Investigation of the Influence of Disturbing Components on a Piezoelectric Force Transducer

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Abstract

For the measurement of the physical quantity force with conventional transducers it is assumed that the preferred direction of the force transducer is the same as that of the vector of the force. In practice this case is rarely being observed. Due to insufficient alignment of the transducer or of the measurement facility mechanically disturbing components such as bending moments, shear forces or additional axial forces occur which may influence the measurement result significantly.

This paper deals with the investigation of the influence of static mechanical disturbing components on a piezoelectric force transducer. To determine a disturbing sensitivity of a piezoelectric force transducer different kinds of experimental setups are discussed. The measurement results show a characteristic direction depending disturbing sensitivity of piezoelectric force transducers, which is well known of piezoelectric accelerometers. The investigations point out that the influence of mechanical disturbing components on piezoelectric force transducers cannot be neglected for precision measurements.

Introduction

To embrace highest requirements well known uniaxial force components are used to calibrate force transducers in force standard machines according to [1]. With that the preferred direction of the force transducer is the same as that of the vector of the force generated in the force standard machine.

Classical applications for piezoelectric force transducers are crash walls, biomechanics, and force measurements of cutting forces and in manufacturing control. However accurate force introduction into the force transducer is rarely guaranteed, moreover the influence of mechanical disturbing components on piezoelectric force transducer is widely unknown.

For the first time influences of static bending moments and shear forces as mechanical disturbing components on piezoelectric force transducer are discussed within this contribution. To apply static forces on piezoelectric force transducers the calibration methods presented in [2,3,4] are used.
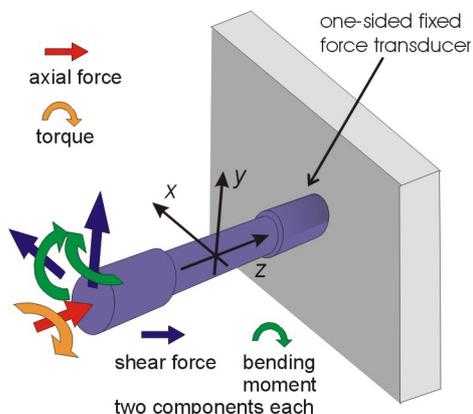

Figure 1: Picture of a force transducer and acting force and moment

Definition of mechanical disturbing components

To investigate the influence of disturbing components on piezoelectric force transducers an accurate definition of mechanical disturbing components in necessary. As shown in figure 1, the forces and couples (moments), applied on the free end of a one-sided fixed force transducer can be divided in three force respectively moment components [5].

The three force components can be classified in one axial force component F_z (in the main direction of the force transducer) and two orthogonal shear force

components F_x and F_y. In the same way the three moment components can be classified in a torque component M_z in the main direction of the force transducer and two orthogonal bending moment components M_x and M_y. Such components are called mechanical disturbing components which are not in main direction of the force transducer. Among the shear forces F_x and F_y this also includes the bending moments M_x and M_y. Thus the torque component M_z is not a mechanical disturbing component and will not be considered below.

Experimental setups to investigate influences of mechanical disturbing components

In principle the shear forces F_x and F_y occur in combination with the bending moments M_x and M_y. This is shown by the following experimental setups, which are based on practical applications:
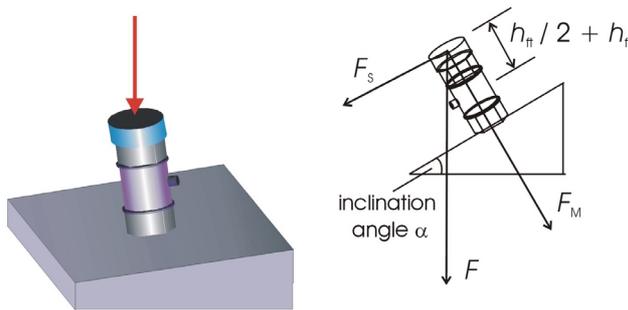

Figure 2a: Force transducer mounted on an inclined plane

Figure 2a shows a force transducer mounted on an inclined plane with an inclination angle α.

Besides a force component

(1) $F_M = F \cdot \cos \alpha$

in the direction of the main sensitivity of the force transducer this most general case of no-axial force introduction generates a shear force component

(2) $F_S = \sqrt{F_x^2 + F_y^2} = F \cdot \sin \alpha$

and a bending moment

(3) $M_B = F_S \cdot \left(\dfrac{h_{ft}}{2} + h_{fi} \right)$.
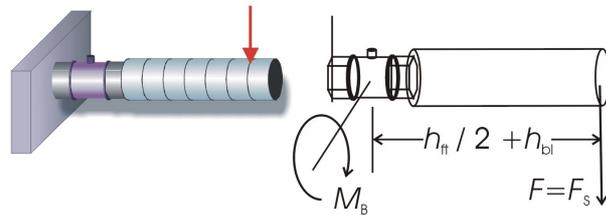

Figure 2b: Force transmission via bending lever

A shear force

(4) $F_S = \sqrt{F_x^2 + F_y^2} = F$

and a bending moment

(5) $M_B = F \cdot \left(h_{bl} + \dfrac{h_{ft}}{2} \right)$.

without a component in direction of main sensitivity has an effect on the force transducer by a force transmission via bending lever (see figure 2b).
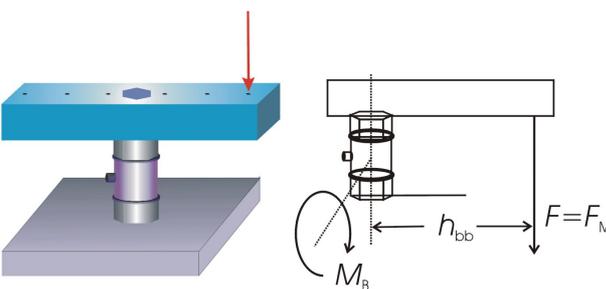

Figure 2c: Force transmission via bending beam

A bending moment

(6) $M_B = F \cdot h_{bb}$

as only disturbing component can be generated by a force transmission via bending beam with the length h_{bb}. Admittedly the force F appears in the direction of the main sensitivity of the force transducer (see figure 2c).

All three experimental setups point out that a disturbing component cannot be applied on the force transducer without a second disturbing component (figure 2a and figure 2b) or a force component in direction of main sensitivity (figure 2a and figure 2c). Consequently these experimental setups are not qualified to determine a shear force- or bending moment sensitivity of the force transducer exactly. Anyhow the influence of mechanical disturbing components can be discussed in principle.

Behavior of piezoelectric acceleration transducers

It is a well known fact that piezoelectric acceleration transducers, which are in principle built like force transducers, show a characteristic, sinusoidal direction dependent disturbance sensitivity [6]. Drawn in a polar coordinates diagram the direction dependency of the disturbing component leads to a characteristic function in the shape of the figure "8" (figure 3).
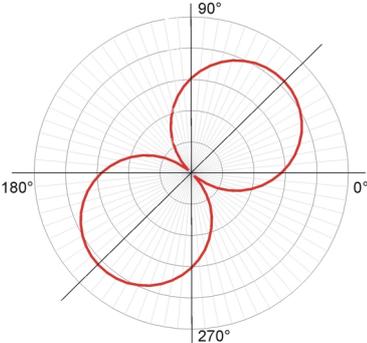

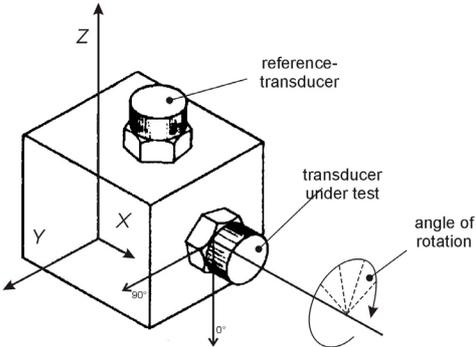Figure 3: Sinusoidal direction disturbance sensitivity of acceleration transducers

Figure 4: Calibration setup to determine the disturbing charateristic of piezoelectric accelerometers

To determine the disturbing characteristic defined transverse accelerations are applied to the acceleration transducer (figure 4).

Dynamic investigations of a piezoelectric force transducer with a discreet excitation frequency of 10Hz ratify a sinusoidal direction dependency of the disturbing sensitivity [7]. But the influence of static mechanical disturbing components on piezoelectric force transducer is unknown.

Investigations using an inclined plane

Subsequently the influence of disturbing components on a piezoelectric force transducer with a nominal load of 5kN is discussed (Inc. Kistler, Type-No. 9311B, SN 234535). For this transducer the shear force load limit is specified as $F_S = 750N$. The maximum bending moment is $M_B = 8Nm$, when a load of $F_Z = 5kN$ is applied on the force transducer and $M_B = 15Nm$, when there is no load applied [8].

The investigations are carried out at PTB in a force calibration machine with a nominal load of 200N.

For a force transmission of non axial forces the force transducer is mounted on an inclined plane shown in figure 5. A maximum inclination angle of $\alpha = 10°$ permits shear forces up to $F_S = 35N$ and bending moments up to $M_B = 0.8\,Nm$ when a force $F = 200N$ is applied on the transducer. To investigate direction dependencies the transducer is rotated stepwise on the inclined mounting plane in angles of 15°.
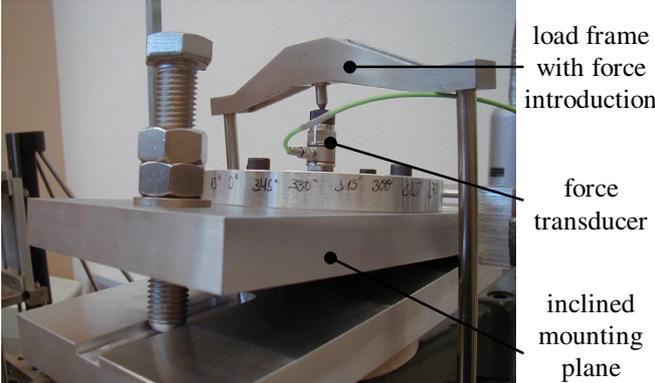

Figure 5: Experimental setup of the force transducer mounted on an inclined mounting plane

Figure 6 shows the relative change of the charge induced when the force transducer is applied with a load $F = 200N$ depending on the orientation of the transducer. The five measurements show different

angles of inclination between $\alpha = 0°$ and $\alpha = 10°$. Even small shear forces of $F_S < 7\,\mathrm{N}$ (is equivalent to a bending moment of $M_B \approx 0,2\,\mathrm{Nm}$ or an inclination angle of $\alpha = 2°$ respectively) show a sinusoidal direction dependency. The signal amplitude of this direction dependency increases with in-

creasing shear force or bending moment respectively. The relative change of the signal amplitude amount 0,45% of the average output signal over all directions when an inclination angle of $\alpha = 10°$ is used.

Figure 6: Relative change of the charge induced when the force transducer is applied with a load $F = 200\,\mathrm{N}$ depending on the orientation of the force transducer

In addition to that the average output signal decreases with increasing inclination. For an inclination angle of $\alpha = 10°$, the average output signal over all directions is 1,3% smaller than the output signal of a force transducer mounted on a plane surface. This is caused by a decreasing force component F_M in the direction of the main sensitivity of the force transducer, when the inclination increases and the nominal load F remains unchanged.
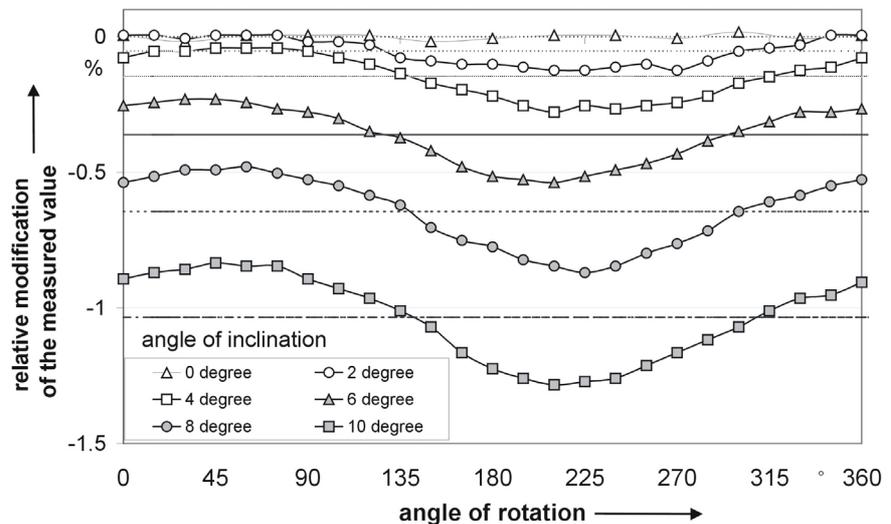
Both the direction dependent effect and the decreasing averaged output signal lead to a relative reduction of the output signal up to 1,25% for an inclination angle of $\alpha = 10°$ compared with the output signal of a force transducer mounted on a plane surface.

Force transmission via bending beam

Because both shear force and bending moment act simultaneously on the force transducer mounted on a inclined plane neither the influence of the shear force nor of the bending moment can be singularly determined.

To analyze the influence of bending moments without shear forces acting on the force transducer a force transmission via a bending beam is necessary. Figure 7 shows the experimental setup. Different length of the bending beam

Figure 7: Experimental setup of a force transmission via bending beam

between 22,5mm and 52,5mm permit bending moments up to $M_B = 10,5\,\mathrm{Nm}$ for a nominal load of $F = 200\,\mathrm{N}$.

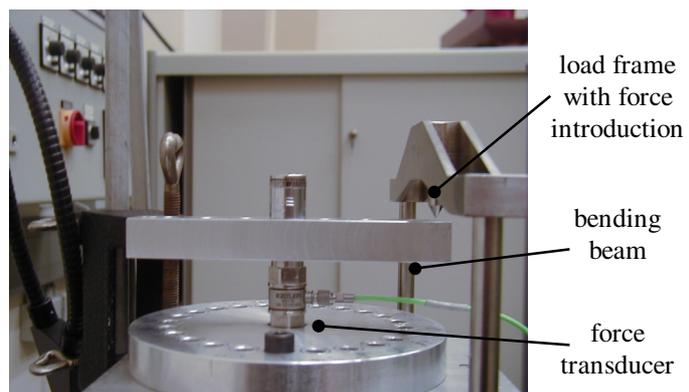To provide a statement about the direction dependency of a bending-moment-sensitivity the bending beam is mounted stepwise in angles of 15° on the force transducer. Because with this experimental

setup no relevant shear forces act on the force transducer the influence of bending moments can be determined immediately.

The graphs in figure 8 shows the influence of a bending moment between $M_B = 1{,}35\,\text{Nm}$ and $M_B = 3{,}15\,\text{Nm}$ with a force component $F_M = 60\,\text{N}$ in the main sensitivity direction of the force transducer.

Two effects are clearly shown by the graphs: first a sinusoid direction dependency, second an increasing averaged output signal over all directions by increasing bending moments.

For a bending moment of $M_B = 3{,}15\,\text{Nm}$ the super-position of both effects leads to a measurement signal depending on the direction between 1% less up to 6% greater than the measurement signal without bending moment. For a bending moment greater than 10Nm the measurement signal is even greater than 10%. Hence even small bending moments acting on the force transducer produce a huge change of the output signal and have to be taken into account for precision measurements.
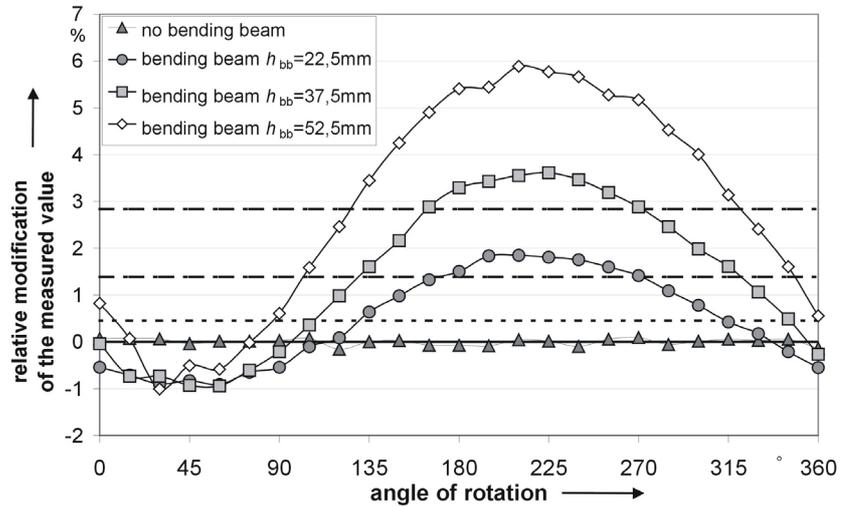
Figure 8: Relative change of the charge induced via bending beam depending on the orientation of the force transducer.
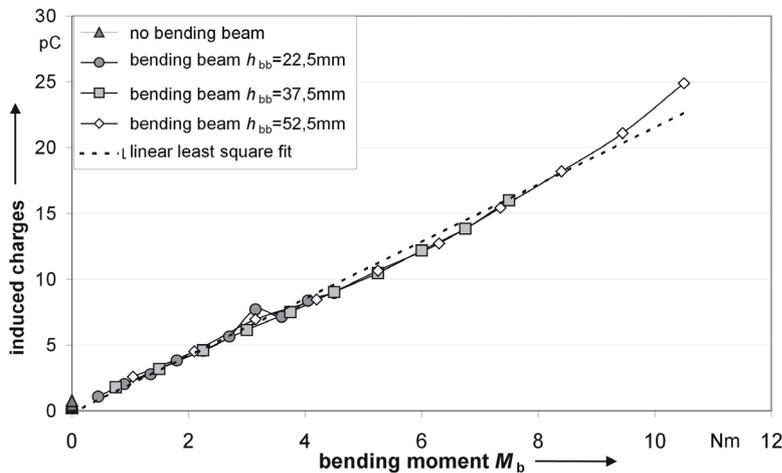
Figure 9: Linear relation between the amplitude of the direction dependent charges induced in the force transducer subject to M_B in the measurement range up to 10,5Nm

To characterize the influence of bending moments on piezoelectric force transducers direction dependent and independent parameters are necessary.

Figure 9 shows the linear relation between the amplitude

$$(7) \qquad \hat{Q}_M = \frac{Q_{max} - Q_{min}}{2}$$

of the direction dependent charges induced in the force transducer subject to M_B in the measurement range up to 10,5Nm.

The direction dependent bending moment sensitivity of the force transducer is determined by means of a linear last square fit with force zero and amounts to $\hat{S}_M = 2{,}14(3)\,\text{pC/N}$.

The direction independent change of the induced charge $\overline{Q}_S$ due to an acting bending moment is calculated by

$$(8) \qquad \overline{Q}_S = \overline{Q} - F \cdot S_H$$

where $\overline{Q}$ is the averaged induced charge over all directions and S_H is the sensitivity of the force transducer in main direction. To specify S_H the method described in [2,3] is used.
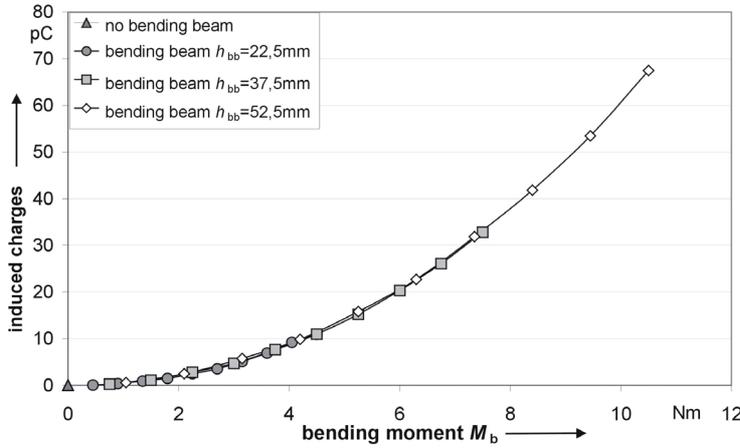

Figure 10: Quadratic correlation between the direction independent change of the induced charge $\overline{Q}_S$ subject to M_B

As shown in figure 10 there is no linear correlation between $\overline{Q}_S$ and M_B. Consequently the specification of a sensitivity is not sufficient to characterize the direction independent behavior of the force transducer investigated. The description of the non-linear behavior requires regression functions of at least second order

$$(9) \qquad \overline{Q}_S = \overline{K}_M M_B^2 + \overline{S}_M M_B.$$

A least square fit with force zero leads to a quadratic coefficient $\overline{K}_M = 0{,}643(5)\,\mathrm{pC}/(\mathrm{Nm})^2$ and a linear coefficient $\overline{S}_M = -0{,}40(4)\,\mathrm{pC}/\mathrm{Nm}$.

Force transmission with a bending lever

Figure 11 shows the experimental setup for a force transmission with a bending lever.

Contrary to a force transmission with a bending beam both shear forces and bending moments act on the force transducer. However there is no force component in main direction of the force transducer when the influence of no relevant force components is negligible.

A length of the bending lever between $b_{bh} = 12\,\mathrm{mm}$ and $b_{bh} = 60\,\mathrm{mm}$, a height $h_K = 30\,\mathrm{mm}$ of the force transducer and a maximum force of $F = 100\,\mathrm{N}$ permit bending moments up to $M_B = 7{,}5\,\mathrm{Nm}$, if equation (3) is taken into account.

laser interferometer to measure the bending displacement

load frame with force introduction

bending lever

force transducer (covered)

Figure 11 Experimental setup of a force transmission via bending lever

Similarly to the force transmission via bending beam the investigations point out both a sinusoid direction dependency of the measurement signal and a increasing averaged output signal over all directions with increasing bending moments.

Figure 12 documents these result for a bending moment between $M_B = 1{,}62\,\mathrm{Nm}$ and $M_B = 4{,}5\,\mathrm{Nm}$ and a shear force of $F_S = 60\,\mathrm{N}$.
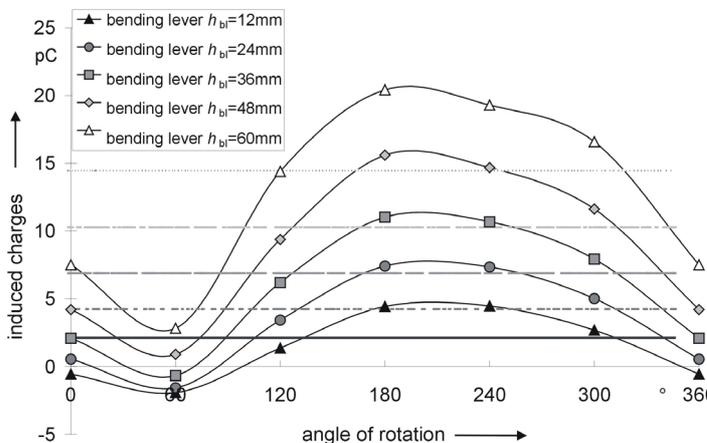

Figure 12: Relative change of the charge induced via bending lever depending on the orientation of the force transducer.

	$\hat{S}_{\mathrm{M}}$ $[\mathrm{pC/N}]$	$\overline{K}_{\mathrm{M}}$ $\left[\mathrm{pC}/(\mathrm{Nm})^{2}\right]$	$\overline{S}_{\mathrm{M}}$ $[\mathrm{pC/N}]$
bending beam	2,14(3)	0,643(5)	–0,40(4)
bending lever	1,96(1)	0,655(2)	0,29(1)

Table 1   Coefficients $\hat{S}_{\mathrm{M}}$, $\overline{K}_{\mathrm{M}}$ and $\overline{S}_{\mathrm{M}}$, determined with bending beam and bending lever.

To characterize the influence of the acting bending moment and shear force the same coefficients as defined for a force transmission via bending beam are used. Table 1 shows the results of the coefficients $\hat{S}_{\mathrm{M}}$, $\overline{K}_{\mathrm{M}}$ and $\overline{S}_{\mathrm{M}}$, determined with bending beam and bending lever.

Whereas $\hat{S}_{\mathrm{M}}$ and $\overline{K}_{\mathrm{M}}$ have the same algebraic sign and approximately same value, $\overline{S}_{\mathrm{M}}$ shows a substantial difference. This is the result of additional shear forces F_{S} acting on the force transducer when a bending lever is used. Thus a direct comparison between the coefficients $\hat{S}_{\mathrm{M}}$, $\overline{K}_{\mathrm{M}}$ and $\overline{S}_{\mathrm{M}}$, determined with bending beam and bending lever, is not possible.

Results of numerical simulations

To verify the experimental results investigations using the numerical method of finite elements (FEM) have been carried out and are subsequently discussed. For the simulations the geometry of the force transducer is taken into account. Figure 13 shows the results of these simulations when direction dependent shear forces of 200N are applied on the force transducer. In addition the influence of incorrect orientations of the sensor element in respect of the cristallographic axis of the quartz crystal as piezoelectric material is taken into account.

An optimally orientated sensor element with an angle error $\delta = 0°$ shows no significant shear force sensitivity. Consequently the sinusoid direction dependency of the piezoelectric force transducer is not exclusively influenced by the anisotropic character-istic of the piezoelectric sensor element.
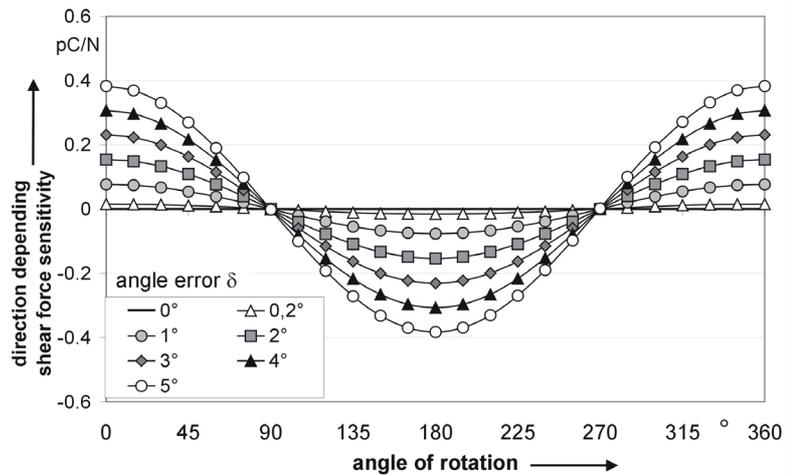

Figure 13:   Shear force sensitivity simulated with FEM depending on the orientation of the force transducer

But an angle error $\delta \neq 0°$ has an important influence on the shear force sensitivity and mainly influences the direction dependency. With first approximation the simulations supply an amplitude of $\hat{S}_{\mathrm{S}} = 0,077(1)\,\mathrm{pC/N}$ per degree angle error of the shear force sensitivity.

Nevertheless conclusions concerning the angle error of the force transducer used in experimental investigations are not possible. On the one hand the simulated model of the force transducer is strongly simplified, on the other hand geometric non-linearities are not taken into account.

Conclusions

This paper discusses for the first time the influence of static mechanical disturbing components such as shear forces and bending moments on a piezoelectric force transducer. Experimental investigations point out that particularly the influence of bending moments may lead to an error of measurement of about a

few percent. Consequently the influence of bending moments cannot be neglected for precision measurements.

The investigations verify a sinusoid direction-dependent bending moment sensitivity $\hat{S}_M$, which is well known for acceleration transducers. In addition to that a non-linear direction independent sensitivity is characterized by at least two more coefficients, $\overline{S}_M$ and $\overline{K}_M$.

The experimental setups discussed in this paper also point out, that a determination of a shear force sensitivity is not possible, because shear forces only occur simultaneously with bending moments. The determination of a bending moment sensitivity without influences of shear forces or axial forces in the direction of the main sensitivity requires continuation measurements in measurement devices specially designed for this purpose [5].

Numerical simulations with FEM point out, that the sinusoid direction dependency is caused by anisotropic material properties of the force transducers piezoelectric sensor elements. But an optimally orientated sensor element in respect of the cristallographic axis shows no significant shear force sensitivity. A significant shear force sensitivity occurs first due to angle errors between the orientation of the sensor element and the cristallographic axis of the quartz crystal as piezoelectric material.

With the numerical simulations carried out, statements about a shear force or bending moment sensitivity are not possible. This is because of the available simulation models at the time of simulation. Neither material non-linearities nor geometrical non-linearities could be taken into account. A consideration of these factors for simulation models in the future will allow a simulation of non-linear direction dependent shear force and bending moment sensitivities if the geometry of the force transducer is well known.

References

[1] EN10002-3: European Standard EN 10002, Metallic materials, tensile test, part 3: Calibration of force providing instruments used for the verification of uniaxial testing machines, 1994

[2] 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 1998, Taejon, Republic of Korea, September 14.-18.1998, pp.310-320

[3] Mack, O.: New procedures to characterise drift and non-linear effects of piezoelectric force sensors. Proceedings of the IMEKO TC3 Conference, 17.-21. Sept. 2001, Istanbul (Turkey), pp. 141-148.

[4] Kumme, R., Mack, O., Bill, B., Haab, R., Gossweiler, C.: Investigation of Piezoelectric Force Measuring Devices in Force Calibration and Force Standard Machines. Proceedings of the IMEKO TC3 Conference, 17.-21. Sept. 2001, Istanbul (Turkey), pp. 92-103.

[5] Röske, D.: Zum Einfluß mechanischer Störkomponenten auf die Messung von Drehmomenten mit DMS-Aufnehmern, Dissertation, Technische Universität Braunschweig, 1999, PTB-Bericht MA-63, ISBN 3-89701-450-5

[6] Weißenborn, C.: Kalibrierung von Beschleunigungsaufnehmern bei mehrachsiger Anregung, Dissertation, Technische Universität Braunschweig, 2001

[7] Lauer, G.: Development of methods for dynamic force calibration, Part 2, Absolute calibration of piezoelectric force transducers by laser interferometry, Commission of the European Communities, Contract N0 3313/1/0/118/86/10-BCR-D(30), 1990

[8] Kistler Instrumente AG Wintherthur, CH-8408 Winterthur, Schweiz, Operating Instructions Quarz-Kraftmesselemente, Type 9301B...9371B06.013Bd-04.96

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