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Force sensors based on strain gages and piezoelectric crystal-based force transducers in mechatronic systems — a comparison

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Abstract

Sensors play a critical role in mechatronic systems, because input quantities are essential to the interaction of mechanical engineering, electronics, and information technology. Measuring forces at high accuracy often is a compulsory requirement in this field. For this purpose, modern sensors based on strain gage and piezoelectric methods are available.

1. Comparison of the functional principles

So called metal foil type strain gauges are widely used as pick-up principle in force measurement. The vast majority of force transducers as well as load cells are based on them. They are available in a wide variety of measuring bodies such as column type, ring torsional design, S-shape type or simply bending beams. Measurement of both, tension and compression force, can be realised without additional effort.

The basic technology is shown in the sketch bellow: The force introduced into the transducer leads to strains on the surface of the spring body. Suitable placed strain gauges pick up this strain. Therefore four strain gauges are used as a minimum number. Two strain gauges are working under negative, two strain gauges under positive strain. All gauges are connected to a so called Wheatsone bridge.

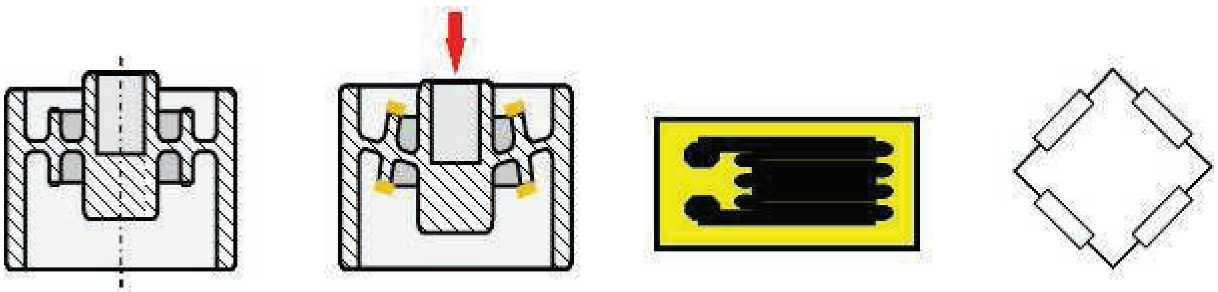


Fig. 1. From left to right: A spring body is affected by an external load. The deformation is measured by strain gauges which are connected to a Wheatstone bridge. A voltage to be measured is the final output.

The output signal is given as a ratio between the voltage supply and the output voltage and can be calculated as follows:

$$\frac{V_o}{V_i} = \frac{1}{4} \cdot \left(\frac{\Delta R_1}{R_1} - \frac{R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4} \right)$$

The ratios $\Delta R / R$ are representing the relative changes in resistance in this equation. It can be seen that an output voltage only can be obtained if the resistances R_1 and R_3 are change in the opposite way of the resistances R_2 and R_4. If all strain gauges change the resistance in the same direction and the same way, there will be no output signal.

Piezoelectric transducers use the piezoelectric effect. Here, monocrystals (e.g. quarz or gallium phosphate) are used. With these materials, charge centers are shifted in specific directions in the crystal; this results in an electric charge that can be detected externally and analyzed using a charge amplifier

Figure two shows the technical realisation of such a kind of transducer. The main difference looking from the mechanical perspective is that the force is led directly through the sensitive element, which is the crystal. Under mechanical stresses the centres of charges is moved so that a measurable charge can be measured at the edges of the crystal.

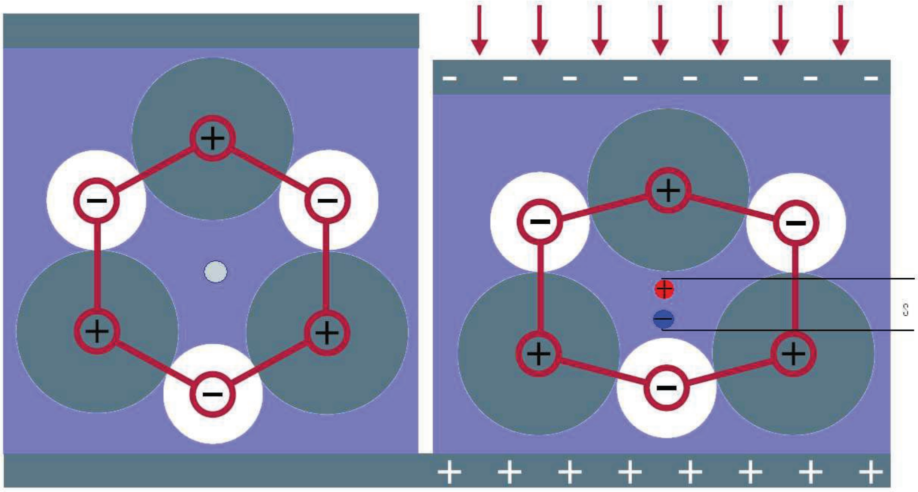


Fig. 2: Under mechanical stress the centres of charges are moving. A charge can be measured at the edges of the crystal.

Looking at strain gauge based transducer the construction of the spring body gives the maximum nominal load as well as the sensitivity of the transducer. With piezoelectric transducer only the kind of the used crystal leads to the sensitivity. Under a certain force the output is independent from the nominal load of the transducer. The output can be calculated with the following equation:

$$Q = q_{11} * F$$

Q is the charged can be obtained, q_{11} is a material depending factor and F is force introduced into the sensor.

2. Criteria for dimensioning of the force measurement chain

The mechanical design of the spring element determines the sensitivity of a strain gage-based force transducer. The measuring chain is thus dimensioned in terms of the nominal (rated) force by selecting the appropriate force transducer - the downstream electronics is universal and can be used with almost all force transducers.

Piezoelectric transducers are characterized by a linear-proportional relationship between the force applied and the electric charge available as an output signal. The proportionality constant between the force and the electric charge is also called piezoelectric coefficient. As this coefficient is only dependent on the material used, the output signal is independent of the sensor. The force measurement chain is thus dimensioned in terms of the nominal (rated) force only by selecting an appropriate charge amplifier, which needs to be able to process the charge present at maximum force.

The resulting benefit is that the piezoelectric transducer can be used with any nominal (rated) force and, at the same time, the resolution of the measuring chain is not adversely affected. In the event of a failure, there is an increased safety margin and no mechanical damage is to be expected

3. Influence of the drift on the measurement accuracy

As described in the introduction, the output signal of a piezoelectric sensor is an electric charge. Finite electric resistances in the charge amplifier and in the connection between sensor and electronics produce a test result that is not stable over time, i.e. a drift develops. The drift amounts to approximately 15 mN/s, depending on the sensor material and the ambient conditions.

Special strain gage passivation methods ensure very high stability of strain gage-based force transducers. When measuring very small forces and/or measuring over a long period of time is required, strain gage measurement technology is superior to piezo-technology.

The relative effect of the drift in case of using piezoelectric sensors on the accuracy is shown in the pictures bellow: As long as the forces to be measured are high or the time the measurement takes is low the drift phenomena is not of any interest, but small forces or long measurement times are the area of strain gauge based transducers. Figure 3 shows the impact of the drift in case of a force of 100N to be measured and in case of a force of 5000N. It can be seen that the drift as only depending on the time has only a very low relative influence for forces need to be measured in industrial surroundings.

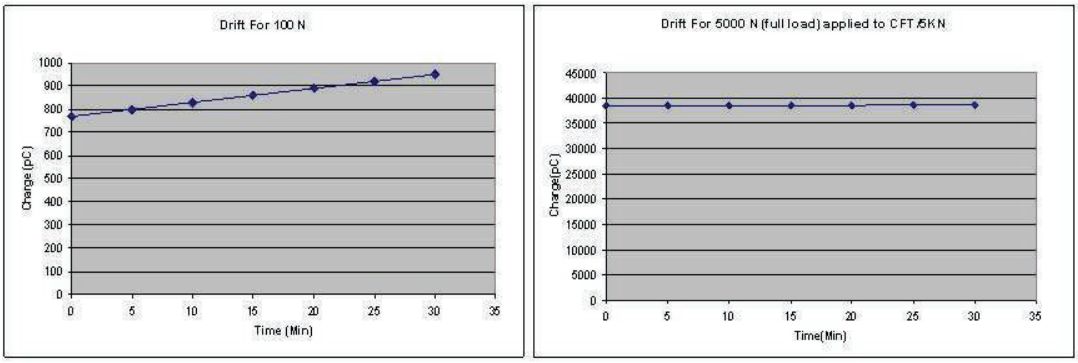


Fig. 3: The impact of drift on a measurement using piezoelectric transducer. Left hand side: 100N to be measured, the drift shows a high impact on the relative stability.

4. Accuracies that can be reached

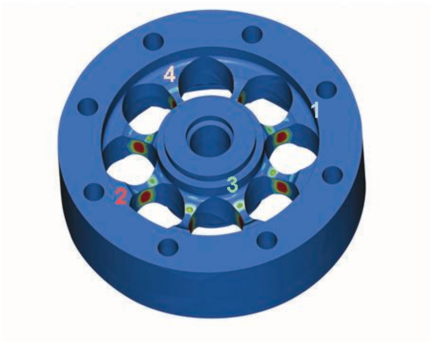
At first glance, the design of strain gage-based transducers appears to be more complex. However, the strain gages electrical circuitry offers multiple compensation options; therefore, strain gage-based force transducers are able to attain excellent accuracies. In addition to temperature effects (temperature effect on zero point, temperature effect on sensitivity), systematic linearity errors can be compensated for; furthermore, any desired sensitivity can be adjusted at high precision.

Piezoelectric force transducers offer a very simple and robust design, however, they do not enable the above mentioned error influences to be compensated for by electrical circuitry

The temperature coefficient of the zero point (TCZero) is not of interst looking at piezoelectric transducers, as the effect of drift is far more imortant. Further more the TCZero is only of interest in case of changing temperatures. Looking at the typical applications of piezoelectric transducers it is easy to see that short time, high dynamic measurements are in the focus so that the TCZero is not of interest.

In many cases lateral forces and bending moments do influence a force measurement. It is possible to compensate those forces and moments in an electrical way in case of strain gauge based transducers. Piezoelectric transducers are limited as the only compensation is given is the self compensation effect for bending moments: If the force is not introduced exactly in the middle or if a bending moment occurs, one side of crystal is loaded with higher stresses, while the other side is loaded with lower stresses. In addition the output of the sensor is nearly the same as with a force introduction free of any bending.

Strain gauge based transducers do offer the possibility to adjust the bending moment sensitivity. The can be achieved by setting up the strain gauges in a radial symmetric way. The figure bellow shows an example. The strain gauge based force transducer U10M comes along with four measurement points which are arranged in a symmetric way around the central load introduction. In case of bending one of the positions (1 to 4 in the figure) is loaded with more, the opposite side is loaded with less stress. The big advantage is, that it is possible to adjust all position to exactly the same sensitivity, so that bending moments and lateral force do not show any impact on the measurement value in any way.



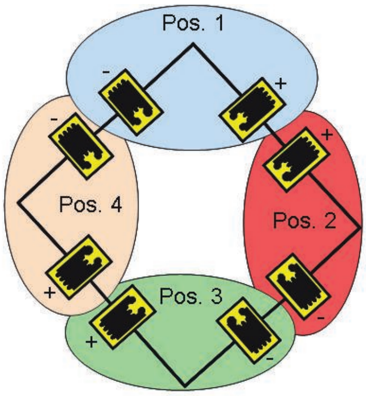


Fig. 4: The principle of the bending moment adjustment: HBM´s U10M comes along with 8 strain gauges in one Wheatstone bridge, arranged at four measurement points. A complete adjustment of the bending moment is possible by adjusting the sensitivity of position “One” to “Four” to exactly the same value.

The way of zero setting in case of piezoelectric transducer is to shortcut the sensor. This fact gives the advantage to use a charge amplifier with a lower imput range than the maximum output of the sensor. This leads to a higher resolution and a better signal/noise ratio. With strain gauge based transducer the zero setting process is a subtraction of the tara value from the measurement value. If a high preload is required only a small range of the amplifier range can be used.

5. Conclusion

Strain gauge bases force transducers show a higher long term stability and most errors can be adjusted. For high precise measurements and monitoring jobs Strain gauge based transducers are the first choice. The main advantage of piezoelectric force sensors is the use under high preload. In this situation a charge amplifier with a small input range can be used with all the following advantages. Further more the piezoelectric sensors show the same sensitivity without any dependence to the nominal load which allows to set up the system with a high overload capability.