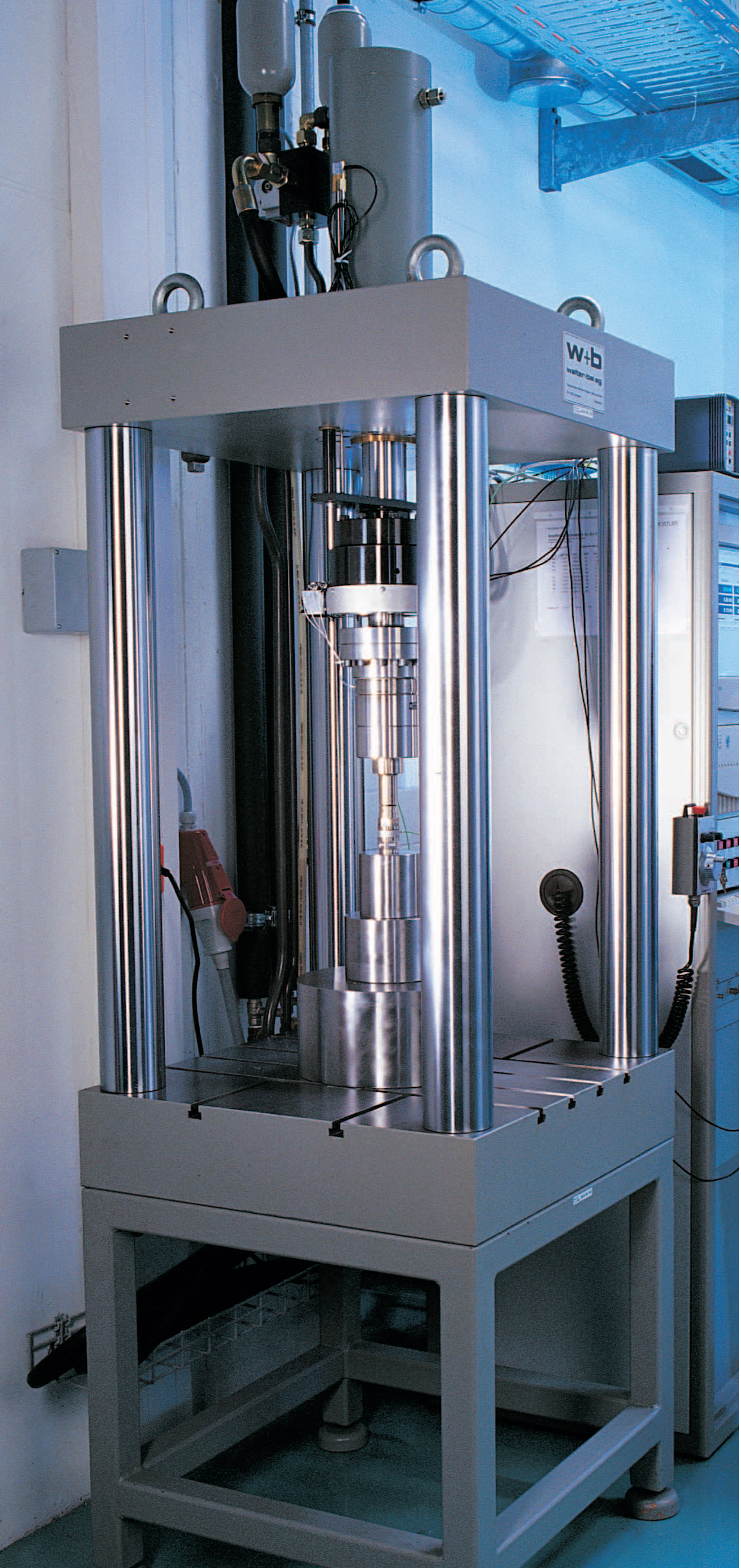

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Force Calibration

Investigation of Piezoelectric Force Measuring Devices in Force Calibration and Force Standard Machines

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Special Print
920-232e-12.03

Investigation of Piezoelectric Force Measuring Devices in Force Calibration and Force Standard Machines.

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Abstract

This contribution describes different measurement facilities and procedures for the calibration of piezoelectric force measuring devices. In National Metrology Institutes forces are generated in force standard machines in force steps. In force calibration machines of industrial calibration laboratories forces can be applied in steps or continuously. The traceability is realised with force transfer standards which are calibrated in force standard machines. A comparison of these different calibration procedures is discussed in this contribution.

1. Introduction

The force standard machines and the force calibration methods described in standards [1] are optimized to calibrate strain gauge force sensors with minimal measurement uncertainty. In these procedures the load is applied stepwise (Fig. 1.1a) with time intervals of typically 60 s per step. Therefore a duration of the order of t_c = 1000 s results for a load cycle.

For the calibration of piezoelectric sensors, where the drift of the charge amplifier is present in the signal, the duration of a load cycle should be shorter in order to reduce the measurement uncertainty. In addition piezoelectric sensors are applied to short term or even to dynamic measurements. Therefore continuous calibration procedures have been developed and established (Fig. 1.1b), where the time interval for a load cycle is typically t_c = 10 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_c = 1 to 0,0001 s are needed (Fig. 1.1c and § 2.3).

For the sake of comparison the load cycle frequency f_c is defined as $f_c = 1/t_c$. For the standard stepwise load cycle this yields f_{cs} = 1 mHz, for the continuous cycle f_{cc} = 100 mHz and for the dynamic calibration typically f_{cd} = 1 Hz ... 10 kHz.

In Fig. 1.2 these frequencies are compared to typical frequency response functions of force sensors, loaded with an additional mass. Due to the exceptionally high stiffness, the piezoelectric sensor shows a significantly higher resonant frequency compared to the strain gauge force sensor. Both the stepwise and the continuous calibration procedure are considered to be quasi-static, avoiding long term and drift errors on the low end of the frequency scale and dynamic effects in the higher frequency range.

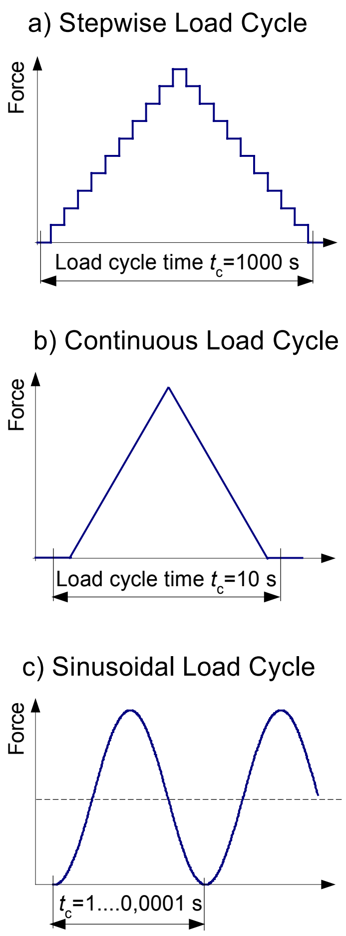

Figure 1.1 Load-time dependence diagrams for stepwise, continuous and sinusoidal (dynamic) load cycles

For strain gauge sensors, too fast continuous measurements can cause creep errors or even dynamic errors. From the frequency response function of the piezoelectric sensor it becomes obvious that too low load cycle frequencies can cause drift errors in the calibration data which increase the measurement uncertainty. For piezoelectric transfer standards, traceably calibrated on force standard machines, the best measurement uncertainty must be achieved. Therefore a modification of the standard calibration procedures is necessary. As a major benefit, lower uncertainty results, especially for continuous calibration procedures, with accordingly calibrated piezoelectric transfer standards.

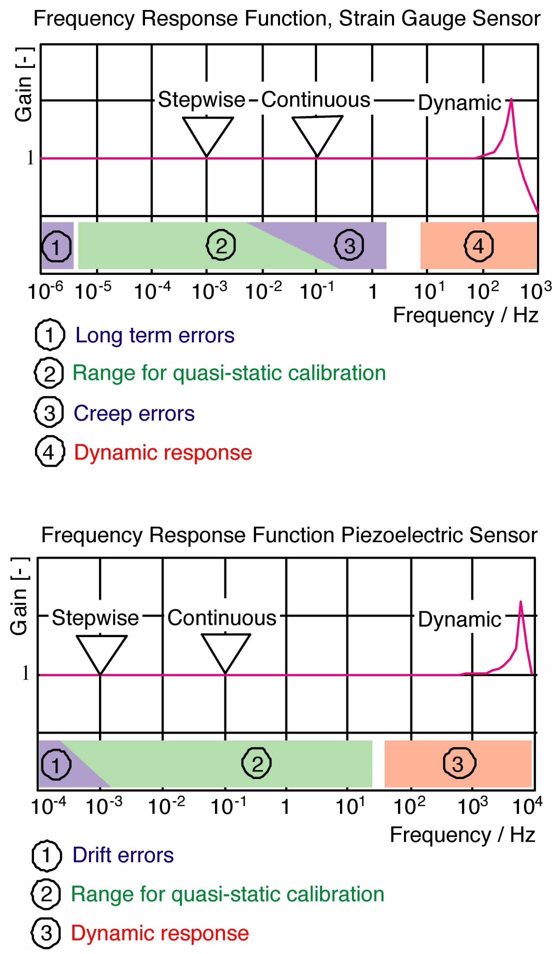

Figure 1.2 Typical frequency response functions of a strain gauge sensor (top) and a piezoelectric sensor (bottom) compared to the load cycle frequencies of different load cycles

2. Force Standard Machines and Measurement Procedures of PTB

2.1 Force Standard Machines

The unit of force is realized in National Metrology Institutes by different types of force standard machines [2]. The lowest uncertainties of less than $2 \cdot 10^{-5}$ are achieved with deadweight force standard machines. Other principles like hydraulic amplification or lever amplification of deadweight forces are used in the higher force range and uncertainties of less than $1 \cdot 10^{-4}$ are possible. Force standard machines are usually designed for the static calibration of force transducers to achieve lowest measurement uncertainties. Because of the physical principle of piezoelectric force transducers [3], static calibration procedures according to standards applied to strain gauge force transducers cannot be directly applied to piezoelectric force measuring devices. However, quasistatic calibrations of piezoelectric force transducers can be carried out with force standard machines if special loading and measuring methods are taken into account [4]. To allow a classification of piezoelectric force transducers based on the characteristic quantities linearity, repeatability error and hysteresis, as in DIN EN 10002-3, the drift behaviour must be taken into account. Besides the method described in DIN EN 10002-3 for the calibration of strain gauge force transducers, different methods which make use of this property are investigated [4]. Therefore in the force standard machines of PTB the influence of the drift of piezoelectric force transducers was investigated. The drift is determined by the charge amplifier and in particular by the measuring ranges and the different settings of the amplifier. To reduce the measurement uncertainty, the measurement procedures used for strain gauge transducers are modified and advanced, according to the properties of piezoelectric force measuring devices.

2.2 Methods and Procedures for Quasi-Static Calibration

According to DIN EN 10002-3 force transducers are calibrated by a procedure using stepwise loading and unloading. Figure 2.1a shows the load-time dependence diagram of force transducers in force standard machines. Discrete increasing and decreasing load steps at equidistant time intervals are plotted. Figure 2.1b shows the respective signal-time dependence diagram of a piezoelectric force measuring device.

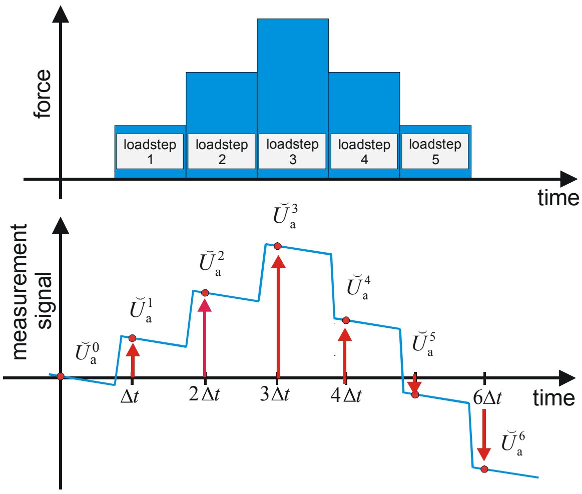

Figure 2.1a Load-time dependence diagram, 2.1b signal-time dependence diagram of a piezo-electric force measuring device according to DIN EN 10002-3

The acquisition of the measured values was made at equidistant time intervals Δt independent of the time necessary for applying the load step. DIN EN 10002-3 specifies that the acquisition of the measured value may take place 30 seconds after application of the load, at the earliest. As can be concluded from the figure, the drift particularly affects the measuring signals of the decreasing load steps, and here primarily the load steps for small forces at the end of the measurement series. Another possibility of measuring force changes dicussed in [4] consists in resetting the charge amplifier to zero prior to the application of each new load step.

If the force standard machine allows fast loading and unloading, the force transducer can be unloaded between every increasing and decreasing load step. The advantage of this method is a reduction of the drift influences. However, determination of the hysteresis is not possible because it requires the application of a monotonically increasing or decreasing force to the transducer. Unloading of the force transducer prior to the application of a new load step therefore only allows investigations of the repeatability and not of the hysteresis to be made and is not further discussed in this paper.

2.3 Principle of Dynamic Calibration

The dynamic calibration of force measuring devices is traceable to the base units because well-defined forces of inertia are generated with the facility shown in Fig. 2.2 [2]. For this purpose the piezoelectric force transducer is mounted on a shaker and a load mass m_l is coupled to the force transducer. Excitation by the shaker results in a dynamic force F acting on the force transducer:

$$F = \left(m_l + m_e\right) \cdot \ddot{x}_l \qquad (2.1)$$

where $\ddot{x}_l$ is the acceleration of the load mass m_l and m_e is the end mass of the force transducer. The acceleration on the load mass is measured by acceleration transducers which are calibrated by interferometric procedures. The simple equation (2.1) does not take into account the effects of the relative motion of the load mass and the influences of side forces which must be considered because force is a vector quantity. Side forces can be reduced by using air bearings. To allow for the effect of relative motion, the dynamic force must be determined from the acceleration distribution $a(x,t)$ and the mass distribution with density ρ according to

$$F = \int_V \rho \cdot a(x,t) \cdot dV \, . \qquad (2.2)$$

For the determination of the acceleration distribution, multicomponent acceleration measurements must be carried out as shown in Fig. 2.2, and the theory presented in [5] must be used to calculate the dynamic force. According to Eq. (2.1) or, more accurately, to Eq. (2.2), the dynamic force is traceable to the definition of force according to Newton's law.

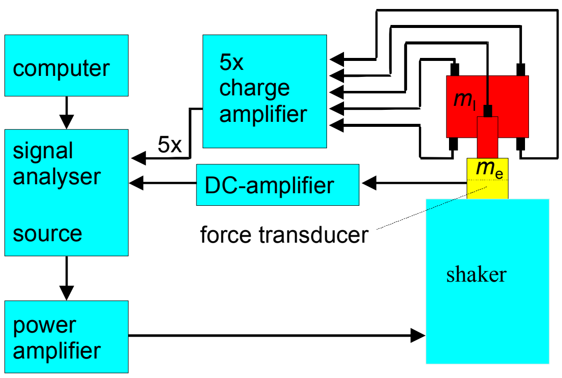

Figure 2.2 Calibration facility for dynamic force measurement

This calibration procedure allows the dynamic sensitivity of the force measuring device to be determined, comprising the piezoelectric force transducer and the charge amplifier.

The frequency response function of a piezoelectric force measuring device is the product of the frequency response function of the force transducer and of the frequency response function of the charge amplifier, provided that transducer and amplifier are non-interacting.

If the frequency response of the force measuring device and charge amplifier is known, the frequency response of the piezoelectric force transducer can be calculated by division. The charge amplifiers are therefore calibrated with a well-known capacitance.

3. Calibration Machines and Measurement Procedures of Kistler

3.1 Calibration of the Working Standard Against Transfer Standards; Traceability

In Fig. 3.1, three different methods of calibrating a working standard against a traceably calibrated transfer standard are shown. The methods a) and b) are commonly used procedures, according to DIN EN 10002-3. With both methods, a measurement uncertainty of <0,1 % is achieved (0,2 % at the ends of the force scale).

In method a), the piezoelectric working standard is calibrated stepwise with curtailed time intervals against a strain gauge transfer standard. Several strain gauge transfer standards are necessary for the calibration of one piezoelectric working standard, since the latter can be used in partial ranges by appropriate switching of the charge amplifier. This important feature of piezoelectric sensors can be illustrated as follows: a sensor with a nominal range of 200 kN and a sensitivity of e. g. –4 pC/N can be calibrated in the 20 kN partial range with the same uncertainty as a sensor with 20 kN nominal range and –4 pC/N. Therefore, a strain gauge transfer standard with 20 kN nominal range should be used to calibrate a 200 kN working standard in the partial range of 20 kN to maintain best measurement uncertainty.

In method b), the piezoelectric working standard is calibrated with continuous loading and unloading against a piezoelectric transfer standard.

The novel advanced procedure c), described in this paper, yields a better measurement uncertainty for the piezoelectric transfer standard and therefore for the working standard too, compared to the method b).

Figure 3.2 shows the experimental setup for the calibration of a piezoelectric working standard against a strain gauge transfer standard with method a). At the bottom, there is the traceably calibrated strain gauge transfer standard. Built in into the piston-rod of the hydraulic press, there is the piezoelectric working standard to be calibrated. A strain gauge force sensor for the automatic force control of the hydraulic press is mounted above the working standard. The figure also shows that the force to the strain gauge transfer standard is introduced over a lamp cap.

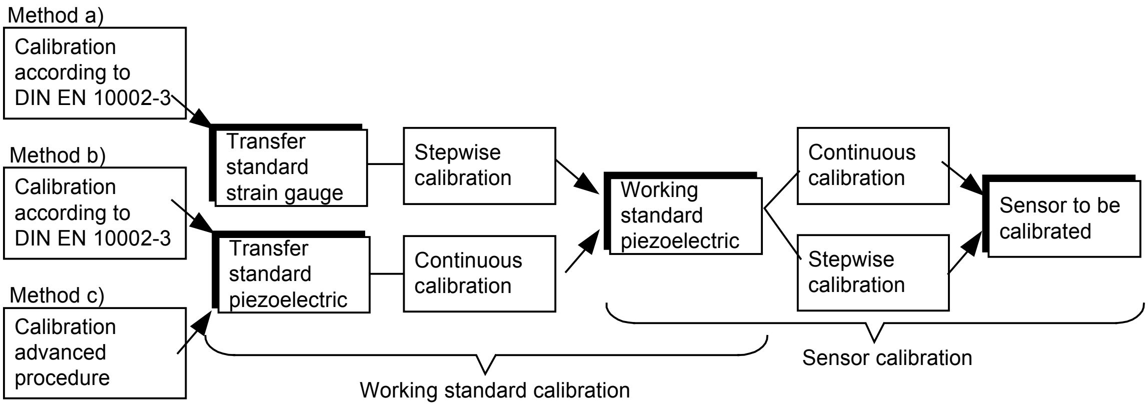

Figure 3.1 Traceability and methods of piezoelectric working standard calibration

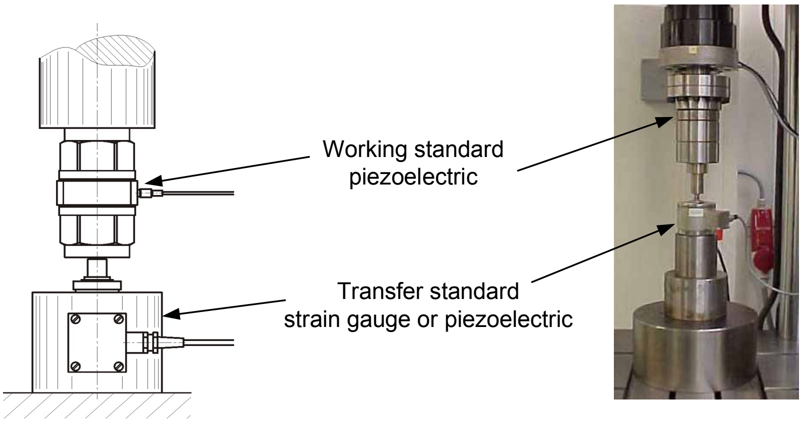

Figure 3.2 Set up for working standard calibration

3.2 Force Calibration Facilities at Kistler

Figure 3.3 shows a typical force calibration facility. Usually, the force is generated by a hydraulic press. The working standard as well as the unit under test are positioned in the same action line. The introduction of force (uniaxial as well as multi-axial) is accomplished in such a way that it is free of bending moments and lateral forces. The force ranges from 0 ... 0,5 N up to 0 ... 400 kN are provided by means of different calibration facilities.

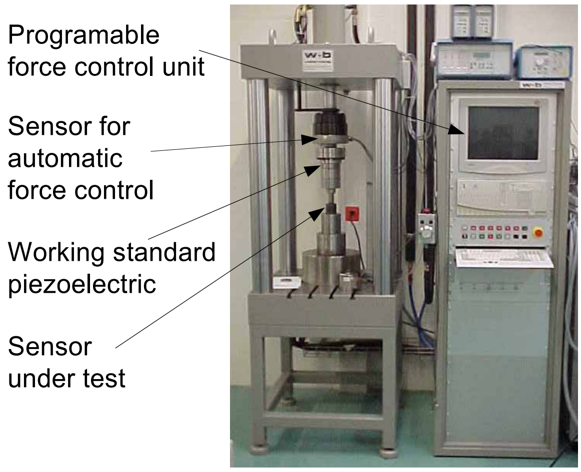

Figure 3.3 Typical calibration facility comprising a servo-hydraulic press (200 kN), a piezoelectric working standard and a control unit

3.3 Calibration of Piezoelectric Units Under Test

Within the framework of the Swiss Calibration Service (SCS), the stepwise loading and unloading, according to DIN EN 10002-3, is applied. For standard calibrations, the continuous loading and unloading method is used. The results are evaluated by means of the method of the best straight line (BSL), and are specified as sensitivity, linearity error and hysteresis (see Fig. 3.4).

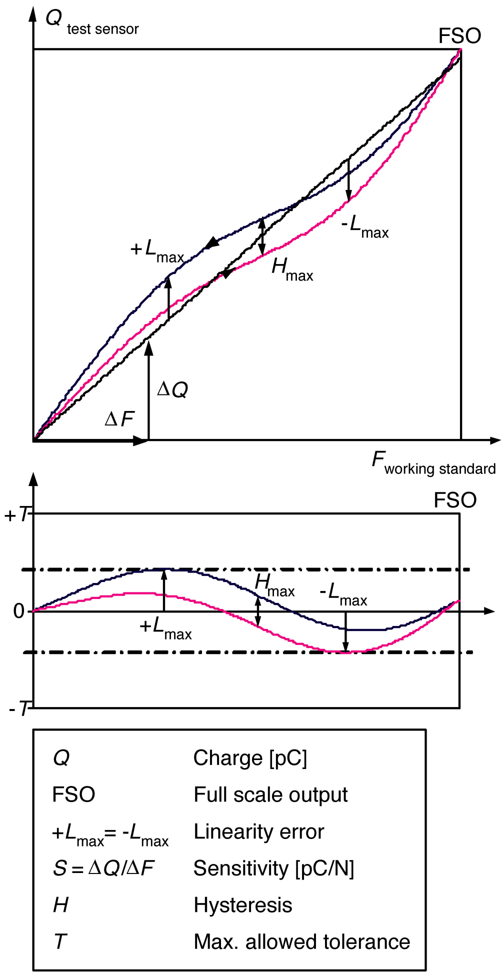

Figure 3.4 Response curve of a continuous calibration with BSL (upper diagram). The signal of the sensor under test is plotted versus the signal of the working standard. The deviation between response curve and best straight line is plotted in the lower diagram.

The BSL is defined as a straight line through zero which minimizes the maximum deviations from the response curve (Tchebycheff aproximation). A continuous calibration of the force sensor type 9331A yielded a sensitivity of –3,93 pC/N in the 20 kN nominal load range. This value is directly comparable to the results of the stepwise calibration (see section 4.5).

4. Measurement Results

The discussion of the measurement results shows that, taking account of the drift dependence, good agreement with the measurements in the National Metrology Institute was achieved.

Moreover, dynamic investigations are being carried out at PTB with piezoelectric force measuring devices of particularly high rigidity and small dimensions and which are therefore especially useful in dynamic applications.

4.1. Influence of Measurement Time and Drift

When piezoelectric force measuring devices are calibrated in force standard machines, the drift is to be taken into account. As shown in [6,7], the drift can be assumed to be linear if the insulation resistance of the negative feedback capacitor of the charge amplifier is high enough. The negative feedback capacitor itself serves to set the range of measurement of the charge amplifier. Large ranges of measurement ask for high capacitances C_g of the negative feedback capacitor.

A force transducer subjected to the force F generates the time-dependent measurement signal U_a

$$U_a = \frac{S_{KA} \cdot F + I_D \cdot t}{C_g}. \quad \textbf{(4.1)}$$

at the charge amplifier output, where S_{KA} is the static sensitivity of the force transducer and t the time after the measurement has been started. The drift current I_D is responsible for the linear drift of the charge amplifier, which is due to offset voltages and leakage currents of the input transistors of the charge amplifier [6,7]. The drift thus is independent of the force but inversely proportional to C_g.

$$D = \frac{I_D}{C_g} \quad \textbf{(4.2)}$$

As can be seen in equation (4.2), constant drift currents I_D cause greater drift in small than in large ranges of measurement.

To investigate long term drift effects, piezoelectric force measuring chains are examined directly after mounting and after a rest period of 48 hours. Figure 4.1. shows the drift behaviour of a force transducer with a nominal load of 20 kN if a charge amplifier with a measurement range of 8000 pC/V is used.

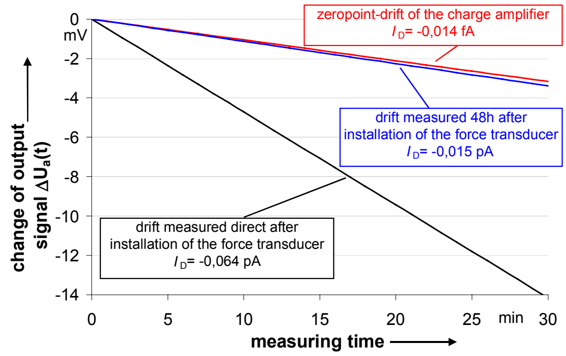

Figure 4.1 Influence of electrostatic charges due to connectors and cables on the drift of piezoelectric force measuring devices

The zero point drift current of the charge amplifier without a force transducer connected is I_D = –0,014 pA and is in accordance with a drift of D = –1,8 µV/s. The measurement shows a high linear time dependency.

Directly after mounting of the force transducer the measurement results show a high linear drift with a drift current of I_D = –0,064 pA. This four times higher drift current is caused by electrostatic charges of cables and connectors with halftimes of a few hours.

48 hours after the installation, the drift measured is substantially smaller and only slightly greater than the zero point drift of the charge amplifier. The electrostatic charges of cables and connectors faded away almost completely.

Hence it is shown, that the drift strongly depends on the rest period. Precision measurements with small drift rates require long rest periods of the system.

4.2. Repeatability and Reproducibility

In common standards like DIN EN 10002-3 for the calibration of force measurement devices the drift is not taken into account. Because of the settling time the acquisition of the measurement values takes place at least 30 seconds after application of the respective force, but firm measuring times are not fixed. Figure 4.2. documents the large influence of the measurement time on the repeatability of a piezoelectric force transducer with a nominal load of 20 kN in a partial measurement range of 2 kN. The measurement range of the charge amplifier is 800 pC/N.

The repeatability is determined from two corresponding measurement series of discrete load steps at increasing force according to DIN-EN 10002-3. Graph ⌘ shows the repeatability if the measurement time is not taken into account and different equidistant time intervals for each measurement series are chosen. At this examination the time interval is Δt=20 s for the first measurement series and Δt=60 s for the second one. The repeatability is greater than 0,15 % and thus very high.

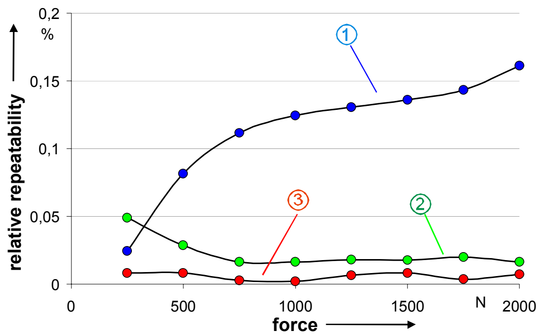

Figure 4.2 Relative repeatability in the same mounting position at different time intervals Δt and under different drift conditions

A drastic reduction of the repeatability is brought about by data acquisition at identical time intervals for both measurement series like shown in graph ✣. The acquisition of the measurement values is carried out at time intervals of Δt=20 s for both measurement series. The repeatability achieved now is smaller than 0,05 %, but the drift behavior is not taken into account yet. In the case of the examination represented in graph ✣ the drift currents of the two measurement series vary widely between I_D = –0,038 pA and I_D = –0,019 pA.

A further improvement of the repeatability can be obtained if the drift behavior is also taken into account. Beside identical measurement times both measurement series should show the same drift behavior. Graph ✥ shows the repeatability for measurements at equidistant time intervals of Δt=20 s for both measurement series. Beyond this the two measurement series have approximately identical drift currents of I_D = –0,033 pA and I_D = –0,038 pA. Now the determined repeatability is even smaller than 0,01 % and allows a classification in class 00 according to DIN EN 10002-3.

As shown in figure 4.2. due to the drift, a statement on the repeatability of force transducers is not possible if neither the measurement time nor the drift is taken into account. If both the measurement time and drift are taken into account, the measurements provide excellent results and suggest a very small repeatability of piezoelectric force transducers.

Measurements in larger measurement ranges of the charge amplifier with a correspondingly smaller drift lead to a repeatability being further reduced. Figure 4.3. shows measurements of the force transducer in the nominal load range of 20 kN with a charge amplifier attitude of 8000 pC/N.

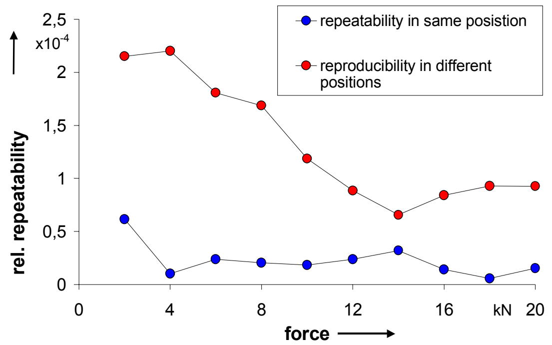

Figure 4.3 Relative repeatability when the force transducer is loaded with a nominal force of 20 kN in the same and relative reproducibility in different mounting positions

The repeatability in the same mounting position is smaller than $6{,}2 \cdot 10^{-5}$ on the complete measurement range and smaller than $3{,}2 \cdot 10^{-5}$ in the load range from 4 kN up to 20 kN.

The reproducibility in different mounting positions specify the direction dependency of piezoelectric force transducer. Expectedly the determined reproducibility of 0,022 % is greater than the repeatability in the same mounting position. Nevertheless the piezoelectric force transducer shows an excellent reproducibility which allows a classification in class 00 according to DIN EN 10002-3.

In regard to repeatability and reproducibility the investigated piezoelectric force transducer and precision strain gauge force transducer show comparable results.

4.3. Hysteresis

A marked dependence on the time interval Δt and thus on the acting drift is shown by the relative hysteresis. The relative hysteresis of a piezoelectric force measuring device in the nominal load range up to 20 kN is represented in Figure 4.4.

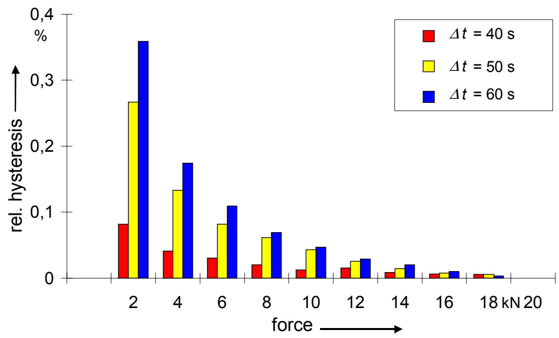

Figure 4.4 Relative hysteresis (relative reversibility error) of a piezoelectric force transducer in the nominal load range of 20 kN

While the relative hysteresis (relative reversibility error) is smaller than 0,1 % when the data are recorded at small time intervals Δt = 40 s, time intervals of Δt = 60 s result in a relative hysteresis of 0,4 %. In smaller ranges of measurement with a higher drift, the hysteresis may, however, also be some percent when identical time intervals are selected. Due to the strong dependence of the relative hysteresis on the time interval Δt and the acting drift, a statement on the hysteresis of the force transducer is not possible. However the investigations suggest a small reversibility of the force transducer.

4.5. Reproducibility of Sensitivity

In practical application piezoelectric force transducers are characterized by a linear sensitivity coefficient, which is well-defined in a fixed load range. Typical load ranges are the nominal load range of the force transducer and a partial load range up to 10 % of the nominal load range. To minimize the influence of drift manufacturers of piezoelectric force transducers determine the sensitivity by continuous calibration methods. In force standard machines used at PTB static forces are generated in force steps. To ensure comparability with continuous calibrating methods the load is applied in ten different increasing and decreasing load steps. The sensitivity is determined by a linear least squares fit with forced zero over these ten load steps. Due to partly slow load changes from one load step to the next the measuring time and thus the drift influence cannot be neglected. Figure 4.5 shows the drift influence on the sensitivity of the force transducer in the nominal load range of 20 kN and a partial load range of 2 kN. Twelve independent measurements m_1 to m_{12} in both load ranges are represented to investigate the reproducibility of sensitivity. To investigate the influence of the drift, the measurement values are recorded at equidistant time intervals between Δt = 20 s and Δt = 180 s.

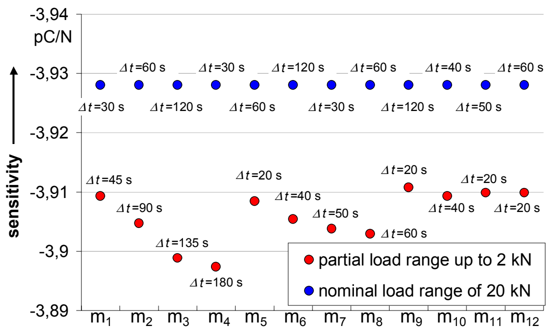

Figure 4.5 Sensitivity of a piezoelectric force transducer in the partial load range up to 2 kN and in the nominal load range up to 20 kN at different time intervals Δt

In the partial load range up to 2 kN the sensitivity shows a relative variation of $4{\cdot}10^{-3}$ between –3,8974 pC/N and –3,9108 pC/N. The relative standard deviation of the twelve sensitivities is $8\cdot10^{-4}$. Furthermore the sensitivity shows a marked dependence on the time interval Δt. The longer the time interval Δt, the smaller is the absolute value of the sensitivity. The reason for this behavior is the high drift due to a charge amplifier setting of 800 pC/V in this measurement range.

However, in the nominal load range of 20 kN a very good reproducibility of the sensitivity is obtained. Up to 20 kN the sensitivity shows a relative variation of $8\cdot10^{-4}$ between –3,926 pC/N and –3,929 pC/N. The relative standard deviation of the twelve sensitivities is $2\cdot10^{-4}$. Though the sensitivity shows the same dependence on the time interval Δt and thus the drift. Yet a smaller drift due to a wider charge amplifier range with an setting of 8000 pC/V reduces the drift influence. A substantially better reproducibility of the sensitivities determined can be achieved.

The sensitivity determination based on the stepwise force calibration (Figure 1.1) is in good accordance with the sensitivity determined by the continous calibration method (Figure 1.2) given in chapter 3.3 and is a fundamental quantitiy for dynamic forces measurement (Figure 1.3). However, the frequency dependency has to be determined with dynamic methods according chapter 2.3.

The measurements show a dependency between sensitivity and drift. The larger the drift, for example due to small measurement ranges of the charge amplifier, the more the sensitivity is influenced by the drift. Admittedly in the case of a large measurement range of the charge amplifier and thus a small drift a very good reproducibility of the sensitivity can be obtained. Better results can be achieved only by analytical methods of drift compensation.

5. Conclusion

Different calibration facilities and methods for piezoelectrice force transducers are described in this paper. It is pointed out that different influences and particularly the drift of the charge amplifier must be taken into account to reduce the measurement uncertainty in the stepwise force calibration of piezoelectric force transducers. Good agreement was obtained between the sensitivity determined by stepwise force calibration and by continuous calibration. In future, improvements will be possible if the drift dependency and the nonlinearity of piezoelectric force measuring devices is taken into account. New methods are therefore being developed at PTB, as described in [8].

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