XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6−11, 2009, Lisbon, Portugal

ENHANCEMENT OF THE MEASUREMENT CHARACTERISTICS OF PRESSURE TRANSDUCER UP TO 15000 BAR THROUGH MONOLITHIC MEASURING DESIGN AND FOIL STRAIN GAGES

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Abstract – High-pressure measurement technology continues to evolve and the design HBM is promoting for its series P3M pressure transducers has been strongly developed since the beginning of 2000. It involves a monolithic measuring body using foil strain gages for electro-mechanical signal conversion. This design has been tried and tested for years and even developed into the standard in high-pressure measurement technology. The monolithic design of the measuring body offers excellent measurement characteristics and is outstanding for its accuracy, ruggedness and stability. Increasing industry requirements regarding maximum pressure, resistance to overload and, in particular, accuracy resulted in continuing and consistent further development of high-pressure measurement technology. The experiences gained in improving details over the past years have been collected and implemented in a new, enhanced version.

Keywords: Ultra-high pressure transducer, foil type strain gage

1. TRANSDUCER DESIGN

One-piece - monolithic - measuring bodies using high-pressure sealing and assembly technique are used for new developments in a wide nominal (rated) measuring range. The measuring body design offers excellent measurement characteristics. Because of a special manufacturing technique they have no potential weaknesses such as welded seams. The measuring body design, the choice of material and the material thickness considerably influence the high-pressure transducer's measurement characteristics. The strain gages are only installed after the measuring body has been finalized, which offers the advantage of limiting possibilities in design and hindering certain technology steps [1]. Therefore the patented design of the transducer provides excellent measurement behavior, even in high pressure ranges.

2. REVIEW OF DYNAMIC BEHAVIOR

Due to their extremely high natural frequency of up to several 100 kHz, foil strain gages in combination with monolithic measuring bodies are perfectly suited to recording dynamic pressure applications even with pressure peaks. In combination with their generally excellent dynamic properties an ever increasing field of applications is opening up. The maximum number of dynamic load cycles is an important parameter.

Table 1. summarizes the results of prior investigations. The results have been verified in some points by fatigue tests and by the experience gained during operation. At the same time the table confirms the correct dimensioning of the pressure transducer [1].

Table 1. Fatigue strength

Nom. measuring range / static load capacity (bar)	Fatigue strength at nominal pressure (load cycles)	Fatigue 10^7 load cycles (bar)
500	10^6	350
1000	10^6	700
2000	10^6	1400
3000	3×10^3	2100
5000	1×10^3	3500
10000	10^3	5000
15000	5×10^2	6000

With dynamic loading at 100% vibration bandwidth, the 15000 bar sensor therefore has an estimated service life of 500 load cycles. When used at 6000 bar, a pressure transducer rated for 15000 bar is expected to be not fatigue critical (10^7 load cycles).

The expertise and results of prior investigations have been enhanced and implemented in the new generation of P3TCP "Top Class" Blue Line series high-pressure transducers.

Fig. 1. P3TCP “Top Class” Blue Line Transducer

3. IMPROVEMENTS

The following improvements were implemented to increase accuracy of the new generation of pressure transducers and thus meet the requirements of the industry for more accurate devices.

- Minimization of temperature effects on temperature coefficients
- Cubic interpolation function for minimizing characteristic curve deviation.

In general, cost-effectiveness is the limiting factor to compensating for reproducible errors. This aspect needs to be taken into account in adaptation. Hence, the above mentioned improvements that can be compensated for are reduced to the same level as the errors that cannot be compensated for (e.g. hysteresis).

4. TEMPERATURE EFFECTS

In general, external and internal effects on the measuring body and thus on the strain gage such as, for example, heat result in structural changes.
Temperature changes directly affect the stability of the zero point. The temperature dilatation of the measuring body material and the temperature-dependent change in resistance of the strain gage are influencing factors that need to be considered [2].
The relative resistance change of a strain gage resulting from the change in temperature comprises a thermal and a mechanical (i.e. caused by strain) portion [2].

$$\left(\frac{\Delta R}{R}\right)=\left(\frac{\Delta R}{R}\right)_{therm}+\left(\frac{\Delta R}{R}\right)_{mech} \quad (1)$$

ΔR = change in resistance
R = basic resistance

4.1. Temperature effect on zero point

Since all four strain gages are connected in a Wheatstone bridge and have identical resistance values, the thermal portions ideally should largely compensate each other.

$$\left(\frac{\Delta R_1}{R_1}\right)_{therm}=\left(\frac{\Delta R_2}{R_2}\right)_{therm}=\left(\frac{\Delta R_3}{R_3}\right)_{therm}=\left(\frac{\Delta R_4}{R_4}\right)_{therm} \quad (2)$$

However, manufacturing tolerances can result in remaining errors. If demanded for accuracy purposes, the remaining error can be compensated for by completing the Wheatstone bridge with a temperature-dependent resistor. A huge advantage of electro-mechanical conversion using foil strain gages is that it enables measurement directly at the point – i.e. the point of installation – where thermally induced interference develops. In general, this enables highly precise temperature compensation of the zero point.

The temperature coefficient on zero point is a absolute value. This is the reason why the coefficient can have a huge impact to the measured signal, if the pressure transducer is only working at partial load [3]. If highly precise pressure measurement is required, a device with the smallest possible measuring range should be selected.

Table 2. shows how adequate measures and enhanced manufacturing techniques considerably improved the temperature-dependency of the zero point of series P3TCP "Top Class" Blue Line transducers.

Table 2. Temperature coefficient on zero point

	P3TCP "Top Class" Blue Line	Standard pressure transducer
Temperature coefficient on zero point TK_0	0,05 %/10K	0,1 – 0,2%/10K

4.2. Temperature effect on sensitivity

The sensitivity of a transducer is defined as the span between the signal values at nominal pressure and the initial signal of the unloaded transducer [3].

$$C = S_n - S_0 \quad (3)$$

C = sensitivity
S_n = nominal output signal
S_0 = initial signal

Temperature changes also affect sensitivity. The thermal change in sensitivity results from the temperature dependency of the Young`s modulus of the material used for the measuring body. Decreasing of the modulus causes additional strain for the same stress (load) level. Calculation of material stresses are based on the Hooke’s law [4].

$$\sigma = \varepsilon \cdot E \quad (4)$$

σ = material stress
ε = strain
E = Young`s modulus

Fig. 2 shows the Young`s modulus of different series of possible transducer materials. It shows clearly that the modulus decreasing with increasing temperature [5].

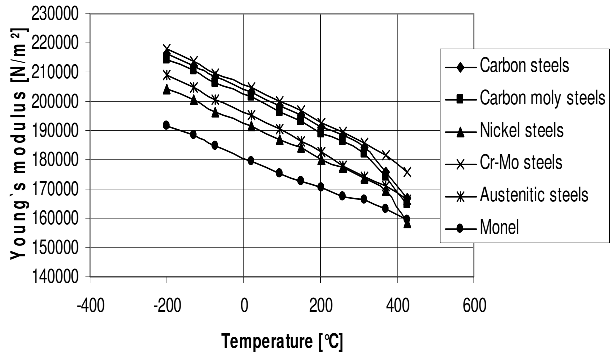

Fig. 2. Typical temperature dependence of the Young`s modulus of different metals and alloys

This means that at higher temperatures a uniformly loaded measuring body is strained more than at lower temperatures.

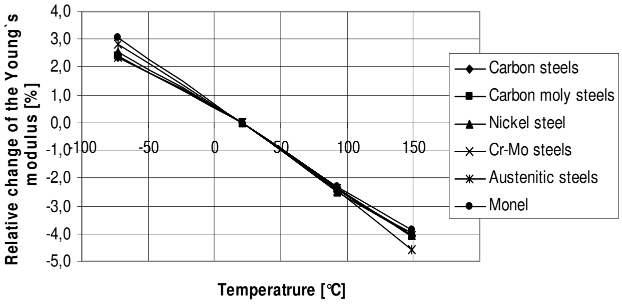

Fig. 3. Typical relative change of the Young`s modulus

In a wide temperature range the relative change in the Young`s modulus shows a linear character.

A measure of the sensitivity of a strain gage is the gage factor and can be expressed as [6].

$$k = \frac{(\Delta R / R)_{mech}}{\varepsilon} \tag{5}$$

k = gage factor
ΔR = change in resistance
R = basic resistance
ε = strain

The gage factor is a measure of the sensitivity of the strain gage. Fig. 4 shows that the gage factor is also susceptible to temperature effects.

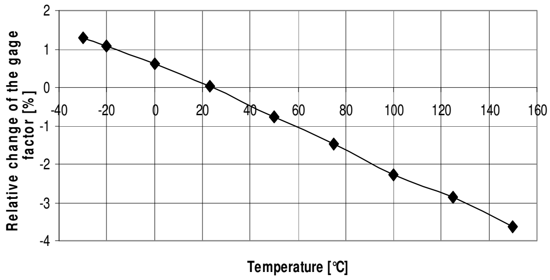

Fig. 4. Typical temperature dependent change in sensitivity of a strain gage

The relation between the gage factor and the Young`s modulus is obvious if one substitutes (4) into (5).

$$\left(\frac{\Delta R}{R}\right)_{mech} = \sigma \frac{k}{E} \tag{6}$$

ΔR = change in resistance
R = basic resistance
σ = material stress
k = gage factor
E = Young`s modulus

Equation (6) shows that the change in resistance and therefore the sensitivity of a transducer as a function of temperature is primarily related to the change in the Young`s modulus of the transducer material and the change in gage factor of the strain gage. Minimizing the deviation of the ratio, k/E, enables the influence of temperature effects to be substantially reduced. Temperature induced change of the Young`s modulus can be effectively controlled by a negative temperature dependence of the gage factor. With this method no additional compensation elements are necessary anymore. To get the best overall result also passive measures – such as optimal body design, choice of material etc. has to be taken into account to balancing the interaction.

In some cases also additional temperature-dependent resistors are connected to the excitation line of the Wheatstone bridge for compensation. If the transducer is subjected to temperature, the excitation voltage of the measuring bridge is reduced to the same degree as the resistance change and thus the output signal is increasing as a result of the temperature effect [7]. As a consequence, the sensitivity of the Wheatstone bridge remains constant.

The temperature coefficient on sensitivity is a relative value and therefore not critical if the pressure transducer is partial loaded.

Optimized use of the measures described above enables the influence of temperature effects on nominal sensitivity to be further substantially reduced.

Table 3. Temperature coefficient of sensitivity

	P3TCP "Top Class" Blue Line	Standard pressure transducer
Temperature coefficient of sensitivity TK_C	0,05 %/10K	0,1 – 0,2%/10K

5. CHARACTERISTIC CURVE DEVIATION

5.1. Linearity

The Linearity describes the maximum deviation of the curve (d_{lin}) of the best-fit straight line (BFSL) for a pressure transducer's characteristic curve determined at increasing load from zero to nominal pressure (p_n).

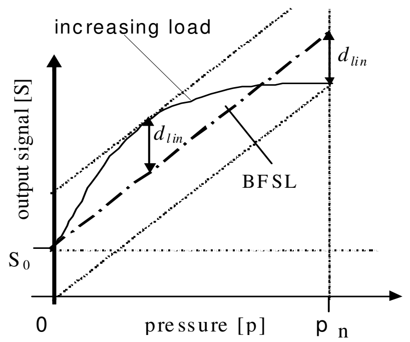

Fig. 5. Linearity

To achieve the most accurate overall result it is common to construct a so-called zero based “Best Fit Straight Line” (BFSL) through the measured points in such a way that the maximum deviation of the curve from the ideal line is minimized.

5.2. Hysteresis

Hysteresis corresponds to the maximum difference of the output signal when measuring the same pressure at increasing and decreasing load.

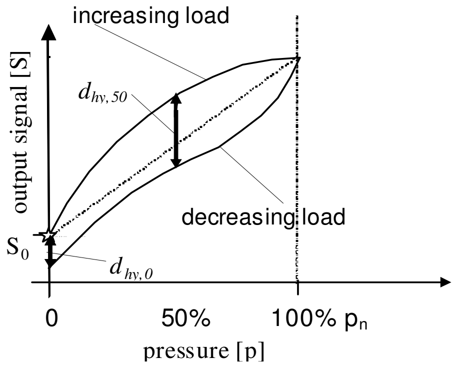

Fig. 6. Hysteresis

The determination of the effect of hysteresis is based on measurements at a number of predefined points in the load cycle (e.g. 0%, 50%, 100%).

5.3. Curve deviation

Hysteresis typically incorporate with linearity to define the accuracy of the pressure transducer. To determine the characteristic curve deviation (d_{lh}) both effects has to be taken into account.

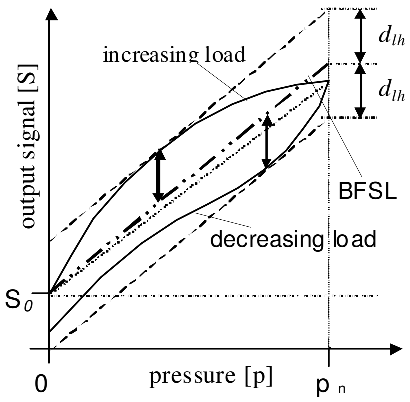

Fig. 7. Curve deviation

For the determination of the curve deviation the interpolation of the BFSL thru zero is applied in such a way that the maximum deviation (increasing / decreasing) from the measured points have the same amount. Characteristic curve deviation can also be interpreted as half of the tolerance band that is symmetrical about the BFSL.

5.4. Cubic interpolation

Applying a cubic interpolation function - instead of linear interpolation - to the test values determined at increasing and decreasing load- enables the relative interpolation error to be reduced. For this reason, the series P3TCP “Top Class” Blue Line calibration protocol explicitly specifies the cubic interpolation function applied [8].

$$f(x) = a_3x^3 + a_2x^2 + a_1x + a_0 \tag{7}$$

f(x) = pressure
x = output signal
$a_0 \ldots a_3$ = coefficients

The coefficients of the cubic function are individually determined and specified for each pressure transducer. For a given series of tests, the required interpolation points and thus the coefficients can be determined, for example, using the polynomial approach [8].

$$f(x)=a_0+a_1(x-x_0)+a_2(x-x_0)(x-x_1) \\ +a_3(x-x_0)(x-x_1)(x-x_2)+.....+a_n....(x-x_{n-1}) \tag{8}$$

Fig. 8 shows an example for a characteristic curve deviation applying a linear interpolation function of a 10000 bar pressure transducer

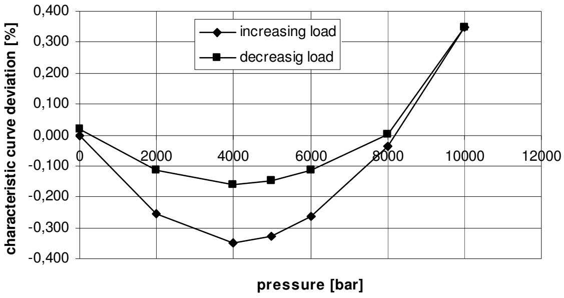

Fig. 8. Linear interpolation

The maximum characteristic curve deviation in this case is correspondent to 0,35%.
Applying the cubic interpolation function specified in the series P3TCP "Top Class" Blue Line calibration protocol, the maximum curve deviation can be further effectively reduced.

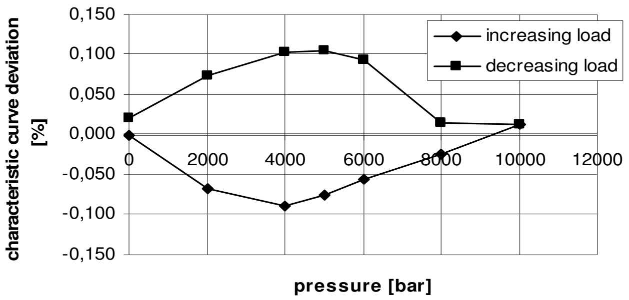

Fig. 9. Cubic interpolation

Fig. 9 shows that the maximum characteristic curve deviation is about 0,1%. Applying cubic interpolation enables the characteristic curve deviation to be reduced by a factor of 3,5. The degree of reduction is always dependent on the transducer. This means that - applying the cubic interpolation function - the improvement of accuracy can varies from transducer to transducer.

6. CONCLUSION

In general, hysteresis or long-term stability cannot be compensated for. Adequate measures for further minimizing the temperature effect on zero point and sensitivity and application of a cubic interpolation function for further minimizing the characteristic curve deviation are very suitable. Each individual measure provides a relatively small improvement; however, the overall quality of measurement is substantially increased. This enables users - if necessary - to further considerably minimize the characteristic curve deviation and the temperature effects on sensitivity and the zero point again.

High load cycles in combination with optimized dimensioning of the patented sensor with regard to accuracy set new standards in high-pressure measurement technology.

From the very beginning of the P3 pressure series until today, many aspects of pressure transducers have been optimized. For the future, we see new applications in the consistently growing high-pressure market. The outstanding measuring body design in combination with the high number of possible load cycles and improved accuracy give us the opportunity to master future challenges this market.

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