Proceedings of the 17th International Conference on Force, Mass, Torque and Pressure Measurements,
IMEKO TC3, 17-21 Sept. 2001, Istanbul, Turkey

# New Procedures to Characterize Drift and Non-Linear Effects of Piezoelectric Force Sensors

Oliver Mack
*Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany*

## Abstract

This contribution describes new methods to characterize and determine both, the drift and the non-linearity of piezoelectric force measuring devices. The influence of the drift and different procedures for the drift calculation are presented. In addition the influence of different load regimes and evaluation procedures is discussed. The measurements carried out reveal that not the drift, but in particular the non-linearity is the criterion crucial for a classification of piezoelectric force transducers according to standards commonly applied to strain gauge force transducers. The results of this contribution are necessary and important for the development of standards required for the calibration of piezoelectric force measuring devices in force standard machines.

## 1. Introduction

Considering the drift inherent in piezoelectric force measuring devices, static and quasistatic measurements of high accuracy seem to be infeasible. Because of this, only few investigations were executed to develop procedures for the calibration of piezoelectric force measuring devices in force standard machines [1, 2].

As is shown in [3, 4, 5, 6], in the case of great time constants of the charge amplifier, piezoelectric force measuring devices show a linear drift behaviour which is independent of the load step applied.

Knowledge of the drift and the measurement of load steps at increasing and decreasing force according to DIN EN 10002-3 [7] at equidistant time intervals [8,9] enable an analytical drift compensation, which leads to a reduction of the measurement uncertainty of piezoelectric force measuring devices.

The following discussion of the sensitivity and linearity of the force transducer examined produces surprising results.

## 2. Procedure for the Determination of the Drift

Discrete load steps at increasing and decreasing force have been plotted. Acquisition of the measurement values takes place at equidistant time intervals $\Delta t$, and not, as specified in DIN EN 10002-3, at least 30 seconds after application of the respective force. Due to $\Delta t$, load changes at different time intervals do not influence the measurement results. The charge amplifier‘s output signal of the i<u>th</u> load step is:

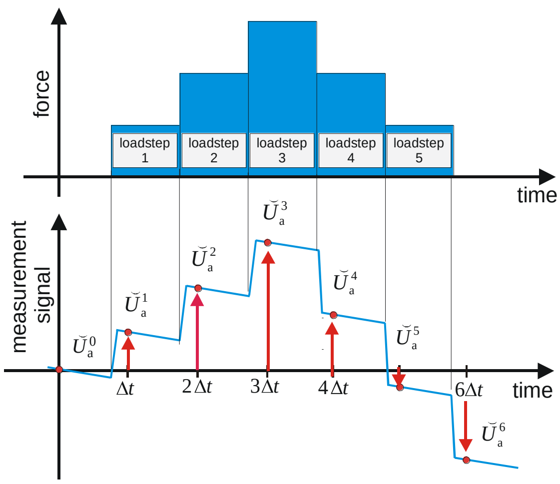


**Figure 1**. shows the load-time dependence diagram of force transducers in force standard machines according to DIN EN 10002-3.

$$\breve{U}_a^i = U_a^i + i \cdot D \cdot \Delta t \tag{1}$$

Where $\breve{U}_a^i$ is the measurement value affected by drift and $U_a^i$ the measured value without drift. $D$ is the linear drift coefficient.

Offset voltages and currents in the input circuit of the charge amplifier cause the drift. In addition, the connecting leads and plugs expert a strong influence on the drift, which is not reproducible.

Three different procedures for the determination of the drift are presented and discussed in the following.

The simplest procedure analyses the first and last value of a measurement series at increasing and decreasing load. The resulting active drift during the entire measurement time is determined according to

$$D = \frac{\breve{U}_a^0 - \breve{U}_a^{2n_L}}{2n_L \cdot \Delta t} \tag{2}$$

where $n_L$ is the number of different load steps. However, this procedure does not allow the linearity of drift to be estimated.

The second procedure determines the drift $D_H$ from the absolute hysteresis

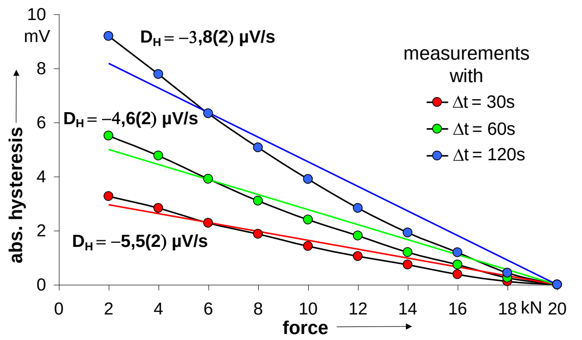


**Figure 2** The absolute hysteresis $\breve{h}_i$ of a piezo-electric force transducers at a nominal load of 20 kN as a function of the applied force and the least squares fit for drift determination

$$\breve{h}_i = \breve{U}_a^{2n_\mathrm{L}-i} - \breve{U}_a^{i} = 2 \cdot \Delta t \cdot (n_\mathrm{L} - i) \cdot D_\mathrm{H} \tag{3}$$

by means of a least square fit

$$D_\mathrm{H} = -\frac{3 \cdot \left( \sum_{i=1}^{n_\mathrm{L}} i \cdot \breve{h}_i - n_\mathrm{L} \cdot \sum_{i=1}^{n_\mathrm{L}} \breve{h}_i \right)}{\Delta t \cdot \left( n_\mathrm{L}^3 - 3n_\mathrm{L}^2 + n_\mathrm{L} \right)} \tag{4}$$

Figure 2 shows the absolute hysteresis of a piezoelectric force transducer at a nominal load of 20 kN as a function of the applied force.

The expected rise of $\breve{h}_i$ with increasing $\Delta t$ can be recognized.

Moreover, a non-linear behaviour of $\breve{h}_i$ is detected. The hysteresis of the force transducer as well as its non-linear behaviour are reasons for the non-linearity measured. Admittedly, neither the hysteresis nor the non-linearity can be explicitly calculated by the least squares fit equation (4) and both enter into the drift result for $D_\mathrm{H}$.

The third procedure assumes that the hysteresis is negligible. It analyses only the modifications of the measuring signal at within a specific load step.

$$D_\mathrm{W} = \frac{\sum_{i=1}^{n_\mathrm{L}} \left( \breve{U}_\mathrm{a}^{i} - \breve{U}_\mathrm{a}^{i-1} + \breve{U}_\mathrm{a}^{2n_\mathrm{L}-i+1} - \breve{U}_\mathrm{a}^{2n_\mathrm{L}-i} \right)}{2\Delta t \cdot n_\mathrm{L}} \tag{5}$$

Predictions concerning the hysteresis of the force transducer are not possible; however, the non-linear behaviour of the force transducer does not enter into the drift value found.

In all following equations the drift is determined according to equation (5).

## 3. Determination of the Sensitivity According to DIN EN 10002-3

The sensitivity $S_\mathrm{KA}$ of a piezoelectric force transducer, taking the drift into account, is

$$S_\mathrm{KA} = \breve{S}_\mathrm{KA} - \phi_\mathrm{Dr}\,, \tag{6}$$

where

$$\breve{S}_\mathrm{KA} = \frac{1}{S_\mathrm{LV}^\mathrm{stat}} \cdot \frac{\sum_{i=0}^{n_\mathrm{L}} \left( F_i \cdot \breve{U}_a^{i} \right)}{\sum_{i=0}^{n_\mathrm{L}} \left( F_i \right)^2} \tag{7}$$

is the drift-influenced sensitivity and

$$\phi_\mathrm{Dr} = \frac{D_\mathrm{W} \cdot \Delta t}{S_\mathrm{LV}^\mathrm{stat}} \cdot \frac{\sum_{i=1}^{n_\mathrm{L}} \left( F_i \cdot i \right)}{\sum_{i=1}^{n_\mathrm{L}} \left( F_i \right)^2} \tag{8}$$

the drift factor. $F_i$ is the static force of the i<u>th</u> load step, and $S_\mathrm{LV}^\mathrm{stat}$ is the static sensitivity of the charge amplifier in used.

Figure 3 shows the test results of a piezoelectric force transducer at a nominal load of 20 kN in the nominal and partial load range up to 2 kN.

The relative modification of the sensitivity

$$\Delta S_\mathrm{rel} = \frac{\breve{S}_\mathrm{KA} \left( \phi_\mathrm{Dr} \right)}{S_\mathrm{KA}} - 1 \tag{9}$$

as a function of $\phi_{\mathrm{Dr}}$ is represented.

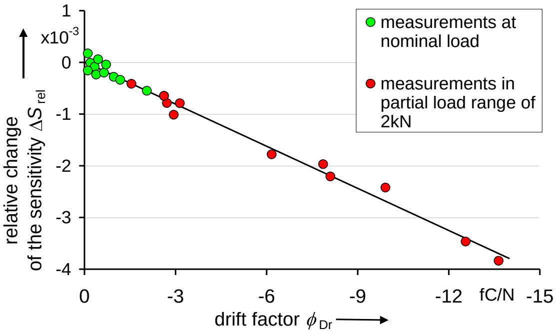


**Figure 3.** Relative modification of the sensitivity related to $S_{\mathrm{KA}}$ as a function of $\phi_{\mathrm{Dr}}$

For all the twenty-two series of measurements, $\Delta t$ ranges between $20\,s$ and $180\,s$. In the partial load range up to 2 kN the drift $D_{\mathrm{W}}$ is between $-19{,}0\,\mu\mathrm{V/s}$ and $-51{,}9\,\mu\mathrm{V/s}$. The drift factor $\phi_{\mathrm{Dr}}$ ranges between $-1{,}55\ \mathrm{fC/N}$ and $-13{,}65\ \mathrm{fC/N}$.

For larger measuring ranges, a higher negative feedback capacitance $C_{\mathrm{g}}$ of the charge amplifier is used. In the nominal load range of the force transducer the drift is, therefore, smaller and amounts to between $D_{\mathrm{W}} = 0{,}59\,\mu\mathrm{V/s}$ and $D_{\mathrm{W}} = -4{,}93\,\mu\mathrm{V/s}$. Accordingly, for these measurements $\phi_{\mathrm{Dr}}$ is smaller by up to $-2{,}05\ \mathrm{fC/N}$. The measurement results illustrate the linear relation between $\phi_{\mathrm{Dr}}$ and $\breve{S}_{\mathrm{KA}}$, which is independent of the maximum load and the adjusted negative feedback capacitance $C_{\mathrm{g}}$ of the charge amplifier.

The drift-affected sensitivity $S_{\mathrm{KA}}$ corresponds to the absolute value of the ordinate of figure 2. However, $S_{\mathrm{KA}}$ strongly depends on the load range. The nominal load range has a sensitivity of . The partial load range of 2 kN shows a sensitivity smaller by $4 \cdot 10^{-3}$, i.e. $S_{\mathrm{KA}} = -3{,}9281$ pC/N. This points to a non-linear behaviour of the force transducer.

## 4. Determination of the Sensitivity by fast Loading and Unloading of Discrete Load Steps

When the hysteresis is not taken into account, application of procedures according to DIN EN 10002-3 with discrete increasing and decreasing loads is not mandatory. Fast loading and unloading of each load step (see figure 4) enable a mathematically simpler description of drift and sensitivity.

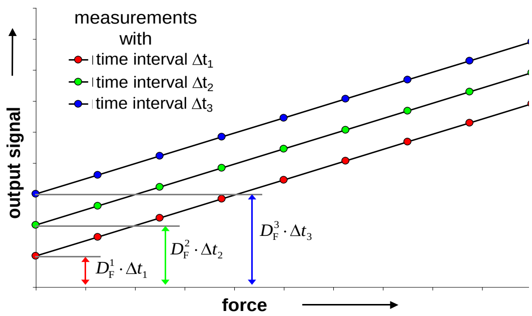


**Figure 4**. Load-time dependence diagram and signal dependence diagram of a piezoelectric force measuring device upon fast loading and unloading

The i^th load step furnishes at the output of the charge amplifier:

$$\breve{U}_{\mathrm{a}}^{i} = U_{\mathrm{N}}^{i} - U_{\mathrm{V}}^{i} = U_{\mathrm{a}}^{i} + D_{\mathrm{F}} \cdot \Delta t \qquad (10)$$

$U_{\mathrm{V}}^{i}$ and $U_{\mathrm{N}}^{i}$ are measurements preformed before and after the load of the i$^{\underline{\mathrm{th}}}$ load step was set. In contrast to equation (1), here each load step is affected by the same signal shift due to the drift. By a least squares fit without forced zero $S_{\mathrm{KA}}^{\mathrm{F}}$ and $D_{\mathrm{F}}$ can be determined directly:

$$S_{\mathrm{KA}}^{\mathrm{F}} = \frac{n_{\mathrm{L}} \cdot \sum_{i=1}^{n_{\mathrm{L}}} \left(F_i \cdot \breve{U}_a^i\right) - \sum_{i=1}^{n_{\mathrm{L}}} F_i \sum_{i=1}^{n_{\mathrm{L}}} \breve{U}_a^i}{S_{\mathrm{LV}}^{\mathrm{stat}} \cdot \left[ n_{\mathrm{L}} \sum_{i=1}^{n_{\mathrm{L}}} \left(F_i^2\right) - \left( \sum_{i=1}^{n_{\mathrm{L}}} F_i \right)^2 \right]} \qquad (11)$$

$$D_{\mathrm{F}} = \frac{\sum_{i=1}^{n_{\mathrm{L}}} F_i^{\,2} \cdot \sum_{i=1}^{n_{\mathrm{L}}} \breve{U}_a^i - \sum_{i=1}^{n_{\mathrm{L}}} F_i \cdot \sum_{i=1}^{n_{\mathrm{L}}} \left(F_i \cdot \breve{U}_a^i\right)}{\Delta t \cdot \left[ n_{\mathrm{L}} \cdot \sum_{i=1}^{n_{\mathrm{L}}} F_i^{\,2} - \left( \sum_{i=1}^{n_{\mathrm{L}}} F_i \right)^2 \right]} \qquad (12)$$

The systematic relation is represented in figure 5.

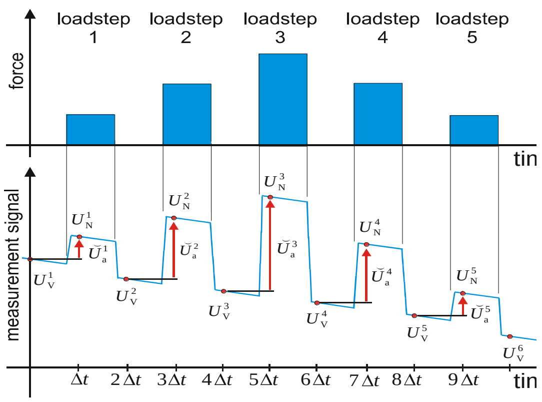


**Figure 5.** Schematic representation of the output-load dependency for different drift values and different time intervals

Neither the drift $D_{\mathrm{F}}$ nor the time interval $\Delta t$ influences the gradient of the output force graph and thus the sensitivity $S_{\mathrm{KA}}^{\mathrm{F}}$.

Table 1 shows the medial sensitivities $S_{\mathrm{KA}}^{\mathrm{F}}$ determined in two different load ranges from a total of sixteen independent measurements carried out during fast loading and unloading, compared with the values obtained by the method of DIN-EN 10002-3 shown in figure 3.

**Table 1.** Sensitivity of a piezoelectric force transducer determined by different procedures and in different load ranges

| | 2kN | 20kN |
|---|---|---|
| $S_{\mathrm{KA}}$ according to DIN EN 10002-3 | -3,9124(4) pC/N | -3,9281(5) pC/N |
| $S_{\mathrm{KA}}^{\mathrm{F}}$ least squares fit with forced zero | -3,9133(2) pC/N | -3,9360(3) pC/N |

The relative deviation of $S_{\mathrm{KA}}$ and $S_{\mathrm{KA}}^{\mathrm{F}}$ in the load range up to 2 kN amounts to $3 \cdot 10^{-4}$. The relative standard deviation of the individual sensitivities $S_{\mathrm{KA}}$ and $S_{\mathrm{KA}}^{\mathrm{F}}$ as a measure for the reproducibility of the measurements are smaller by about one of magnitude. In the nominal load range up to 20 kN the relative deviation of sensitivities found amounts to $2 \cdot 10^{-3}$ and is thus much larger. So the load regime and the evaluation procedures chosen strongly influence the sensitivity values found. Non-linear characteristics of the force transducer are responsible for this behaviour.

## 5. Determination of the Interpolation Error

A measure of the non-linear behaviour of a force transducer is the interpolation error. It can be shown that the absolute interpolation error

$$\tilde{f}_{\mathrm{C}}^{\,i} = \breve{U}_{\mathrm{a}}^{i} - \breve{S}_{\mathrm{KA}} \cdot S_{\mathrm{LV}}^{\mathrm{stat}} \cdot F_i \tag{13}$$

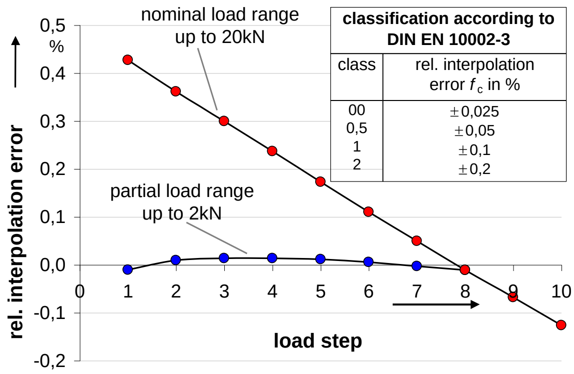


**Figure 6.** Relative interpolation error of the examined force transducer in two different load ranges

is independent of the resulting drift if the force is applied at equidistant intervals $\Delta F$. In figure 6 the relative interpolation error

$$f_{\mathrm{C}}^{\,i} = \frac{\tilde{f}_{\mathrm{C}}^{\,i}}{\breve{S}_{\mathrm{KA}} \cdot S_{\mathrm{LV}}^{\mathrm{stat}} \cdot i \cdot \Delta F} \tag{14}$$

for the partial load range up to 2 kN and the nominal load range up to 20 kN of the force transducer examined is represented.

The investigations furnish a relative interpolation error of $f_{\mathrm{C}}^{\,i} < 0{,}02\%$ in the partial load range up to 2 kN, which corresponds to an assignment to class 00 according to DIN EN 10002-3.

In the nominal load range the relative interpolation error amounts to $f_{\mathrm{C}}^{\,i} > 0{,}4\%$ and is therefore very large. A classification according to usually standards applied to strain gauge force transducers is not possible.

It is therefore not the drift influence to which the sensitivity found is subject but the drift-independent interpolation error, which is the reason for the impossibility of classifying piezoelectric force transducers according to DIN EN 10002-3.

These results are unfirmed by the examination of other piezoelectric force transducers and point to a systematic behaviour.

## 6. Description of Piezoelectric Force Transducers by Higher Order Regression Functions

The description of the non-linear behaviour of a force transducer requires regression functions of at least the second order

$$U_{\mathrm{a}}^{i} = \frac{Q_{\mathrm{KA}} \cdot F_i^{2} + S_{\mathrm{KA}} \cdot F_i + D_{\mathrm{F}} \cdot \Delta t}{S_{\mathrm{LV}}^{\mathrm{stat}}}\,, \tag{15}$$

or, better, of the third order

$$U_{\mathrm{a}}^{i} = \frac{K_{\mathrm{KA}} \cdot F_i^{3} + Q_{\mathrm{KA}} \cdot F_i^{2} + S_{\mathrm{KA}} \cdot F_i + D_{\mathrm{F}} \cdot \Delta t}{S_{\mathrm{LV}}^{\mathrm{stat}}}\,.$$

$Q_{\mathrm{KA}}$ and $K_{\mathrm{KA}}$ are the square and cubic coefficients, respectively, of the regression function. Table 2 shows the results of a cubic regression function of the investigations discussed in table 1.

Contrary to the results given in table 1, $S_{\mathrm{KA}}$ and $Q_{\mathrm{KA}}$ here are independent of the load range examined. The larger standard deviation in the partial load range is attributed to the larger drift in this measurement range. Only the very small coefficient $K_{KA}$ shows a load range dependency.

The causes of the non-linear behaviour are at present examined. Possible reasons are interactions between the isotropic force introduction made of steel and the isotropic piezoelectric material (see figure 7), geometrical non-linearity's and non-linearity's of the material.

**Table 2.** Cubic regression coefficients of a piezoelectric force transducer determined in different load ranges

| | 2kN | 20kN |
|---|---|---|
| $S_{KA}$ | $-3{,}910$([illegible])$\cdot 10^{-12}\,\frac{C}{N}$ | $-3{,}9096(6)\cdot 10^{-12}\,\frac{C}{N}$ |
| $Q_{KA}$ | $-1{,}3(3)\cdot 10^{-18}\,\frac{C}{N}$ | $-1{,}30(3)\cdot 10^{-18}\,\frac{C}{N}$ |
| $K_{KA}$ | $5(2)\cdot 10^{-24}\,\frac{C}{N}$ | $-90(60)\cdot 10^{-24}\,\frac{C}{N}$ |

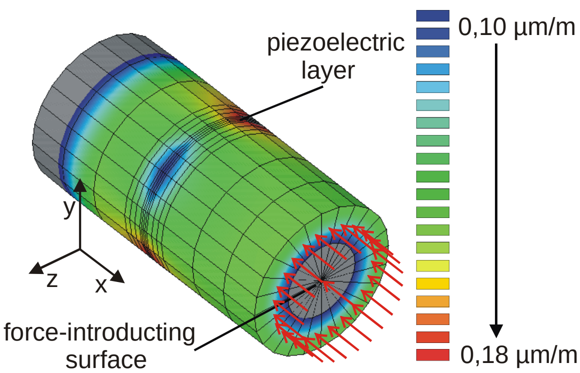


**Figure 7.** Simulations with finite element method (FEM) of the direction-dependent deformation in the yz-layer of a piezoelectric force transducer under load

## 7. Conclusions

This paper demonstrates that the quasistatic calibration of piezoelectric force transducers installed in force standard machines is possible with high precision if the drift is taken into account. However, it is also shown that the determination of the drift lead to a loss of information. Either the linearity or the hysteresis of the force transducer investigated cannot be determined.

A modified procedure for the calibration of piezoelectric force transducers according to DIN EN 10002-3 and a method with fast loading and unloading in each load step is presented and discussed.

A comparison of the procedures proves good reproducibility of the sensitivity of both procedures if the drift is taken into account.

However, the two procedures produce strongly different results in particular in the nominal load range of the force transducer.

The measurements prove that not the drift but the non-linearity is the criterion crucial for a classification of piezoelectric force transducers according to standards commonly applied to strain gauge force transducers.

A substantially better characterization of piezoelectric force transducers results from 2nd and 3rd order regression functions. The reasons for the non-linear behaviour and the resulting measurement uncertainty budget will be discussed in further publications.

## 8. References

[1]. Tichý J.; Gautschi G., *Piezoelektrische Meßtechnik: Physikalische Grundlagen, Kraft-, Druck- und Beschleunigungsaufnehmer*, Verstärker. Springer Verlag Berlin Heidelberg New York, 1980

[2]. Kumme R.; Mack O., Bill B., Gossweiler, Ch.; Haab, H.*: Investigation of piezoelectric force measuring devices in force calibration and force standard machines*. Presentation on the 17th International Conference on Force, Mass and Torque Measurements, Istanbul, Turkey, September 17.-21. 2001

[3]. Mahr W., *Messen und Verarbeiten von Ladungssignalen piezoelektrischer Aufnehmer*. Technisches Messen 49 (1982), pp. 149-158

[4]. Kail R., Mahr, W.: *Piezoelektrische Meßgeräte und ihre Anwendungen.* Messen und Prüfen 20 (1984), Hans Holzmann Verlag, Bad Wörishofen

[5]. Spescha G., Volle E., *Piezoelektrische Meßgeräte*. Messen und Prüfen, Verlag Erwin Geyer, Bad Wörishofen, 1972

[6]. Mack O., Kumme, R.: *Quasistatische Untersuchungen piezoelektrischer* Kraftmeßeinrichtungen. PTB-Jahresbericht 1998, ISSN 0340-4366, pp. 171-172

[7]. EN 10002-3: European Standard EN 10002-3, Metallic materials, tensile test, part 3: *Calibration of force proving instruments used for the verification of uniaxial testing machines*, 1994

[8]. Mack O., Kumme R., *Quasistatic and dynamic investigation methods of piezoelectric force measurement devices*. Proceedings of the 16th International Conference On Force, Mass and Torque Measurements in Parallel with Asia-Pacific Symposium on Measurement of Mass and Force IMEKO TC3/APMF ’98, Taejon, Republic of Korea, September 14.-18. 1998, pp. 310-320

[9]. Saffar J.M.E., Camarano D.M., Ferreira Marques, E.M.: *Behaviour of elastic force-measuring instruments under different load regimes*. Proceedings of the 14th IMEKO World Congress, Tampere, Finland, 1.-6. June 1997, pp. 19-24