

A NEW CALIBRATION METHOD WITH STATIC LOADS FOR PIEZOELECTRIC FORCE TRANSDUCERS

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Abstract: This paper presents a new method for calibrating piezoelectric force transducers with static forces. Load cycles with pilgrim-steps and a special evaluation of the measuring results permit the determination of transducer coefficients that are independent of the linear drift of the charge amplifier. Consequently, the coefficients are independent of the measurement time and the time of load change of the force standard machine in use. It is shown that the new calibration method contributes essentially reducing the uncertainty of piezoelectric force transducers that are used in quasistatic and dynamic precision force measurements.

Keywords: piezoelectric force transducer, calibration method, static force

1. INTRODUCTION

For a long variety of industrial applications, not only static, but also continuous or dynamic precision force measurements are necessary [1,2]. Thereby, dynamic influence quantities affect the measurement results and contribute to an extensive increase in the measurement uncertainty [3]. Consequently dynamic calibration methods increasingly gain in importance. However for dynamic precision measurements it is still necessary that the exact static sensor qualities are known, e.g. the linear behaviour as well as dynamically not determinable effects of mechanical disturbance properties [4].

As an example of acting mechanical disturbance properties, fig. 1 shows schematically the bending moments and shear forces which act on the force transducers of a force measuring plate under load as used in crash barriers.



Car crash barrier of several force plates in modular design

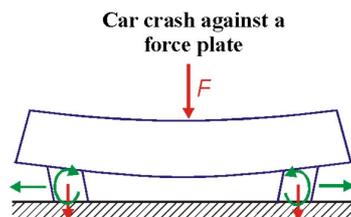


Fig. 1: Car crash against a crash barrier made of several force plates in modular design and schematic drawing of the forces and moments acting on a force plate

Despite through a force component F which acts simply in the normal direction of a force plate, shear forces and bending moments are produced due to deflections of the force plate under load. If the force transducers are sensitive with regard to these influence quantities, measurement errors result. However, investigations of mechanical influence quantities are only possible with static forces.

Due to their small dimensions and high stiffness, piezoelectric force transducers (PFs) are predestinated for dynamic force measurements as impact force measurements in crash tests, for example [1,5]. Different types of these transducers with nominal loads between 5 kN and 20 kN are shown in fig. 2.



Fig. 2: Different types of PFs with nominal loads between 5 kN (PF B_1) and 20 kN (PF A_1 and C_1)

Although PFs show a good dynamic behaviour, static sensor qualities such as linearity, hysteresis, sensitivity, reproducibility and effects of mechanical disturbance properties which are necessary for precision measurements are widely unknown [6,7]. This is due to their active measuring principle - the mechanical energy resulting from forces acting on the PF is directly transformed into electrical energy in the form of induced charges [1,5]. As a result of finite insulation resistance, the induced charges show an exponential decrease. Static high-precision measurements are in principle not possible [8].

To measure the induced charge Q , inverting DC amplifiers with a highly insulating range capacitor as capacitive feedback, so-called charge amplifiers, are used [8]. The capacitive feedback works like an integrator for electric charges induced by load changes acting on the force link. Due to a finite insulating resistance R_G , the range capacitor has an exponential discharge characterized by a time constant τ_G . In addition, a linear drift current I_D , caused by leakage currents of the electronic components in the input circuit of the charge amplifier and offset voltages of the DC

amplifier, affects the measurement. Furthermore, influences of cables, connectors and memory effects of force links may cause a strong and non-reproducible drift rate. With a sensitivity S_{CA} of the charge amplifier and a sensitivity S_{FT} of the PF, the time-dependent output voltage $U_A(t)$ due to a static force F is given by

$$U_A(t) = (S_{CA} \cdot S_{FT} \cdot F + I_D \cdot S_{CA} \cdot t) \cdot e^{-\frac{t}{\tau_G}} \quad (1)$$

and shows that static force measurements with piezoelectric devices are not possible for long-term intervals [8,10].

By the means of insulating resistances $R_G \geq 10^{14} \Omega$ and capacities $C_G \approx 100$ nF of the range capacitor, special charge amplifiers reach time constants of up to $\tau_G \approx 10^7$ s. This corresponds to a relative change of the measurement signal of $6 \cdot 10^{-6}$ within 60 seconds, and less than 0.02 % within 30 minutes. In this case the drift behaviour is characterised by a linear drift current I_D smaller than 0.03 pA for specially modified low-drift charge amplifiers [8]. In conjunction with these amplifiers, static force and weighing measurements are possible for piezoelectric force measuring devices if the measuring times and the times of load change are in the range of a few minutes [2,10]. Thereby, calibration procedures for PFs with static forces should be possible.

The complete piezoelectric force measuring chain is shown in the schematic drawing in fig. 3.

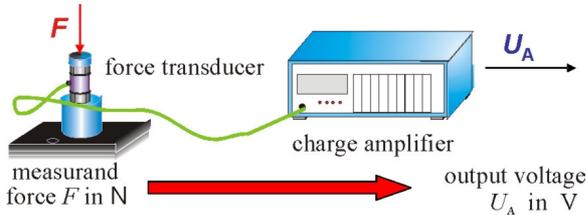


Fig. 3: Schematic drawing of a piezoelectric force measuring chain with a PF as force sensor and a charge amplifier to measure the induced charge

2. CURRENT METHODS AND PROCEDURES FOR STATIC FORCE CALIBRATION

The calibration procedure generally applied at PTB for force measuring devices is given in ISO standard 376 and is not limited to a special measurement principle as, e.g., strain-gauge or piezoelectric [9]. A schematic drawing of the load variation as a function of the measuring time t is shown in fig. 4.

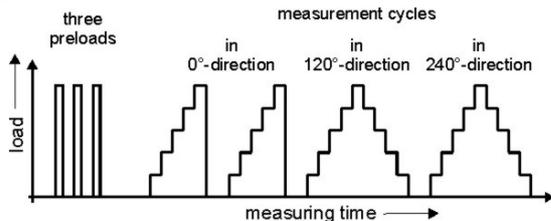


Fig. 4: Schematic drawing of the load variation according to ISO standard 376 as a function of the measuring time t

The force transducers are calibrated by a procedure with stepwise loading and unloading forces. After three preloads,

two increasing measurement cycles are fulfilled. The effect of mechanical disturbance properties is determined by means of $n_{Rot} \geq 2$ additional measurement cycles of increasing and decreasing loads, whereas in relation to the original mounting position the force transducer is mounted around an angle of

$$\varphi_{Rot} = \frac{360^\circ}{n_{Rot} + 1} \quad (2)$$

turned into the force calibration machine.

To evaluate force transducers, the criteria given in ISO 376 are the reproducibility in identical and different mounting positions, the linearity, the hysteresis, the zero error and the creep effects. Linear, quadratic or cubic regression functions describe the metrological characteristic of the transducers.

The acquisition of the measured value may take place 30 seconds after application of the load at the earliest. Thereby, the transient response of the force transducer, e.g., is considered. Admittedly, due to unspecified load change times of the force calibration machine, the total measurement times of a measurement cycle are not specified accurately. Consequently, this calibration procedure is unsuitable for piezoelectric force measuring devices as a result of the linear drift [10].

A modified calibration procedure according to ISO 376, adapted to the requirements of piezoelectric force measuring devices, enables a measurement value acquisition in equidistant time intervals Δt and achieves a better reproducibility of the calibration results [7]. Fig. 5 shows the load variation of this calibration procedure and the respective signal-time dependence diagram of the output signal of a piezoelectric force measuring device with a measurement acquisition in equidistant time intervals.

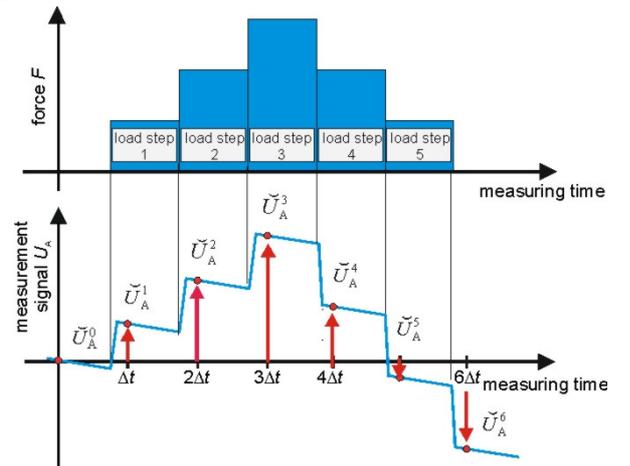


Fig. 5: Load-time dependency of a force standard machine and the respective signal-time dependency of the output signal of a piezoelectric force measuring device with a measurement acquisition in equidistant time intervals

It can be concluded from the figure that the drift affects particularly the measurement signals of the decreasing load steps, and here primarily the load steps for small forces at the end of a measurement cycle. Accordingly, the relative zero error, defined in ISO 376 as the difference between the

measurement value before and after a measurement cycle and divided by its maximum measurement value, shows a strong dependency with respect to the time interval Δt , or to the total time of a measurement cycle.

Investigations carried out with a 20 kN PF confirm this behavior. Fig. 6 shows the relative zero error determined with a 20 kN PF in a partial load range up to 2 kN and its nominal load range as a function of the time interval Δt .

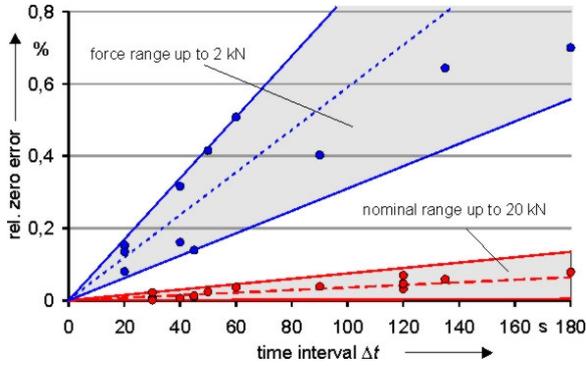


Fig. 6: Rel. zero error as a function of Δt , determined with a 20 kN PF in a partial load range of 2 kN and in the nominal load range

As expected, in both the partial as well as the nominal load range, the relative zero error increases with increasing time interval Δt or with the total time of a measuring cycle. Admittedly, as a consequence of a higher sensitivity of the charge amplifier in the partial load range up to 2 kN, the observed higher drift leads to a substantially higher zero error in this measurement range. Furthermore, the investigations show that also when we consider constant time intervals Δt , the results show a low reproducibility. The causes of this behaviour are triboelectric effects induced in connecting leads and plugs which strongly affect the drift current I_D [1]. Thus, a calibration procedure according to ISO 376 is not a suitable method to calibrate PFs. A calibration of PFs with static forces is in principle only possible when the drift is taken into account. However, the nature of the drift of piezoelectric force measuring devices is widely unknown and requires comprehensive investigations.

3. INVESTIGATIONS OF THE DRIFT BEHAVIOUR

Up to now PFs are calibrated by the manufacturer, using continuously increasing and decreasing forces generated in a hydraulic force press [6,10]. Due to the short total measuring times of a continuous measurement cycle, drift effects are negligible. On the other hand, dynamic effects and a measurement quantity force which is not directly traceable to national standards lead to an increased relative uncertainty of $2 \cdot 10^{-3}$ ($k=2$) [6].

For static calibration, the force is generated at PTB in force standard machines with much smaller relative uncertainties up to $2 \cdot 10^{-5}$ ($k=2$) [11]. Indeed, as pointed out in fig. 6, the drift behaviour of piezoelectric force measuring devices in combination with a total measuring time in a range of a few minutes leads to a measurement error and increased measurement uncertainties.

Measurement errors are based on systematic influence quantities, they are, in principle measurable and can thus be compensated or be considered by a suitable analytic model.

In contrast to this, measurement uncertainties can be estimated according to the ‘‘Guide of the Expression of Uncertainty in Measurement’’, e.g., and are based on metrologically not determinable, stochastic influence quantities [12].

For piezoelectric force measuring devices, the linear drift of the charge amplifier is a systematic influence quantity, which can, in principle, be compensated, whereas measurement signal variations due to triboelectric effects and temperature gradients are inherently stochastic and partially affect the drift significantly. Due to these stochastic effects a precise, reproducible prognosis of the drift at any time of a measurement is practically impossible [10]. In addition, effects of the PFs on the drift behaviour which so far have been unknown have to be considered, as illustrated in fig. 7.

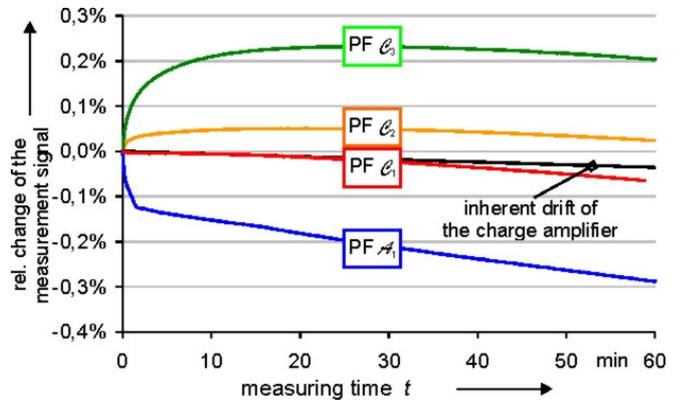


Fig. 7: Relative change of the measurement signal of different 20 kN-PFs under nominal load and the inherent drift of the charge amplifier as a function of the measuring time t .

Fig. 7 shows the relative change of the measurement signal of four 20 kN-PFs under nominal load as a function of the measuring time t . The inherent drift of the charge amplifier in use ($S_{CA} = 1/8000$ V/pC), which is also shown in this figure, is determined, as the appropriate charge is produced not by a PF under load, but by a charge calibrator. Thereby, the examined PFs show behaviours with regard to the drift influence which clearly differ partially from each other.

While PF \mathcal{E}_1 scarcely affects the linear drift of the charge amplifier, PF \mathcal{A}_1 shows a significantly higher drift within the first minutes after loading. On the other hand, the loading drifts of PF \mathcal{E}_2 and \mathcal{E}_3 provide a non-linear increase in the measurement signal of up to 0.05 % (for PF \mathcal{E}_2) and more than 0.2 % (for PF \mathcal{E}_3), despite a decreasing drift signal of the charge amplifier. Admittedly, also a reduction in the measurement signal is observed with these PFs approximately 30 minutes after the load application.

Similar drift behaviour, with reverse sign, is observed due to the subsequent unloading of the PF. For the first time, investigations reveal a characteristic loading and unloading drift effect of PFs which depends on the load history of the

PF as well as on the load change. In addition, the investigations show, just about 30 minutes after a load change, that only the linear drift of the charge amplifier provides a significant drift contribution.

Thereby, the observed long-term drift behaviour of piezoelectric force measuring devices offers the possibility of estimating both an expected drift value D_0 for the linear drift component as well as the variability δD of the drift specified by upper and lower drift limits (see fig. 8).

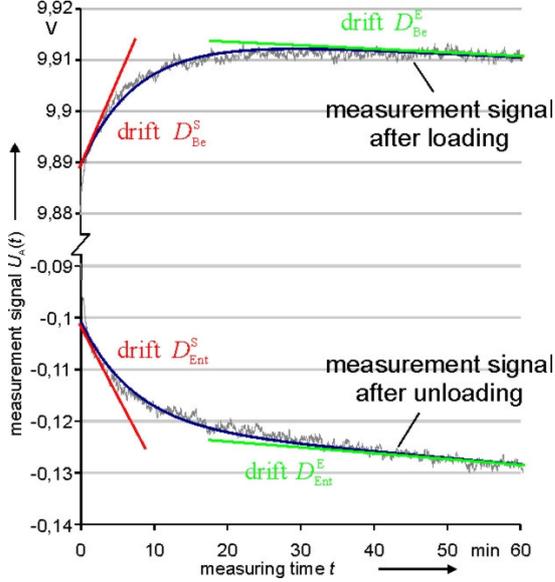


Fig. 8: Measurement signal while loading and unloading PF \mathcal{C}_3 with a nominal load of 20 kN as a function of the measuring time t

If D_{Be}^E and D_{Ent}^E indicate the measured linear drift at the end of the loading and unloading period, the expected drift value D_0 is the calculated mean value

$$D_0 = \frac{D_{Be}^E + D_{Ent}^E}{2} \quad (3)$$

This value corresponds as far as possible to the linear drift of the charge amplifiers, but considers also triboelectric effects, if these are characterised by means of sufficiently large time constants in the range from hours to days [1].

The drift variability δD is defined as the maximum occurring drift deviation during a loading and unloading cycle. Maximum drift deviations are observed immediately after loading and unloading a PF. If D_{Be}^S is the drift directly after loading and D_{Ent}^S the corresponding drift directly after unloading, the variability δD is given by

$$\delta D = \pm \max(|D_{Be}^S - D_0|; |D_{Ent}^S - D_0|). \quad (4)$$

The investigations carried out supply a partially substantial variation δD of the drift, δD of PF \mathcal{C}_3 for example, amounts to 50 times (!!!) the expected drift value D_0 . This large drift variability illustrates the problems which arise when analytical procedures are used for drift compensation in combination with static calibration methods as those described, e.g., in ISO 376. Even if the time of load change of the force standard machine (FSM) is taken into account and

the drift D_0 is well known, due to long total measurement times a high time stability of the drift is necessary for acceptable measurement uncertainties, in particular for the small load steps at the end of a measurement cycle. As shown in fig. 7 and 8, this cannot be assumed for every PF.

4. THE NEW CALIBRATION METHOD

The previous discussion shows that for calibrating PFs with static forces and a high accuracy, a calibration procedure adapted to the special requirements of this measuring technique is essential. In the following, a recommendation for a new calibration procedure is introduced and discussed. Thereby, the new calibration procedure should

- enable a fast, simple and comprehensive characterisation of the static sensor qualities. If possible, the drift should have no systematic influence on the calibration results.
- ensure the evaluation and comparability of characteristic sensor qualities determined in different FSMs and for different PFs.
- supply a contribution for the reduction in the measurement uncertainty.

In the following, we will look into the possibility of transferring the evaluation criteria for the evaluation of force transducers given in ISO 376 to PFs. The reproducibility of the measurement results under identical metrological boundary conditions and the linearity are important validation criteria also for piezoelectric force measuring devices. Furthermore, as the drift behaviour is affected significantly by the PF (see figs. 7 and 8), this has to be taken strictly into account with the new calibration procedure.

Admittedly, due to the active measuring principle, PFs have no defined zero point. Only load changes are detectable. So the zero error defined in ISO 376 as criterion for the zero point stability of force transducers is not applicable for PFs.

Also very important for strain gauge transducers, but not applicable to PFs, is the reversal error as a criterion to evaluate the hysteresis behaviour.

The hysteresis is caused by load- and time depending creep effects, e.g. mechanical after-effects, which are generated by means of thermal relaxation, atomic diffusion processes and after-effects in inhomogeneous materials [10].

A typical example of atomic diffusion processes is displacement- and shifting processes of the atomic structure, e.g. of metallic materials under load. Synthesised crystalline materials such as α -quartz, e.g., - as is mainly used in PFs -, are largely free of crystal scavengers and imperfections [10]. For this reason, atomic diffusion processes in α -quartz play a negligible role in mechanical after-effects.

Similar results show inhomogeneities in α -quartz which are mainly plastic deformations at grain boundaries, contaminations and imperfections.

What remains is the influence of thermal relaxations during the deformation as a result of an adiabatic change of conditions. A temperature-dependent expansion coefficient leads to a change of strain characterised by a time constant. This is, e.g., a reason for the noticeable hysteresis behaviour of piezoelectric actuators. But this effect does not have an immediate influence on the state of stress within the piezoelectric material and consequently is not responsible for a charge induction.

Simply thermal stress caused by inhomogeneous temperature fields affects the polarisation. But the charges induced by this effect are negligible. Thus, for PFs the effects responsible for after-effects in strain-gauge force transducers are only of inferior relevance.

Another possible cause for hysteresis behaviour is the ferroelectric material property observed in pyroelectric materials as a special kind of piezoelectric sensor material. Admittedly, α -quartz does not belong to the group of pyroelectric materials and thus has no ferroelectric properties [10].

Further possible reasons for hysteresis are mechanical after-effects of the force introduction and the prestressing bolt of a PF [10]. As these sensor components are made of stainless steel they offer mechanical after-effects in the form of additional elongations and transverse strain. This leads to a change of the force shunt and in the sensitivity of the PF. Admittedly, the relative change of the measurement signal as a result of geometric nonlinearities due to elongations and transverse strain under nominal load is less than 10^{-5} [13]. Since mechanical after-effects are at least two or three orders of magnitude smaller than geometrical nonlinearities, they are also negligible.

These theoretical considerations show that hysteresis effects are metrologically of no relevance for PFs. This is confirmed by experimental investigations in [7].

As PFs show neither a significant hysteresis nor zero point variations for strain-gauge force transducers in-applicable load variations in pilgrim-steps with fast loading and unloading of each single load step can be used to characterise these transducers.

The schematic drawing of the load variation of the newly developed static force calibration procedure for PFs as a function of the measuring time t is shown in fig. 9.

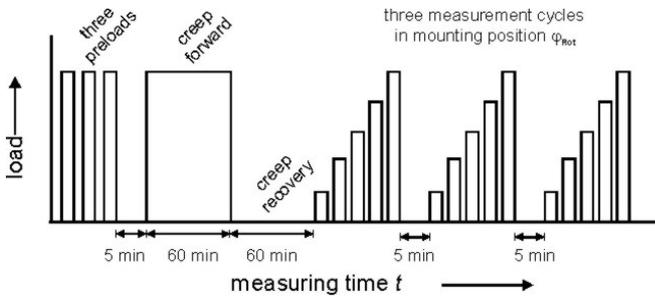


Fig. 9: Schematic drawing of the load variation as a function of the measuring time t of the newly developed static force calibration procedure for PFs

The preload at the beginning of a load variation is evidence for the reduction of long term-effects and to create defined operating conditions of the PF.

The loading break of 5 min which follows ensures the deactivation of time-dependent influence factors having been caused by the preloading. The loading- and unloading behaviour of a PF is measured together with the system's inherent drift of the charge amplifier due to a 60 min creep forward measurement and a subsequent unloading period (creep recovery). The real characterisation of a PF is carried out by at least three measurement cycles in pilgrim-steps, with $8 \leq n_L \leq 10$ increasing, equidistant load steps. According to ISO 376 the three measurement cycles are repeated in $n_{Rot} \geq 2$ other mounting positions of the PF to take the influence of mechanical disturbing properties into account (see eq. 2).

The examination results from the drift-affected change \tilde{U}_{load}^i and \tilde{U}_{unload}^i of the measurement signal while loading and unloading the PF with pilgrim-steps, as schematically shown in fig. 10.

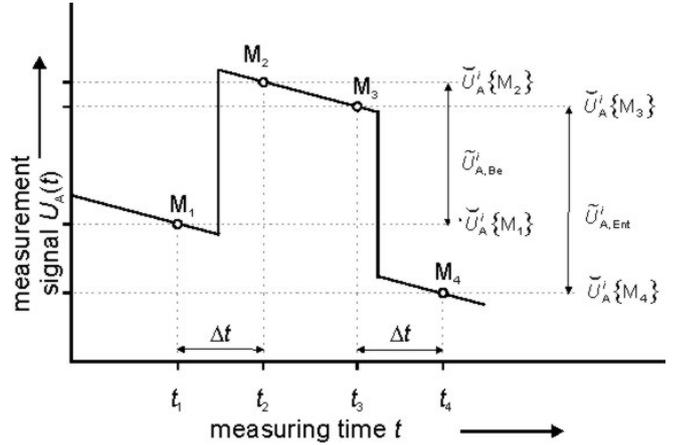


Fig. 10: Schematic drawing of the drift-affected measurement signal while loading and unloading the PF with pilgrim-steps as a function of the measuring time t and the times t_1 up to t_4 of the measurement acquisition

Both the transient response of the measurement system as well as the maximum time of load change of the force calibration machine in use are considered by a sufficiently long and fixed time interval Δt between the times t_1 and t_2 , respectively t_3 and t_4 , of the measurement value acquisition. The calibration procedure thus allows measurements without a defined zero point of the charge amplifier.

If the measurement values are denoted $\tilde{U}_A^i\{M_1\}$ up to $\tilde{U}_A^i\{M_4\}$, the drift-affected change of the measurement signal while loading is given by

$$\tilde{U}_{load}^i = \tilde{U}_A^i\{M_2\} - \tilde{U}_A^i\{M_1\} = U_{load}^i + \underbrace{D \cdot \Delta t}_{\text{linear drift fraction}} \quad (5)$$

and described by

$$\tilde{U}_{unload}^i = \tilde{U}_A^i\{M_3\} - \tilde{U}_A^i\{M_4\} = U_{unload}^i - \underbrace{D \cdot \Delta t}_{\text{linear drift fraction}} \quad (6)$$

for unloading the PF. The corresponding measurement values without a time-dependent drift fraction are called U_{load}^i and U_{unload}^i .

As eq. (5) and eq. (6) show identical, but directly opposed linear drift fractions by means of averaging the measurement value,

$$U_A^i = \frac{1}{2}(\tilde{U}_{\text{load}}^i + \tilde{U}_{\text{unload}}^i) = \frac{1}{2}(U_{\text{load}}^i + U_{\text{unload}}^i) \quad (7)$$

is independent of the linear drift of the charge amplifier and thus independent of the time interval Δt . The result in eq. (7) thus considers a systematic, but unknown linear drift of the charge amplifier without determining the drift explicitly. Consequently, a new calibration procedure with static forces is available for PFs. This calibration procedure is both independent of the total time of a measurement cycle and independent of the maximum time of load change of the FSM in use. The existent drift behaviour of a piezoelectric force measuring device simply affects the uncertainty. Since the time of a load change is in a range from a few seconds up to a few minutes for any FSM, the expected uncertainty of the calibration result is significantly smaller compared to results achieved with analytical drift revised calibration procedures according to ISO 376.

5. RESULTS

Subsequent calibration results achieved with the new calibration procedure with static forces are presented and discussed for the PFs \mathcal{A}_1 , \mathcal{C}_1 and \mathcal{C}_3 . Initially, fig. 11 shows the different uncertainty contributions of the sensitivity in percent of the total uncertainty determined for PF \mathcal{C}_1 with a partial load of 2 kN.

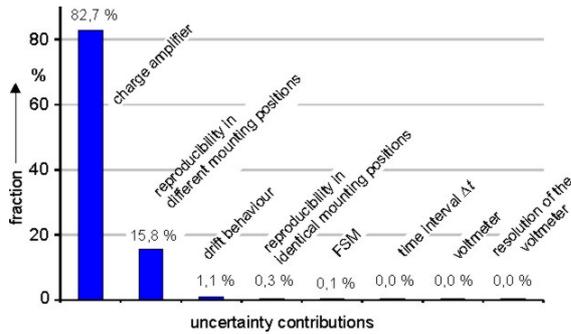


Fig. 11: Different uncertainty contributions of the sensitivity in percent of the total uncertainty determined for PF \mathcal{C}_1 with a partial load of 2 kN

The resolution of the voltmeter used for analysing the output signal of the charge amplifier as well as the uncertainty of the time interval Δt make virtually no contribution to the total uncertainty. Furthermore, the uncertainty contributions of the FSM (0.1%) and the reproducibility of the measurement results in identical mounting position (0.3%) are negligibly small. With a value of 1.1% the uncertainty contribution as a result of the drift variation δD (see eq. 4) is surprisingly small. But as shown

in fig. 7, PF \mathcal{C}_1 affects the linear drift of the charge amplifier only marginally and thus explains the small uncertainty contribution of the drift variation.

With 15.8% the reproducibility in different mounting positions provide a considerable uncertainty contribution which is exceeded only by the uncertainty of the charge amplifier (82.7%). The large uncertainty contribution of the charge amplifier is due to a relative uncertainty of $7 \cdot 10^{-4}$ ($k=2$) of a charge calibrator to generate static charges necessary to calibrate charge amplifier.

Accordingly, the relative extended uncertainty of PF \mathcal{C}_1 , estimated for a partial load of 2 kN, is mainly affected by the uncertainty of the charge amplifier and amounts to $8 \cdot 10^{-4}$ ($k=2$). This uncertainty is smaller by an order of magnitude of one than the uncertainty of $2 \cdot 10^{-3}$ ($k=2$) which has been evaluated with manufacturer-specific continuous calibration procedures [3].

Compared with \mathcal{C}_1 , the uncertainty contributions of the sensitivity determined for PF \mathcal{A}_1 and \mathcal{C}_3 with a partial load of 2 kN are mainly affected by the variation δD of the drift (see fig. 12).

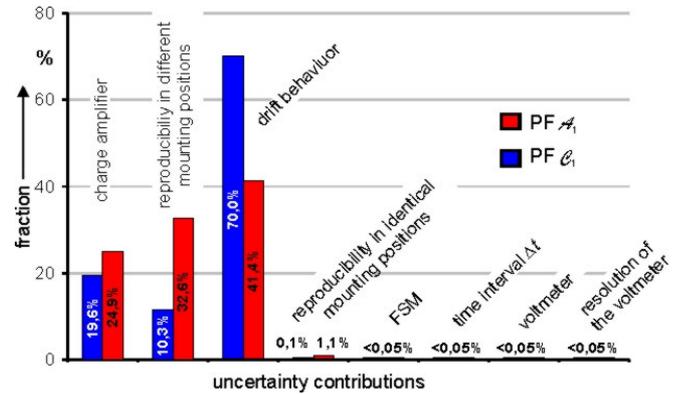


Fig. 12: Different uncertainty contributions of the sensitivity in percent of the total uncertainty, determined for PF \mathcal{A}_1 and \mathcal{C}_3 with a partial load of 2 kN.

For PF \mathcal{A}_1 with a value of 32.8%, the reproducibility in different mounting positions contributes to the total uncertainty even more than the uncertainty contribution of the charge amplifier (24.9%). This result suggests a high sensitivity of PF \mathcal{A}_1 with regard to the effects of shear forces and bending moments and underlines the necessity to study mechanical disturbance effects more comprehensively.

The relative extended uncertainty of PF \mathcal{A}_1 and \mathcal{C}_3 for a partial load of 2 kN amounts to $2 \cdot 10^{-3}$ ($k=2$) and is thus essentially larger than for PF \mathcal{C}_1 .

6. CONCLUSION

The presented new calibration method offers for the first time an opportunity to calibrate PFs with static forces. The method is both independent of the time of load change of a FSM and independent of an unknown linear drift of the charge amplifier. This ensures the evaluation of PFs with

static sensor characteristics, which are widely independent of the FSM and the charge amplifier used for determination.

Consequently, not only strain-gauge force transducers, but also piezoelectric force transducers can in principle be calibrated with the FSM used at PTB. The uncertainty achieved with the new calibration method is up to the order of magnitude of quantity smaller than the uncertainty determined by manufacturers of PFs with continuous calibration methods. Admittedly, more, and more comprehensive investigations are necessary to gain enough confidence in this procedure to standardise it.

The investigations carried out with the new calibration method reveal a significant uncertainty contribution of mechanical disturbing components. This result underlines the necessity to investigate the shear force sensitivity and the bending moment sensitivity of PFs. Corresponding investigations require examination methods with static forces, as specified with the new calibration method.

Beyond this, the investigations demonstrate the need of static sensor characteristics also for dynamic precision measurements. Particularly with regard to dynamic applications as, e.g., measurements of impact forces at crash barriers, mechanical disturbing components affecting the result have not been considered up to now.

But also in weighing technology, the new calibration method is of particular importance. As shown in [2], PFs are qualified for applications in weighing technology if the measurement time is in a range of a few minutes. But a certification of PFs according to the international recommendation OIML-R60 for load cells is difficult [2]. In conformity with ISO 376 the recommendation OIML R60 considers the drift behaviour of a piezoelectric force measuring device only insufficiently. In principle, the measurement cycles with pilgrim-steps and the evaluation method presented in this article can be transferred to a procedure to certify PFs as load cells.

Furthermore, potentially different aspects of the calibration method are suitable to be used as a standard practice also for the calibration of torque-, pressure- or acceleration transducers with static loads.

7. ACKNOWLEDGMENTS

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