compensated.

4.6.2 Charge amplifiers for piezoelectric transducers

4.6.2.1 Structure

Charge amplifiers convert the charge output of a piezoelectric transducer into a proportional voltage. A charge amplifier consists of an inverting voltage amplifier with high internal amplification and capacitive negative feedback. The input is equipped with a MOSFET (Metal Oxide Semiconductor Field Effect Transistor) or JFET (Junction Field Effect Transistor) to ensure the necessary high insulation resistance and the lowest possible leakage current.

With a sufficiently high internal amplification A, the output voltage U_0 only depends on the charge Q at the input of the charge amplifier and on the range capacitor C_r:

$$U_0 = \frac{-Q}{C_r} \quad \textbf{(1)}$$

The amplifier acts as an integrator and constantly compensates the electrical charge delivered by the transducer with a charge of equal magnitude and opposite polarity at the range capacitor. The voltage generated by the range capacitor is proportional to the charge delivered by the transducer and thus also proportional to the measured quantity.

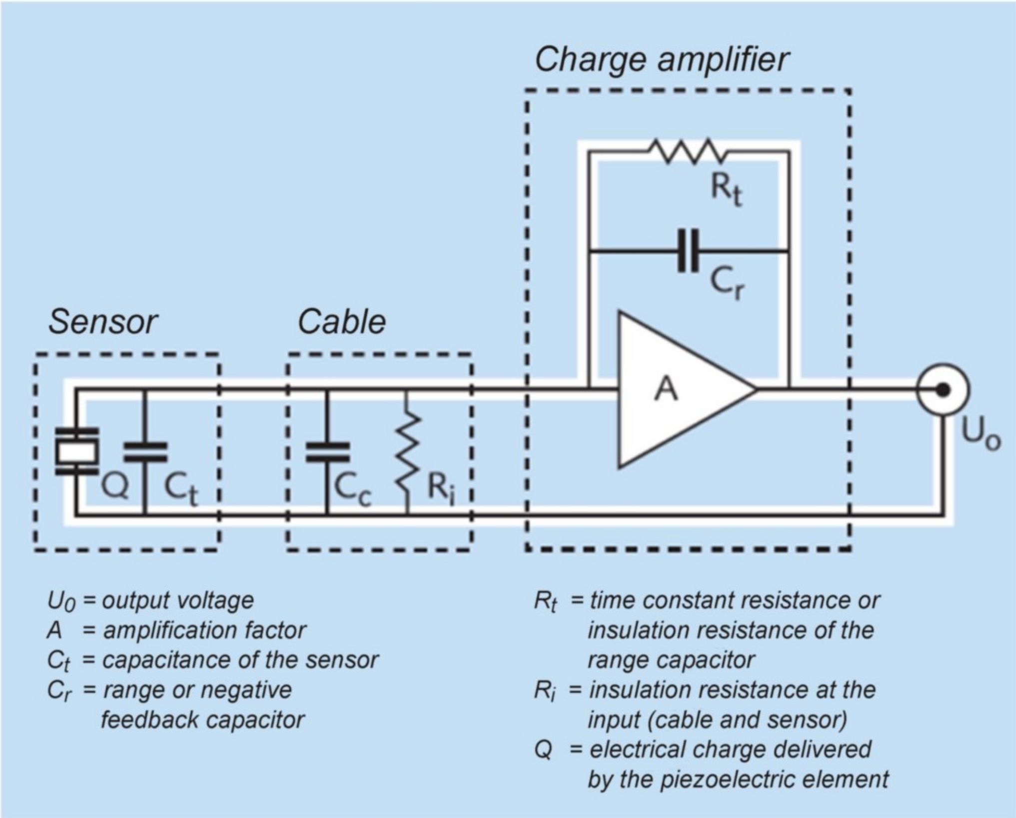


Figure 13: Schematic illustration of a charge amplifier for converting the charge of a piezoelectric transducer into a proportional voltage

4.6.2.2 Time constant and drift

Two important characteristics of the charge amplifier are the time constant and the drift. The time constant τ of a charge amplifier is determined by the product of the capacitance C_r of the range capacitor and the time constant resistance R_t:

$$\tau = R_t \cdot C_r \quad \textbf{(2)}$$

The term *drift* stands for an unwanted change in the output signal over a longer period of time which is not a function of the measured quantity. Even the best MOSFETs and JFETs have leakage currents which are mainly responsible for the drift. An insufficient insulation resistance R_i at the input can cause additional drift. However, so long as the insulation resistance in the negative feedback circuit is sufficiently high (> 10^{13} Ω) and no additional time constant resistance is connected in parallel, the charge amplifier only drifts very slowly into the positive or negative limit.

4.6.2.3 Frequency range

The time constant τ defines the cut-off frequency

$$f_\mathrm{u} = \frac{1}{2\pi \cdot \tau}, \qquad (3)$$

at which an amplitude attenuation of 3 dB (30 %) occurs for sinusoidal signals. The longer the time constant, the lower the threshold frequency and the longer the usable measurement time. Accordingly, it should be noted that for extremely slow dynamic measurements, the measurement signal is affected by the characteristics of the charge amplifier.

Similarly, an amplitude attenuation must be considered for the upper frequency range resulting from the transmission characteristics of the charge amplifier. Typical values for the upper cut-off frequency of a charge amplifier are above 100 kHz. Depending on requirements, a low-pass filter can be connected which shifts the cut-off frequency (amplitude attenuation of 3 dB) accordingly towards lower frequencies. The cut-off frequencies of the low-pass filters used in each case can be found in the manufacturer's instructions.

4.6.3 A/D conversion and signal filtering

Further data acquisition of the voltage signals of the charge amplifier or strain gauge amplifier is carried out using conventional analogue-to-digital converters. The digitally converted signal can then be further processed with standard bus and computer systems for subsequent data transfer, data processing and storage. In view of the manifold A/D conversion methods available, a sufficiently high sampling rate must be ensured. According to the sampling theorem (Nyquist and Shannon), the sampling rate must be more than twice the highest frequency to be detected; higher-frequency components must be filtered out by means of an anti-aliasing filter before sampling. In practice, 8-12 samples per period should be taken for a sinusoidal voltage signal of a fixed and known frequency to determine the desired oscillation amplitude from the measured data points without fit method or interpolation procedures.

The cut-off frequency of additional digital filters after A/D conversion for noise reduction must match the highest frequency to be determined in the sampled signal. The filter parameters, i.e. filter cut-off frequency, filter order and filter type must therefore be chosen such that the amplitude of the desired signal preferably remains unchanged.

The selection of other specific parameters (e.g. smoothing, noise reduction, etc.) can also influence the calibration result. Consequently, it is important to know the effects of the parameter settings and to estimate the possible contributions to the measurement uncertainty.

4.6.4 Dynamic calibration of measuring amplifiers and charge amplifiers

If the dynamic measurements are carried out without continuously calibrated measuring chains, the components (force transducer, measuring amplifier, etc.) must be calibrated individually. With respect to the dynamic calibration of measuring amplifiers, the Working Group “Acceleration” of the DKD Technical Committee “Force and Acceleration” is developing a guideline [18] which can be used in the future for the calibration of measuring amplifiers.

4.7 Force generation in fatigue-testing machines

A fatigue test is usually carried out with relatively fast-running fatigue-testing machines. Figure 14 shows the classification of fatigue-testing machines according to [19].

- Machines with positive drive (a) are operated at frequencies between 5 Hz and 50 Hz.
- In the case of resonance machines (b, c, d), the oscillatory system consisting of probe (= hard spring), soft spring and additional mass is excited close to the resonance frequency, thus being able to reach
  - 10 Hz – 130 Hz with mechanical drive,
  - 35 Hz – 300 Hz with electro-mechanical drive
  - and 150 Hz – 1000 Hz with electro-hydraulic drive.
- Volumetrically controlled hydraulic fatigue-testing machines (e) operate at frequencies up to 60 Hz,
- systems with electro-hydraulic servo valves (f, g) at frequencies up to 150 Hz.

When carrying out the fatigue test, either the load limits or the strain limits are kept constant. In the first case, we speak of a voltage-controlled experiment; the resulting strain amplitude depends on the material behaviour. The second case is referred to as strain-controlled, in which case the voltage amplitude is a function of the material behaviour.

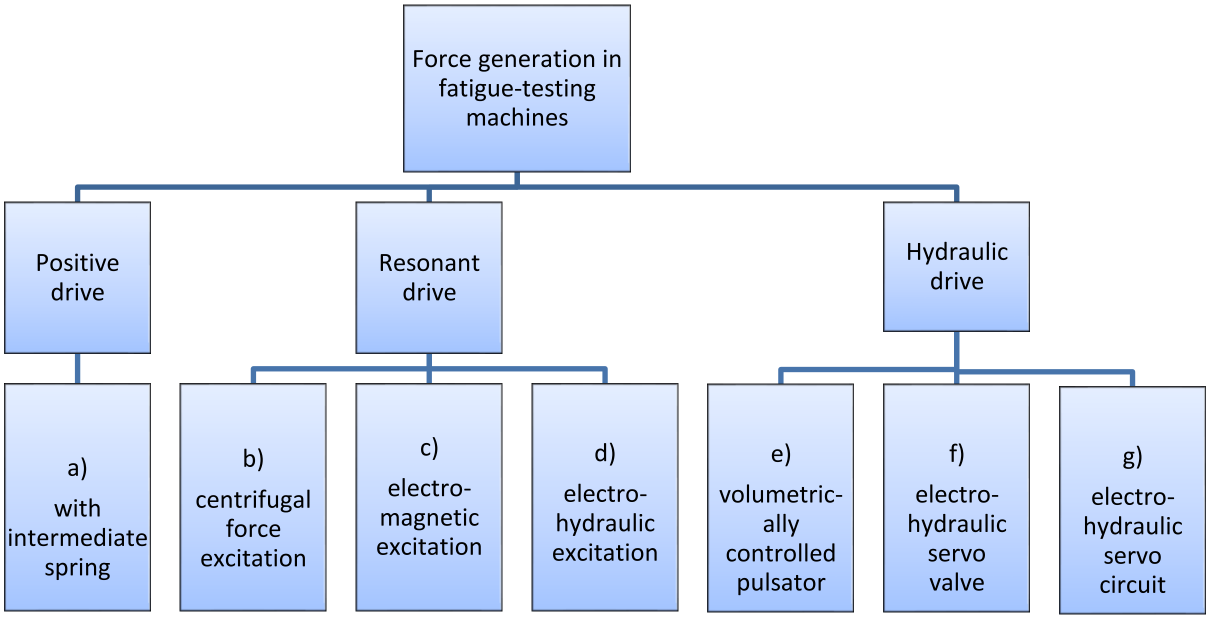


Figure 14: Classification of fatigue-testing machines by type of force generation [19]

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