

INVESTIGATIONS OF PIEZOELECTRIC FORCE MEASURING DEVICES FOR USE IN LEGAL WEIGHING METROLOGY

Oliver Mack

Physikalisch-Technische Bundesanstalt, PTB, Germany

ABSTRACT

In conjunction with low-drift charge amplifiers static force and weighing measurements get more and more important for piezoelectric force transducers if the measuring time and time of load change are in the range of a few minutes. The presented investigations according to the international recommendation OIML R60 [7] point out, that piezoelectric sensors can be used for static applications with low accuracy requirements (e.g. class D for ordinary accuracy weighing instruments). With suitable methods for compensation or adjustment the sensors even meet the higher requirements of medium accuracy class C (e.g. commercial scales). Especially for high nominal loads the piezoelectric measurement technology offer unused potentials also for static precision measurements.

1. INTRODUCTION

Due to their small dimensions and high stiffness piezoelectric force measurement devices are predestinated for dynamic force measurements [1]. They are used e.g. in production control, in walls for crash testing of cars, or in biomechanics to analyse the forces exerted by the feet of humans in walking, running or jumping [2, 3]. The inherent drift of piezoelectric force measuring devices suggest that static measurements of high accuracy are not possible. Admittedly, with modern charge amplifiers quasistatic measurements characterized by a linear instead of an exponential drift are possible [4-6]. Using these special charge amplifiers measurements of static forces and masses become more and more important for piezoelectric force measurement devices if the measurement time and the time of load change is within a range of a few minutes. But the obtainable classifications of piezoelectric force measurement devices according to the international recommendation OIML R60 and the limits of classification are unknown.

2. PRINCIPLE OF PIEZOELECTRIC FORCE MEASUREMENT

A very useful type of force sensor is the so-called load washer (Figure 1a). A load washer is based on a ring-shaped base plate (1) and a top plate (2), both with an E-module E_A , two ring-shaped quartz plates (3) electrically in parallel (E-module E_P) and an electrode placed between the two quartz plates (4).

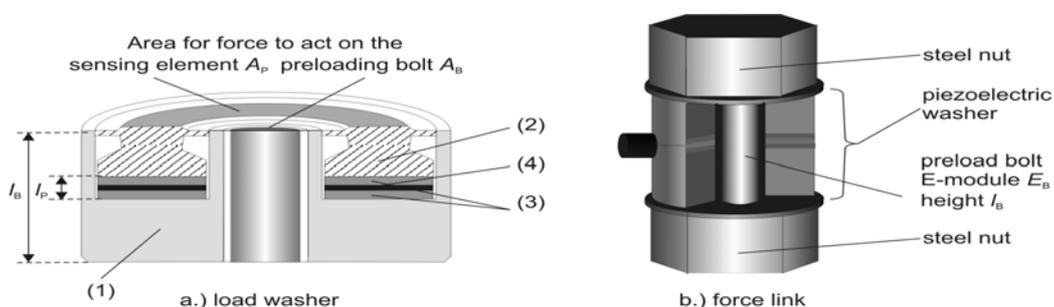


Figure 1: Piezoelectric load washer and schematically assembly of a piezoelectric force link

Load-washer-type force sensors which are already mounted and preloaded by means of two steels nuts and a preloading bolt are known as force links (Figure 1b) and permit compression

and tension force measurements. The measurement range of force links is less than ± 1 kN up to over ± 100 kN [3]. The sensitivity S_{KA} determined by an analytical model described in [8] depends on the geometry and the material properties of the force link and is given by

$$S_{KA} = \frac{Q}{F} = \frac{d_{11}}{\phi + 1} \quad (1)$$

with

$$\phi = \frac{A_B}{A_P} \cdot \left[\frac{I_P}{I_B} \chi \cdot \frac{E_B}{E_P} + \frac{E_B}{E_A} \cdot \left(1 - \frac{I_P}{I_B} \right) \right] \quad (2)$$

The model provides a linear correlation between the acting force F and the charge Q induced. The sensitivity of a x-cut quartz plate normally used as sensor element of load washer is given by the piezoelectric coefficient $d_{11}=2,3$ pC/N [3].

A charge amplifier measures the induced charge Q . Basically a charge amplifier is just an inverting DC amplifier with a highly insulating range capacitor as capacitive feedback [9-11]. 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 . Additionally 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 not reproducible drift rate. With a sensitivity S_{LV} of the charge amplifier the time depending output voltage $U_a(t)$ due to a static force F is given by

$$U_A(t) = S_{LV} \cdot (S_{KA} \cdot F + I_D \cdot t) \cdot e^{-\frac{t}{\tau_G}} \quad (3)$$

and point out piezoelectric measurements of static forces for any long time interval are not possible.

By insulating resistances $R_G \geq 10^{14}$ and capacities $C_G \approx 100$ nF of the range capacitor special charge amplifiers obtain time constants up to $\tau_G \approx 10^7$ s. This is equal 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 [11]. In conjunction with these amplifiers static force and weighing measurements are possible for piezoelectric force measurement devices if the measuring time and time of load change is in the range of a few minutes [12].

3. TESTS ACCORDING TO OIML-RECOMMENDATION R60 FOR LOAD CELLS

The subsequently presented investigations are based on the recommendation OIML R60 for load cells and consider the reproducibility, linearity, hysteresis and creep effects respectively the zero point return at 20°C, 40°C und -10°C. The influences of humidity and barometric pressure are not the matter of this paper. Corresponding results are given in [12]. The recommendation OIML R60 approves so called accuracy tests with increasing and decreasing discrete load steps. The recommended test sequence for each test temperature is shown in figure 2.

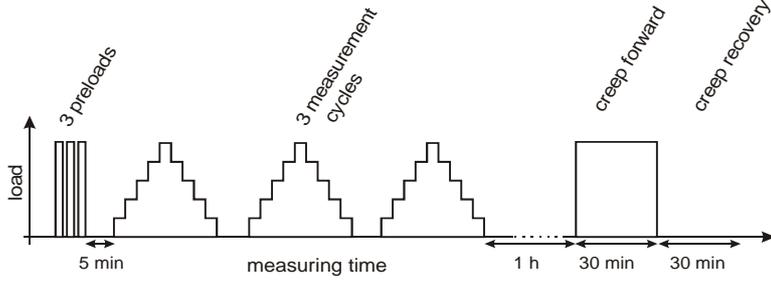


Figure 2: Recommended test sequence for each temperature according to OIML R60

The measurement values are taken at a time interval between 10 seconds and 60 seconds after the initiation of loading or unloading and applicable on the load change. The creep forward and creep recovery are measured for $t_D = 30$ minutes respectively and one hour after the accuracy test. Load cells are classified in four accuracy classes A to D. The maximum number of load cell verification intervals is n_{\max} . The requirements of an accuracy class are fulfilled, if the error of measurement is within a maximum permissible error (mpe). The mpe depends on the maximum load m and n_{\max} . Table 1 shows the accuracy classes and the corresponding maximum permissible errors with a verification interval

$$v = \frac{m}{n_{\max}} \quad (4)$$

Table 1: Accuracy classes and corresponding maximum permissible errors (mpe). The apportionment factor is typically $p_{LC}=0,7$ for load cells.

| mpe | class A | class B | class C | class D |
|----------------------|------------------------------|----------------------------|--------------------------|------------------------|
| $p_{LC} \times 0,5v$ | $0 \leq m \leq 50000v$ | $0 \leq m \leq 5000v$ | $0 \leq m \leq 500v$ | $0 \leq m \leq 50v$ |
| $p_{LC} \times 1,0v$ | $50000v \leq m \leq 200000v$ | $5000v \leq m \leq 20000v$ | $500v \leq m \leq 2000v$ | $50v \leq m \leq 200v$ |
| $p_{LC} \times 1,5v$ | $200000v < m$ | $20000v < m$ | $2000v < m$ | $200v < m$ |

Subsequently not the mass m but the force F acting on the force link is taken into account. The force F is the product of the mass m and the local acceleration of gravity g_{loc} :

$$F = m \cdot g_{loc} \cdot \left(1 - \frac{\sigma_L}{\sigma_m} \right) \quad (5)$$

The correction term considers the buoyant force and depends on the densities σ_m and σ_L of the mass m and the ambient air.

4. CLASSIFICATION LIMITS GIVEN BY THE DRIFT

According to eq. (3) the linear drift of piezoelectric force measurement devices is independent of the acting force F . Respectively the relative drift rate of the measurement signal decrease with increasing force F . Based on the assumption that creep forward and creep recovery measurements are the criterion crucial for classification n_{\max} is given by

$$n_{\max} = \frac{S_{KA} \cdot F \cdot mpe}{I_D \cdot t_D} \quad (6)$$

The theoretically possible classification of piezoelectric force measurement devices with low-drift charge amplifiers depends on the nominal load F and is shown in table 2.

Table 2: Theoretically possible classification of piezoelectric force measurement devices according to eq. (6) with low-drift charge amplifiers and experimental results

| Nominal load F | theoretically | | experimentally | |
|--|---------------|------------|----------------|---------------------|
| | Class | n_{\max} | class | n_{\max} |
| 5 kN | D | 350 | D | 300 |
| 20 kN | C | 1000 | C | 800 |
| 60 kN | C | 4500 | C | 800 ^{1.)} |
| 100 kN | C | 7500 | C | 1000 ^{1.)} |
| ^{1.)} Investigations of load washer carried out in the 100 kN force standard machine without consideration of temperature effects | | | | |

Theoretically force links with a nominal load of 100 kN reach class C7,5 with 7500 verification intervals and allow measurements of static forces with an accuracy in the order of strain gauge load cells. Admittedly force links with smaller loads simply reach more unfavourable accuracy classes for example D0,35 with 350 verification intervals for a nominal load of 5 kN. In opposite to theoretical results experimental investigations supply a lower accuracy class. This is caused by additional drift currents due to the force link, influences of cables, connectors and exponential drift rates if high accuracy classes are chosen.

5. EXPERIMENTAL SETUP

All the following drift measurements and accuracy tests had been carried out at PTB's 5 t (50 kN) dead load force standard machine shown in figure 3.

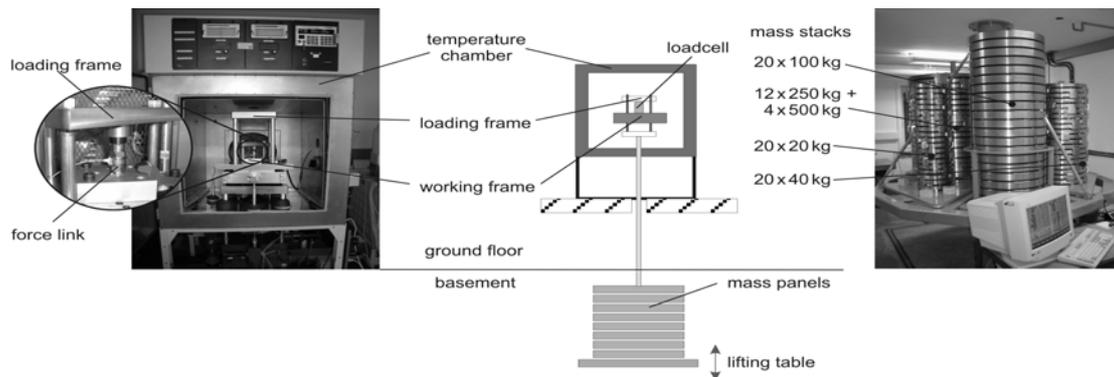


Figure 3: 5 t (50 kN) dead load force standard machine for testing load cells

The force link which will be examined is mounted on a working table. Via a loading frame one of all in all four mass stacks with maximum weights between 400 kg and 5 t is coupled to the force link. A lifting table allows the positioning of the mass stacks and the coupling of single mass panels. For examinations in a temperature range between -10°C and $+40^{\circ}\text{C}$ the working frame, test sample and loading frame are inside a climatic chamber. The following investigations refer to the identical in construction 5 kN and 20 kN force links shown in table 2.

6. RESULTS OF ACCURACY TESTS

Figure 4 shows the characteristic curves of a 20 kN force link under -10°C , 20°C and 40°C conditions. But in principle every 5 kN and 20 kN force link investigated has the same characteristic curves shown in figure 4. This means that the classification according to OIML recommendation R60 is independent of the nominal load if the force links are identical in construction. The results point out because of strong temperature dependencies and nonlinearities the 5 kN and 20 kN force links investigated simply reach the low class D0,12 of ordinary accuracy weighing instruments with 120 verification intervals.

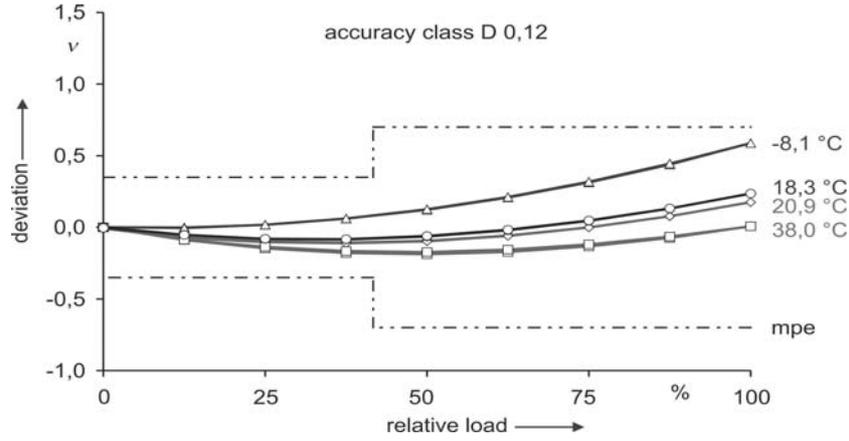


Figure 4: Deviation expressed in verification intervals v as a function of the relative load of a 20 kN force link under -10°C , 20°C and 40°C conditions

This classification is substantially much lower than the experimental and theoretical classifications in table 2 as result of the drift. Consequently not the drift but nonlinearities and temperature effects are the criterion crucial for the classification of piezoelectric force measurement devices.

7. CAUSES FOR TEMPERATURE DEPENDENCY AND NONLINEARITY

Possible causes for the nonlinear behaviour are geometrical nonlinearities and nonlinear material properties. As affiliated in [6] geometrical nonlinearities of a force link under load cannot explain the nonlinear behaviour observed. For this reason subsequently the material properties of quartz as sensor material of x-cut plates are discussed as possible causes for the temperature dependency as well as the nonlinearity.

The temperature coefficient $\tau_{11} = -2,15 \cdot 10^{-4} \text{ K}^{-1}$ based on $\vartheta_0 = 20^{\circ}\text{C}$ characterizes the effect of temperature ϑ on the piezoelectric coefficient d_{11} :

$$d_{11}(\vartheta) = d_{11} (1 + \tau_{11} (\vartheta - \vartheta_0)) \quad (7)$$

The nonlinear behaviour is given by

$$S_{KA}(d\sigma_F, \sigma_V) = \frac{d_{11}}{\phi + 1} + \frac{g_{111}}{\phi + 1} \cdot (2\sigma_V + d\sigma_F) \quad (8)$$

The electroelastic coefficient of x-cut quartz plates is $g_{111} = 62,3 \cdot 10^{-23} \text{ Cm}^2\text{N}^{-2}$ and specifies the quadratic relationship between mechanical stress and induced charge, $d\sigma_p$ qualifies the change of mechanical stress due to a force F acting on the force link and σ_V describes the preload through the preloading bolt.

In practice a generally accepted conservative limit for the preload of quartz is $\sigma_{\max} = 150 \cdot 10^6 \text{ Nm}^{-2}$ [3]. Assuming identical ranges of compression and tension force the maximum change of mechanical stress $d\sigma_p = 75 \cdot 10^6 \text{ Nm}^{-2}$ is realised with a preload of $\sigma_V = 75 \cdot 10^6 \text{ Nm}^{-2}$. Thus after equation (7) and (8) the characteristic curves in consideration of temperature dependency and maximum nonlinearity can be determined analytically. Figure 5 pictures these characteristic curves under -10°C , 20°C and $+40^{\circ}\text{C}$ conditions as a function of the relative load and based on the nominal load.

The high correlation between theory (figure 5) and experiment (figure 4) confirmed both the analytical model and material properties as ultimate cause for temperature dependency and nonlinear behaviour.

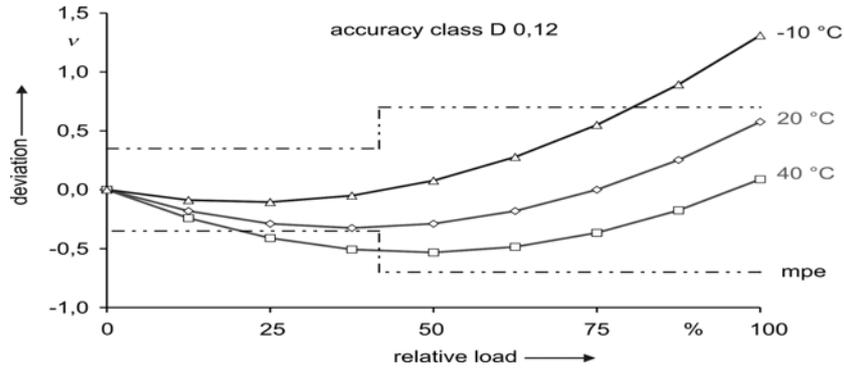


Figure 5: Deviation expressed in verification intervals ν as a function of the relative load of analytically determined characteristic curves of piezoelectric force links under -10°C , 20°C and $+40^{\circ}\text{C}$ conditions

Admittedly the analytical model does not hold the *mpe* of D0,12 experimentally achieved. This is the result of the analytical models' worst case estimation. For real force links the maximum change of mechanical stress $d\sigma_p$ is smaller than $75 \cdot 10^6 \text{ Nm}^{-2}$, because there is a preload essential even if a maximum tension load acts on the force link and result in a reduction of the measurement range.

8. OFFLINE COMPENSATION OF TEMPERATURE DEPENDENCY AND NONLINEARITY

As shown in figure 5 the temperature dependency and nonlinearity are caused by constant material coefficients. The high reproducibility of this coefficients for every x-cut plate offer the use of electronic compensation in the context of so called mechatronic systems. Corresponding systems for digital strain gauge load cells are used to compensate temperature effects, nonlinearities and creep. The digital measurement value is temperate compensated, linearised and standardised. Admittedly appropriate systems for piezoelectric force measurement devices are unknown.

To check the potential of compensation systems figure 6 presents the results under -10°C , 20°C and $+40^{\circ}\text{C}$ conditions of an offline compensation of temperature effects and nonlinearities by example of a 5 kN force link . The parameter to characterise the force link are determined with a new developed calibration methods specified in [1,2].

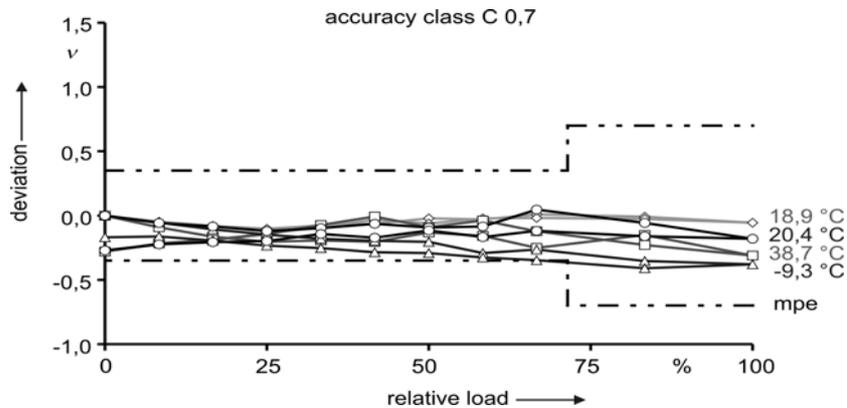


Figure 6: Deviation expressed in verification intervals ν as a function of the relative load of off-line compensated accuracy tests of a 5 kN force link under -10°C , 20°C and 40°C conditions.

For all temperatures the characteristic curves are within an accuracy class C0,7 with 700 verification intervals. Only with these or higher accuracy classes the drift defines the limit of

accuracy.. Particularly in regard to force links with high nominal loads and correspondingly small drift values significant higher accuracy classes are to be expected. Corresponding investigations are still pending.

9. CONCLUSION

The investigations point out piezoelectric force measurement devices in conjunction with low-drift charge amplifiers are simply qualified for low accuracy classes of load cells (e.g. class D for ordinary accuracy weighing instruments) and if the time of load change is in the range of a few minutes. The limiting factor is not as expected the drift. Rather temperature dependencies and nonlinearities describable through material coefficients are the reason for low classification. The piezoelectric material coefficients of quartz are constants and consequently identical for every x-cut plate used in a force links. For this reason force links identical in construction but with different nominal loads show in principle identical behaviour (see figure 4).

The traceability of temperature- and linearity effects to constant material coefficients and the achieved high reproducibility offer compensation methods due to mechatronic systems known from digital load cells. Especially for high nominal loads the piezoelectric measurement technology in conjunction with mechatronic systems and low-drift charge amplifiers seems to offer unused potentials also for static precision measurements.

10. LITERATUR

- [1] Kumme, R.; Mack, O.; Bill, B.; Haab, H. R.; Gossweiler, C., "Dynamic Properties and Investigations of Piezoelectric Force Measuring Devices", *VDI-Bericht 1685*, VDI Verlag GmbH, Düsseldorf 2002, ISBN 3-18-091685-0, pp. 161-172
- [2] Mack, O., "Investigations of the Influence of Disturbing Components on a Piezoelectric Force Transducer", *VDI-Bericht 1685*, VDI Verlag GmbH, Düsseldorf 2002, ISBN 3-18-091685-0, pp.417-424
- [3] Gautschi, G., *Piezoelectric Sensorics*, Springer Verlag, Berlin Heidelberg, 2002 ISBN 3540422595
- [4] Mack, O., "New procedures to characterise drift and non-linear effects of piezoelectric force sensors", *Proceedings of the IMEKO TC3 Conference Istanbul (Turkey)*, pp. 141-148, 17.-21. Sept. 2001
- [5] Mack, O., Kumme, R., "Quasistatic and dynamic investigation methods of piezoelectric force measurement devices", *Proceedings of the IMEKO TC3/APMF, Taejon, (Republic of Korea)*, 14.-18. Sept. 1998, pp.310-320
- [6] Kumme, R.; Mack, O.; Bill, B.; Haab, H. R.; Gossweiler, C., "Investigation of Piezoelectric Force Measuring Devices in Force Calibration and Force Standard Machines", *Proceedings of the 17th International Conference on Force, Mass, Torque and Pressure Measurement, IMEKO TC3, 2001, Istanbul*
- [7] International Recommendation OIML R60 for load cells, Edition 2000, Bureau International de Métrologie Légale, Paris, France
- [8] Mack, O., "Reasons for the nonlinearity of piezoelectric force transducers", *VDI-Bericht 1829*, VDI Verlag GmbH, Düsseldorf 2004, ISBN 3-18-091829-2, pp.153-161
- [9] Kail, R.; Mahr, W., "Piezoelektrische Messgeräte und ihre Anwendungen", *Messen und Prüfen*, Bd.20, 1984, H.7...12
- [10]Tichy, J.; Gautschi, G., "Piezoelektrische Messtechnik", Springer Verlag, Berlin Heidelberg, 1980 ISBN 3-540-09448-2
- [11]Mahr, W., "Messen und Verarbeiten von Ladungssignalen piezoelektrischer Aufnehmer", *Technisches Messen*, **49**. Jahrgang 1982, Heft 4, S.149-158
- [12]Mack, O., Schwartz, R., Möglichkeiten und Grenzen piezoelektrischer Kraftaufnehmer in der Kraftmess- und Wägetechnik, *47. Internationales Wissenschaftliches Kolloquium der Technischen Universität Illmenau*, 23.-26. September 2002

Address of the Author:

Oliver Mack, Department 1.1 Mass, Working Group 1.12 Weighing Instruments, Physikalisch-Technische Bundesanstalt, Bundesallee 100, D-38116 Braunschweig, Germany, Phone: +49(0)531-592-1143, e-mail: Oliver.Mack@ptb.de