The Route to Measurement Transducers

A Guide to the Use of the HBM K Series Foil Strain Gages and Accessories

HBM
an HBK company

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1 Introduction

With their K series of foil strain gages and accessories, HBM offers vital components to enable experienced users of strain gages to design and construct quality transducers, in-house, for electrical measurement of mechanical quantities. In doing so the user will benefit from HBM's many years of experience as manufacturers of not only high-precision transducers but also high quality strain gages.

In addition to the hardware mentioned above, this booklet is intended to provide the necessary theoretical and practical information needed to most effectively use these elements in manufacture of transducers. It is not, however, intended to replace the recognized technical literature dealing with strength of materials and SG technology, nor to replace the instructions for the use of individual components.

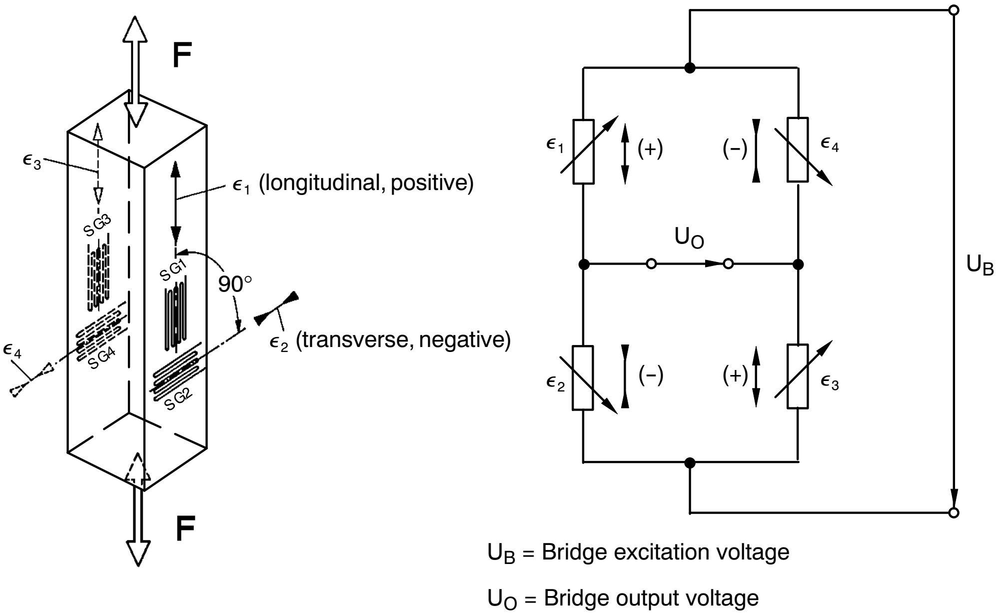
The requirement for force, torque and pressure transducers to be made in-house is usually the result of very special measurement problems or installation circumstances which make it appear to be difficult or maybe impossible to utilize standard commercially available transducers: In many cases certain specific requirements take precedence over accuracy. Moreover, the supposed deadline frequently leaves insufficient time in which to obtain special designs from established transducer suppliers.

However, in spite of all these arguments, it should still be appreciated that transducer design and construction often calls for more know-how, development work and, not least, production and testing capacity than is often assumed. This applies particularly where the aim is to produce transducers with errors of less than 1 %, or where relevant regulations necessitate very accurate and highly reproducible measurements.

Any decision to be made between using a bought-out unit or one made in-house must, therefore, always be based upon a realistic estimate of one's own capabilities in relation to the requirements and expected results.

2 Measurement transducers and SG—two inseparable terms

The transducers dealt with here consists of two primary elements, namely, the elastic element and the strain gage. The elastic elements will deform in response to changes in the measured variable. This deformation will be converted into an electrical signal proportional to the value of the measured variable by the strain gages (SG) installed to the surface of the elastic element, usually connected in the form of a Wheatstone bridge (Fig. 2.1). For further information on the SG principle refer to items [1] to [4] in the Bibliography.



$$\frac{U_O}{U_B} = \frac{k}{4} \cdot (\epsilon_1 - \epsilon_2 + \epsilon_3 - \epsilon_4) \qquad (1)$$

Fig. 2.1: Schematic diagram and basic circuit of a device for measuring force

Transducers employing this principle are used in large numbers in all branches of industry and in research, where they cover a wide range of installations in electrical measurement of mechanical quantities. This dominant position could be achieved because the strain gage principle (metallic resistance SG) combines a number of advantages that virtually predestine its incorporation in measurement transducers. The most important of these advantages are listed below:

– The excellent linearity, hysteresis and reproducibility of the SG in conjunction with the Wheatstone bridge circuit and its compensation capability allows high measurement accuracies to be achieved.
– Forces and variables which can result in changes in force can be measured in both positive and negative directions (determination of positive and negative strain).
– Static and dynamic processes can be monitored.
– The negligible mass of the SG permits very high limit frequencies of the measured quantity.
– The good fatigue characteristics of the SG ensure a long life under alternating loads.
– Despite the comparatively simple design concept, the limits of its installation and the load capacity range are very wide. There is no theoretical upper limit for large rated loads. The lower limit is defined by the mechanics of the system, and lies around 0.1 kg. The strain gage itself has no response threshold.
– SG transducers, properly designed to meet the intended installation, are notable for their high long-term stability.
– Strain gages and thus transducers operating on this principle can be used over a wide temperature range.
– The photochemical processes employed to manufacture modern foil SG's allow individual tailoring to the needs of the specific measurement problem, and the related measuring element.
– The small dimensions of the SG assist in the current search for constantly smaller size.
– The wide freedom of choice in relation to associated amplifiers allows considerable flexibility.

The following information is intended to ensure that these advantages can also benefit the design of custom-made transducers.

3 The Route to the Measurement Transducer

Should you decide to build your own transducers, we recommend that you proceed in the following sequence. In addition to the necessary theoretical aspects, this booklet explains the individual steps on the basis of a simple but clearly illustrative example. The practical considerations relate to an "example transducer" incorporating the knowledge derived from each preceding chapter.

3.1 The design concept of the elastic element

The term "elastic element" for the stressed part already indicates an important property. The deformation must be purely elastic, i.e., it must remain within the range of Hooke's Law. Any permanent set in the elastic element will render it unsuitable for the intended installation. This aspect must govern the geometry, dimensioning and the choice of materials.

3.1.1 Geometry

The prime factor governing the geometry of the elastic element is the nature of the variable to be measured, as well as its magnitude and direction. Important properties of the transducer, such as good linearity, low hysteresis and low creep are also significantly affected by the geometry of the elastic element. SG transducers are suitable not only for measuring forces, although attention is primarily given to variables which can be related to force, e.g., mass, bending moment, torque, pressure, vibration and acceleration. The basic forms of elastic elements suitable for measurement of such variables are shown in Fig. 3.1.

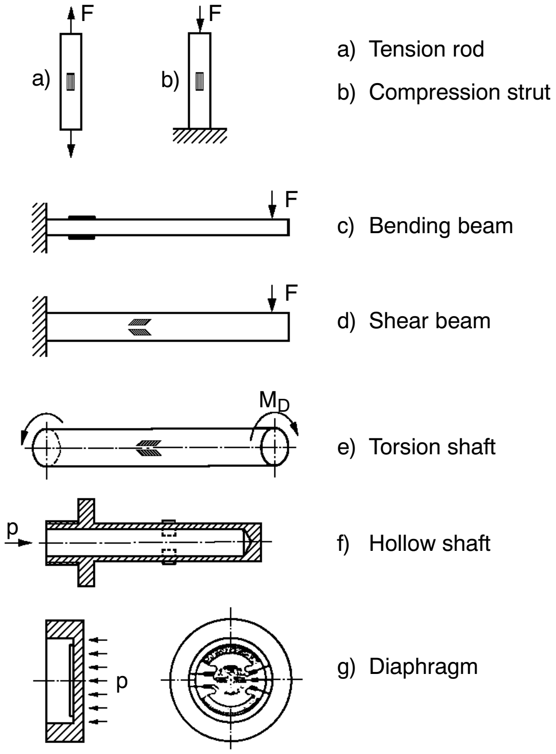


Fig. 3.1: Schematic arrangement of the most important basic forms of elastic element for SG transducers

To achieve the greatest possible sensitivity relative to the measured variable, a full bridge with four active SG arms should be built up wherever possible (see Fig. 2.1) . Consequently the geometry of the elastic element must be such that zones subjected to tensile and compressive stresses to which the strain gages are installed must react simultaneously in response to an installed load. The stress distribution in these zones must, as far as possible, be uniform.

A series of transducer designs can be derived from the basic forms of the elastic element, depending upon the actual requirements. A number of examples are discussed in the following sections.

3.1.1.1 Force transducers

Fig. 3.2 already clearly shows that practical transducers are usually much more complex than the basic forms first illustrated. The elastic member in these variants consists of a thick circular rod with a reduced cross-section in the middle. This cross-section must be selected in relation to the nominal load and the desired sensitivity. Its length and radiused transition to the larger cross-section ensure uniform stress distribution in the region of the SG. The cross-section of the ends is dimensioned significantly larger so that they deform as little as possible, and so do not noticeably contribute to the displacement under load.

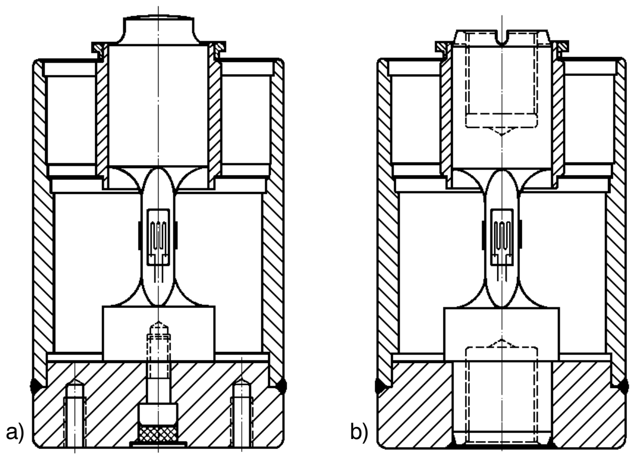


Fig. 3.2: Example of the mechanical design of a transducer. a) for compression loads, b) for tensile loads (also usable for compression loads)

They must also be of adequate dimensions to accommodate the thread by which the tensile loads are introduced (Fig. 3.2 b). A strong housing supports the elastic element against lateral forces and hermetically seals it against the external environment. Protection against lateral forces is necessary to prevent over-loading of the measuring element, and to maintain the accuracy of measurement. To prevent the housing from affecting measurements by providing a force bypass, it is terminated at one end with two series-connected diaphragms which are “soft” in the force measuring direction but transversely are stiff. The column-form of elastic element for force transducers as shown in Fig. 3.2 can be used for measurements in the nominal range 10 kN/1 t to 10 MN/1000 t. Fig. 3.3 shows a modified column form. The H-shaped cross-section provides the element with a considerably greater bending section modulus, and thus better resistance to lateral forces than a uniform cylinder. It is therefore possible to dispense with the supporting function of the housing and is sufficient to design it as a protective casing. The SG’s are mounted on the horizontal web of the H-section, since at that point—near the bending neutral axis—they are exposed to minimal stressing by transverse forces.

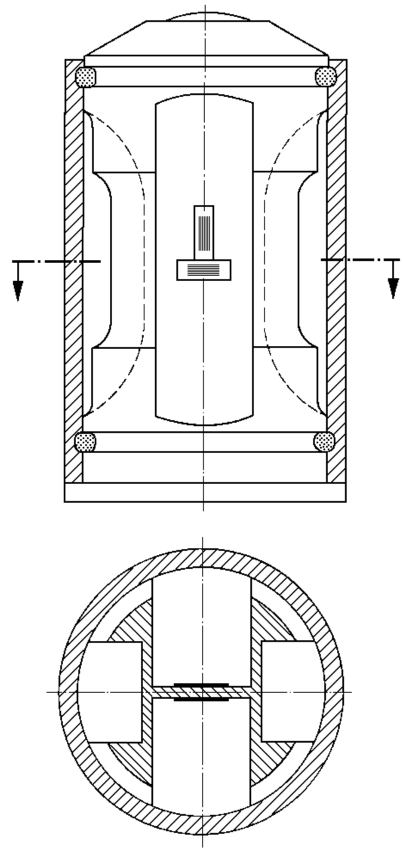


Fig. 3.3: Force transducers with H-shaped cross section for the elastic element

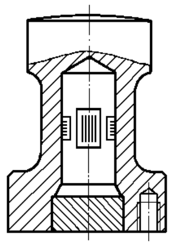


Fig. 3.4: Force transducers with hollow cylindrical elastic element

Another form of construction is shown in Fig. 3.4. Similarly to the H-shaped cross-section, the hollow cylinder has a large bending section modulus, so that it is only slightly affected by lateral forces. The SG installation is well protected within the hollow cylinder, so that a special protective casing is unnecessary. This type of elastic element is suitable for nominal measuring ranges in the order of 100 kN/10 t to 1 MN/100 t.

In many cases problems arise because there is insufficient headroom available in the installation space. This compels the designer to select low-profile elastic elements. However, simple flat discs are not suitable because a uniform stress condition cannot be achieved—even on the most precisely machined force installation surfaces. Yet this state is a pre-requisite for accurate measurements, since all that can be measured is the strain on the surface of the elastic element, whereas the effective strain is irregularly distributed through-out the entire volume. Now, if the strain on the surface is proportional to the mean value, the measurement will be correct. The tubular elastic element in Fig. 3.5 satisfies these requirements more closely than a disc.

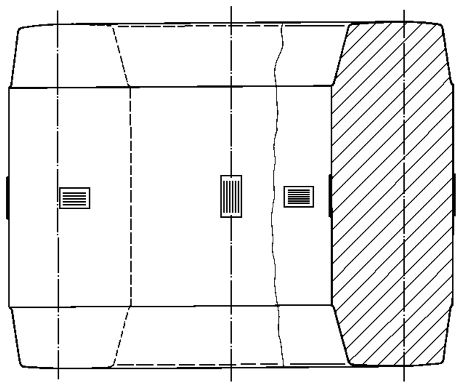


Fig. 3.5: Tubular elastic element

If one wishes to measure in small to micro force ranges, then the method of directly stressing the material by normal forces is generally not suitable. To obtain a specified nominal sensitivity we need a certain surface strain on the elastic element. Since there are limits with small cross-sections and the choice of materials with a low Young's modulus, alternatives must be found. One method is to make use of a lever arm and measure the bending moment. A very simple form of bending beam is shown in Fig. 3.6.

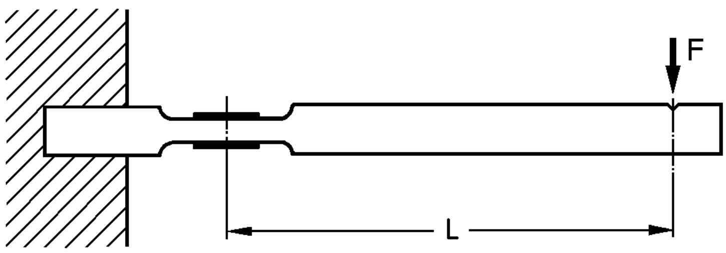


Fig. 3.6: Simple bending beam

In this arrangement the measurement signal is clearly proportional to the bending moment. If we wish to use bending beams to measure forces we must provide a defined and unalterable point at which to introduce the force; in this way the effective length of the lever remains constant. Another factor is the angular offset due to the non-parallel lowering of the force installation point. This phenomenon can only be countered through an additional force feedback system. Because of these circumstances simple bending beams are encountered only on relatively rare occasions. To nevertheless exploit the advantages of the bending beam principle, e.g., their very good linearity, we can consider various arrangements. Fig. 3.7 illustrates three common forms.

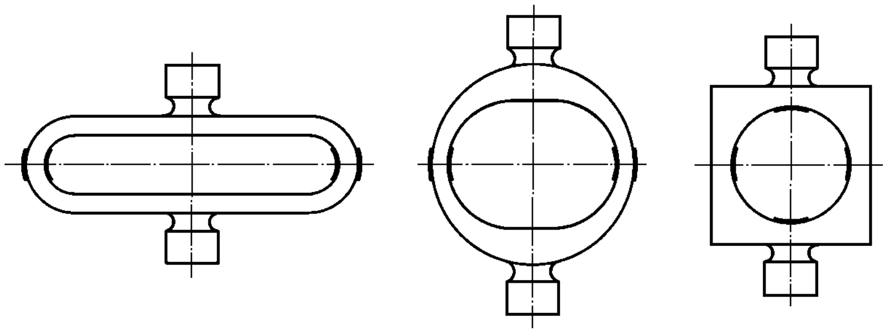


Fig. 3.7: Elastic elements arranged to form bending beams

The left-hand version shows most clearly the relationship with the bending beam. If we were to construct from the three different forms of elastic element transducers with the same nominal value and the same nominal sensitivity, then the left-hand one would have the greatest displacement and the right-hand one the least. The square corners shown on the right-hand model will obviously simplify production, but will serve primarily to stiffen those sections of the ring not used to measure strain, so that the displacement is reduced and the natural frequency of the transducer is raised.

Elastic elements of this and similar construction can be used for nominal ratings from approx. 500 kN/50 t down to 5000 N/500 kg. The end sections shown in Fig. 3.7 must be designed to suit the specified purpose (tensile or compressive load).

For still smaller measuring ranges of down to less than 100 N/10 kg elastic elements have developed, which use the double bending beam principle. Fig. 3.8 shows a number of typical designs.

Due to its high resistance to bending moments and torsion, the double bending beam is less sensitive to disturbance resulting, e.g., from incorrect installation of loads. In addition, it exhibits significantly better guidance properties than the simple bending beam. This design achieves virtually parallel lowering of the load installation point, with almost no angular offset, without resorting to force feedback.

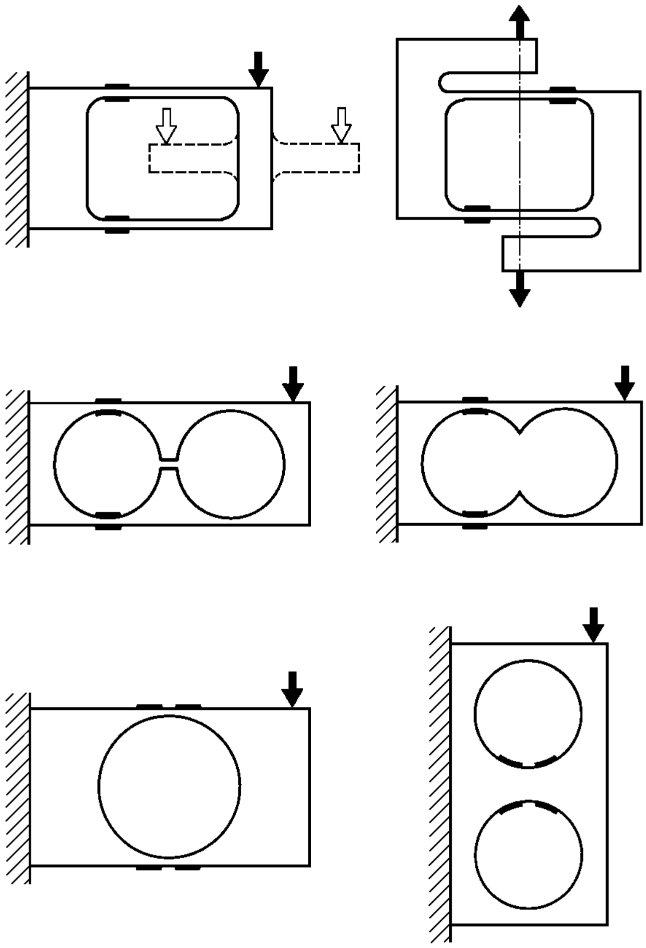


Fig. 3.8: Different forms of the double bending beam

A further design possibility for force measurement is to make use of shear stresses. Shear stresses occur in pure form, e.g., in a torsion, shaft. The resultant principal stresses and principal strains occur at ±45° to the shear load plane with opposite signs. Various versions of shear beams are used to measure forces. The principle is explained in Fig. 3.9. As a result of the mutually superimposed shear and bending stresses, the resultant direction of the principal stress/principal strain alters according to the ratio of shear to bending stress, and thus also with the distance to the neutral axis. The principal strains are consequently only properly measured when the SG's, installed at ±45°, lie directly on the neutral axis. Because of the change in area of the SG, this is only achieved approximately.

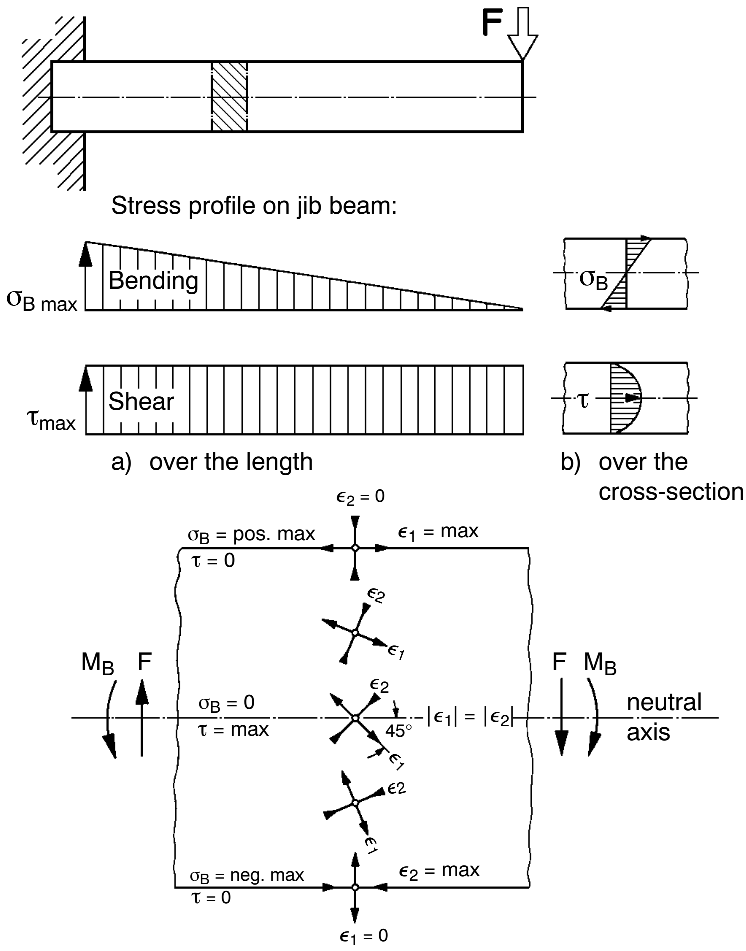


Fig. 3.9: The directions of the principal strains ϵ_1 and ϵ_2 along a cross-section line with superimposed bending and shear stresses

An improvement can be achieved when, at the specified shear stress, we keep the bending stress as small as possible. That is to say, we must distribute the cross-section defined for a given shear stress so that the beam is provided with the greatest possible resistance to bending, e.g., the I-section as shown in Fig. 3.10. In this way the bending stresses will be so small in relation to the shear stresses that, their effect on overall strain (principal strains) in the region of the SG becomes negligible.

The particular advantage of such an elastic element is that the force installation point can wander anywhere along the along the beam's longitudinal axis without adversely affecting the measurement result. This contrasts with the simple bending beam shown in Fig. 3.6.

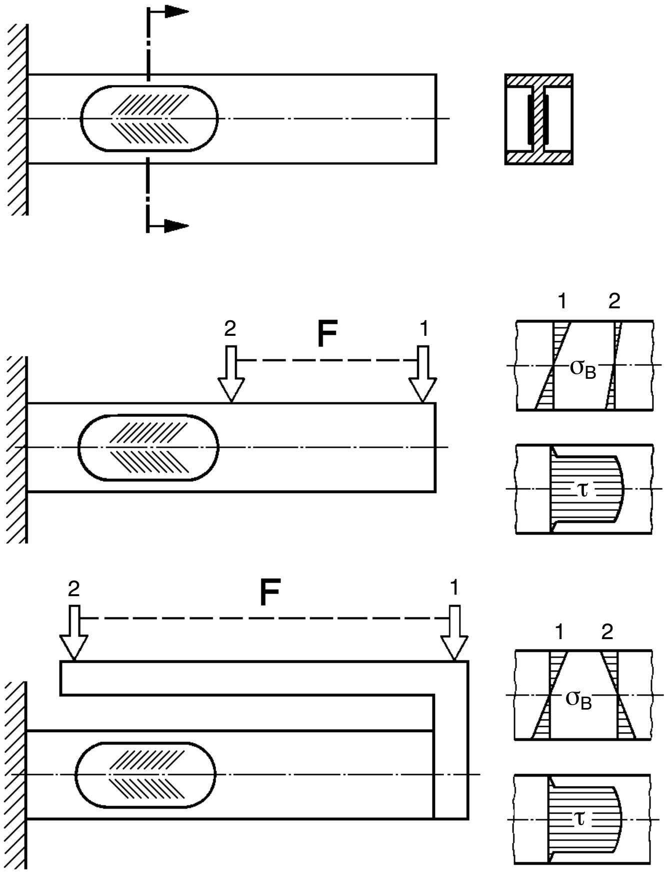


Fig. 3.10: Example of a shear beam with I-profile in the measuring section

3.1.1.2 Torque transducer

As in force transducers, torque transducers need suitable elastic elements to convert the torque into a surface strain which can be detected with SG's. The simplest form of elastic element is a cylindrical shaft, as shown in Fig. 3.11. In this case the strain gages are mounted in the directions of the principal strains ϵ_1, ϵ_2 acting at ±45° to the shear plane and to the axis respectively. As already shown in Fig. 2.1 and taking a force transducer as an example, a complete Wheatstone bridge consisting of 4 active SG's on the elastic element provides, on the one hand a larger measurement signal and on the other compensation capabilities. If we mount the SG's in pairs on opposite sides of the shaft, the superimposed bending stresses will compensate each other both in the X-Y plane and in the X-Z plane. In the same way normal stresses along the X-axis are also compensated.

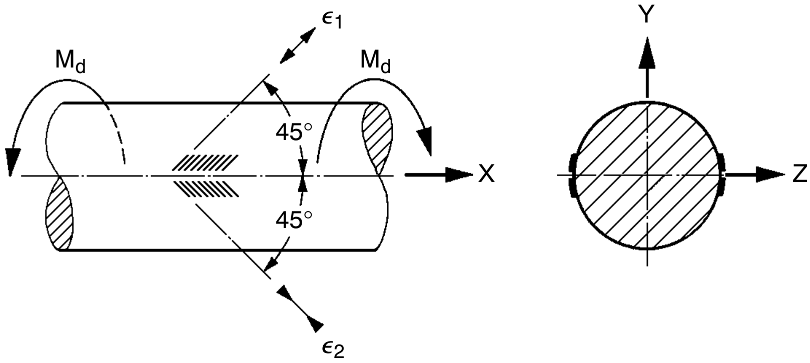


Fig. 3.11: Elastic element in the form of a cylindrical shaft

For small torques the solid shaft is either too rigid and so not sufficiently sensitive for the transducer, or is unacceptably sensitive to bending loads. It is hardly possible to set a limit because several parameters must be considered, such as the length of the shaft, the coupled masses, shocks during running, and similar factors. One solution is to use the hollow shaft illustrated in Fig. 3.12 in which the ratio of bending moment resistance to polar section modulus is more favorable than in the solid shaft. The arrangement of the SG's is the same as for the solid shaft.

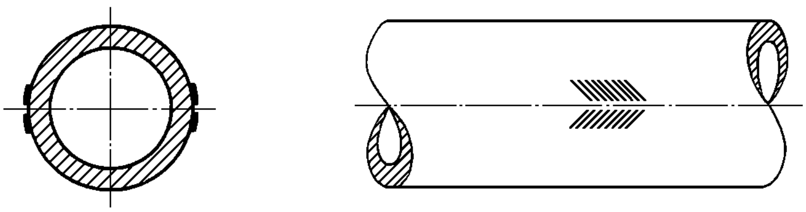


Fig. 3.12: Elastic element in the form of a hollow cylinder

As in force transducers, care must be taken through suitable elastic element shapes to ensure that torque transducers can still generate a sufficiently large measurement signal for small torque values. This requirement must be satisfied particularly in transducers intended for industrial use, since here one must expect high levels of interference from the mains power supply or on the signal transmission paths, which could swamp or distort the measurement signal. Under laboratory conditions or other favorable circumstances it is however possible to obtain a small measurement signal with sufficient accuracy because, in common with other SG transducers, torque transducers have no response threshold.

Fig. 3.13 shows a cage-like elastic element; its measuring range can be varied by altering the number of cage struts, the strut dimensions and the material. To measure the torque in this case use is made of the bending stress in the cage struts and not the shear stress on the shaft.

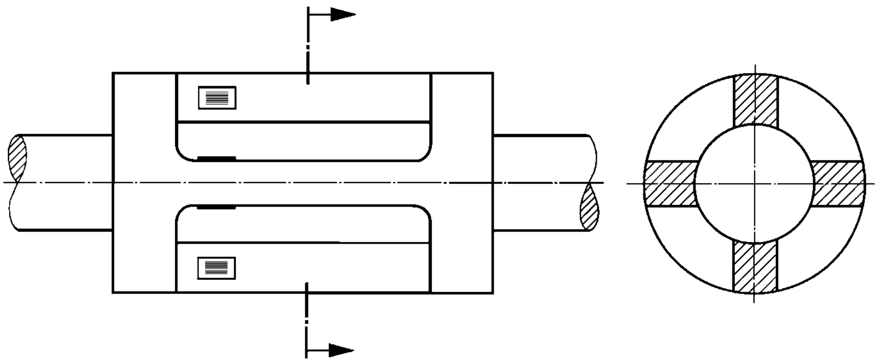


Fig. 3.13: Cage-type elastic element

3.1.1.3 Pressure transducers

Designs of elastic elements in pressure transducers include tubular bodies with different cross-sections, a choice of which is shown in Fig. 3.14. From the point of view of SG technology, the flat tube a) is perfect. With positive gage pressure inside the tube the SG's on the flat sides are subjected to positive strain, whereas those on the curvatures are negative. It is therefore possible to add the strain values of all SG's in the Wheatstone bridge, thus contributing to higher sensitivity and rendering the transducer ideal for measuring low pressures.

In contrast, the hollow cylinder form b) is easier to manufacture; in particular, the interference zones towards the ends of the tube are smaller. Strain distribution is less favorable. In internally pressurized thin-walled tubular bodies (boilers) the tangential stress is double that of the axial stress, both being positive. As a result of this the values of axial and tangential strain subtract, leading to a low sensitivity of the transducer. Help is obtained by leaving an extension (it can be hollow or solid) on the closed end of the tube, and using this to mount the two compensation SG's, i.e., form b'). In this way losses in sensitivity are avoided. A disadvantage is the distance between active and compensation SG's, which can result in temperature errors caused by compensation delays due to considerable differences in temperature (e.g., inflow of the medium).

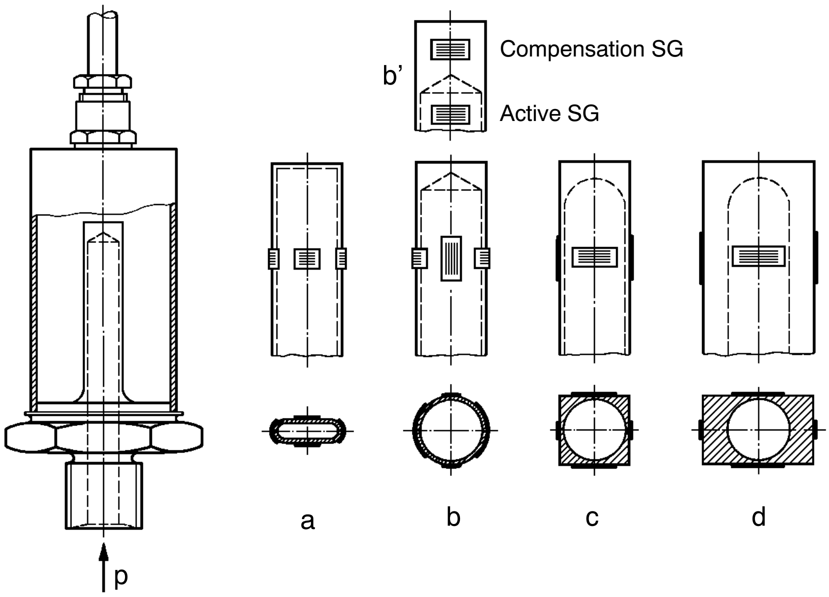


Fig. 3.14: Pressure transducers with tubular-form elastic elements. a) Flat tube, b) Cylindrical tube, b’) Cylindrical tube with extended end, c) und d) modified tubular forms.

Form c) reduces the disadvantages of form b) because its cross-section in the axial direction is greater than that of a simple tubular body. As a result, the subtracting strain of the axial SG becomes smaller and the resultant measurement effect greater. The stress peak (stress concentration or notch factor) provides a further increase in the measurement effect. As all SG’s lie in the same plane, even thermal shocks have no adverse effect. The same arguments as for model c) apply to model d), except that in this case the axial cross-section is even larger.

Transducers of the tubular type are suitable both for static and dynamic pressure measurements, so far as the pressure medium cannot be compressed and fully occupies the interior of the transducer. Gaseous media or entrained air bubbles tend to mask pressure peaks and so restrict the transducer’s suitability for dynamic measurements. In such cases the flush diaphragm transducers without a cavity are better suited, if the design of their elastic elements is sufficiently stiff. Fig. 3.15 shows a schematic diagram of a transducer of this type complete with diaphragm rosette SG.

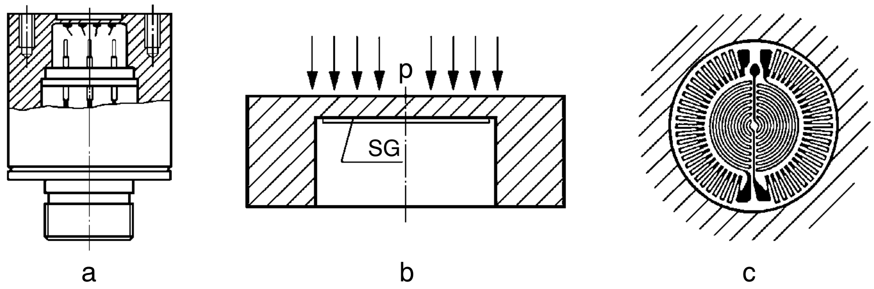


Fig. 3.15: Pressure transducer with flush diaphragm elastic element. a) Sectional drawing, schematic, b) Clamped circular diaphragm, c) Diaphragm rosette SG.

The strain distribution over the surface of a clamped circular diaphragm is illustrated in Fig. 3.16.

The works listed in the Bibliography as items [1] and [2] deal with the different forms of loading and practical mounting of SG's in greater theoretical detail.

Since it would go well beyond the scope of this booklet to deal with all imaginable forms of transducer, we must confine ourselves to a few of the more important examples. It is possible, for example, to measure other variables not directly related to the force; these include displacements (movements, changes in clearance) and strains. But this also requires suitable elastic elements with which to measure the variables. These elastic elements in turn require a finite force to deform and this must be drawn from the object being measured. This technique therefore cannot be used if this force is not available. Although it is possible to have transducers which operate with very little force, truly "forceless" measuring systems do not exist.

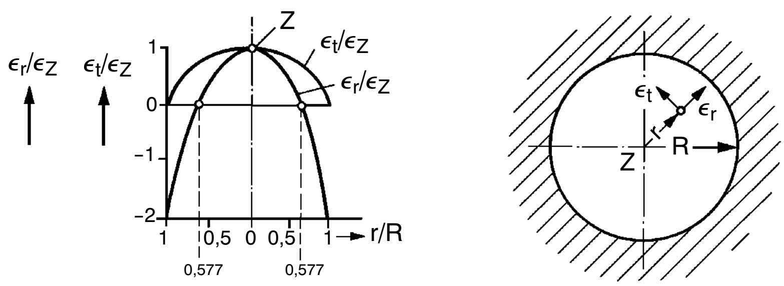


Fig. 3.16: Left: Strain distribution on a clamped circular diaphragm in radial (ϵ_r) and tangential (ϵ_t) direction, Z = center. Right: Explanation of symbols in diagram a).

The question of dimensioning arises for all imaginable elastic element forms. The elastic element should be dimensioned according to the material used, such that a mechanical strain of approx. 1000 mm/m or 1 ‰ respectively occurs under nominal load. These values have proven viable in actual practice. They offer a good compromise between material utilization, and optimum linearity and hysteresis performance. Adequate protection against overloading is offered by the margin from the proportionality limit of the material used in the elastic element (also dependent upon the material hardness) which lies at approx. 4 ‰ ... 6 ‰ strain.

Wherever possible, the elastic element including the clamping areas should be made from a single piece of material because mechanical joints, such as screws or rivets, can lead to friction on the contact surfaces and thus to undesirable hysteresis effects. Even welded joints lead to lower quality results due to their residual stress.

The form and external dimensions of the elastic element are determined to a large extent by the requirements of the actual installation (circumstances, force introduction). The final decision in favor of one form or another can thus only be made by the user.

3.1.1.4 Practical considerations concerning elastic element geometry

As mentioned in the introduction to this section, the use of the “K” series strain gages with their balancing and compensation elements and other accessories are described on the basis of a general, practical example. The aim is to use the simplest possible elastic element, but one which is at the same time most suitable for discussing the individual areas of interest. The bending beam can best be used to demonstrate the important steps in transducer manufacture.

Another factor in favor of this elastic element is that it is a familiar element of mechanics involving simple calculations.

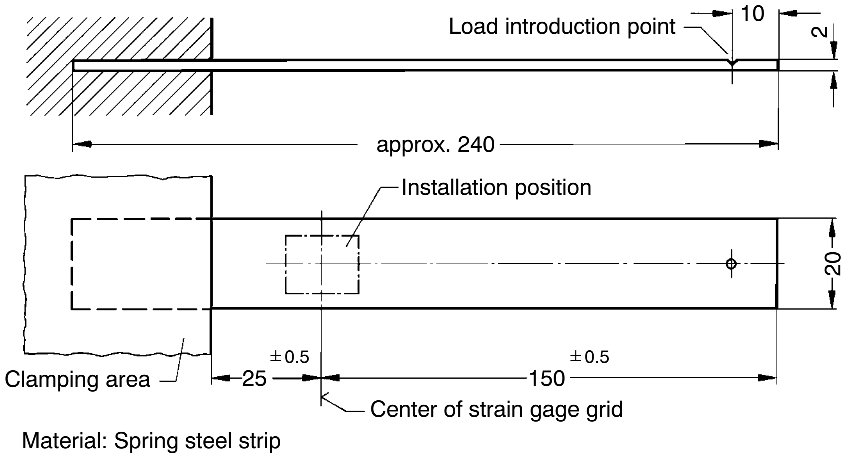


Fig. 3.17: Sketch for practical consideration of the bending beam principle

As is evident from the Section 3.1.1, where a simple bending beam is used as a transducer, it is particularly important to provide a defined and unalterable point at which the load is introduced, and thereby to provide a constant lever length. The elastic element is therefore provided with a center hole at the point at which the load is to be introduced, e.g., via a pointed plunger.

The SG's are later installed 150 mm from the point of installation of the load (relative to the center of the strain gage grid). This distance corresponds to the effective length of the lever arm. In order to achieve a defined point of attachment, the elastic element is clamped in a fixed support with which it effectively forms a solid unit. This unit, which should be regarded as the actual transducer, also ensures that the intrinsic load signals of the freely suspended cantilever bending beam itself are always effectively installed in the same way. In view of these points, problems specially applicable to this form of elastic element, e.g., changes in the lever arm due to angular offset will not be handled in greater detail.

3.1.2 Choice of material

The properties of the elastic element and thus of the complete measurement transducer are very much dependent not only on the type of material used but also on its geometry.

The following basic requirements apply to the material used for the elastic element. It must have:

– A fine-grained, homogeneous texture
– High elastic deformability typified by high strength and a high yield point
– Good creep behavior
– Low hysteresis
– Lowest possible temperature coefficient of Young's modulus
– Good thermal conductivity

By selecting materials with a low Young's modulus (compared with steel), it is possible, for a given load and dimensions to achieve a higher level of strain.

The metal alloys listed in Tab. 3.1 have made their mark in transducer construction and since they fully satisfy the stated requirements, they can be regarded as standard materials for transducer manufacture.

Tab. 3.1: Summary of commonly used elastic element materials and their characteristic values. Non-metallic materials at present play only a minor role, and are therefore not mentioned here.

	Designation	Material-No.	Young's modulus (N/mm^2)	Approx. values temperature coeff. of Young's modulus $\Delta E/\Delta\vartheta$ ($10^{-5}/K$)	Thermal expansion coefficient α ($10^{-6}/K$)	Misc.
Spring steel	51CrV4	1.2241	210000	–26	11	rusting
Spring steel	X5CrNi CuNb1744	1.4548	207000	–19	11	stainless
Copper-beryllium	CuBe2	2.1247	130000	–35	17	—
Aluminium	AlCuMg2	3.1355	73000	–58	23	—-

3.1.3 Determination of the SG installation position

This aspect is closely related to the geometry of the elastic element as discussed in the preceding section, and with the choice of SG dealt with later. Inter-relationships necessitate taking both of these points into consideration at a very early stage.

3.1.3.1 Strain gages

To achieve the maximum possible sensitivity, the SG's should be installed at the position where the maximum strain occurs. To fully utilize the advantages of the Wheatstone bridge circuit, such as signal gain and compensation capability there should be four active strain gages, two being in tension and two in compression. [2]

The installation positions most suitable for the commonly used elastic elements in the previous examples (see Fig. 3.1) are marked in the illustrations and mentioned in the text.

3.1.3.2 Balancing and compensation elements

As will be mentioned later, balancing and compensation elements can be installed to the measuring body in the same way as SG's.

The choice of position for these elements generally depends upon resolving two conflicting requirements: On the one hand, the elements should be installed in zones where strain is at a minimum, so that their electrical resistance does not change in response to load. This means that they must be installed at great distance from the area of maximum strain and consequently also from the SG's. On the other hand, the elements, whose resistance changes in accordance with temperature, should be close to the SG or be directly on the elastic element in order to "experience" temperatures which are as fast as possible the same as those of the SG. In case of doubt, priority must be given to the temperature requirements, since these elements have only a very low strain sensitivity.

In addition to the above-mentioned points, care should be taken in respect of the strain gages and these elements to ensure that the selected installation points result in a symmetrical circuit with wiring links which are as short as possible and of equal length. The actual installation surfaces must comply with the general requirements for installing foil-type SG's (see Bibliography item [4]). These call for the surfaces to be smooth and to take into account the minimum permitted radius of curvature of the strain gages.

3.1.3.3 Practical considerations concerning determination of the installation position

The diagram in Fig. 3.18 shows the strain distribution over the length of the example elastic element, with indication of magnitude and sense of strain. From this it can be seen that two SG's must be installed to the top and bottom of the elastic element each as close as possible to the clamping point.

In view of the very simple geometry of the elastic element, there are naturally hardly any alternative positions for the SG's. The theoretical requirement to place the SG as close as possible to the clamping point is hindered by the fact that interference effects can be induced from the clamp, so that immediately adjacent to the clamping point, there will be a non-uniform strain field.

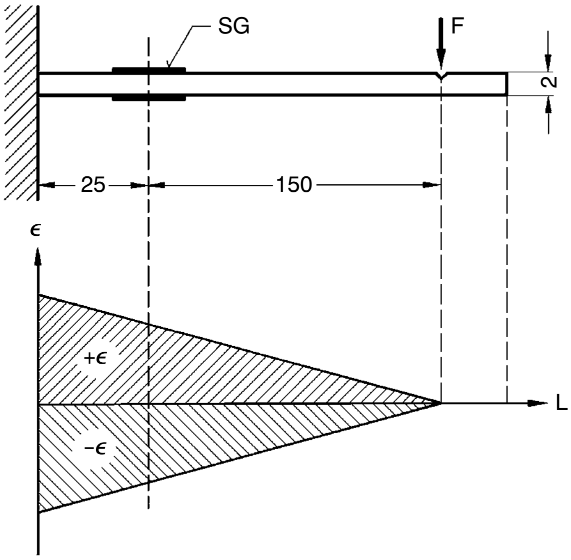


Fig. 3.18: Strain distribution and SG installation position—a practical example

In addition, the element for temperature compensation of the zero point must be close to the SG for the reasons already discussed. To take account of these problems yet still permit a simple circuit and practical routing of the measurement leads, the SG installation position is moved away from the clamping point. This necessitates positioning the remaining elements as shown in Fig. 3.19.

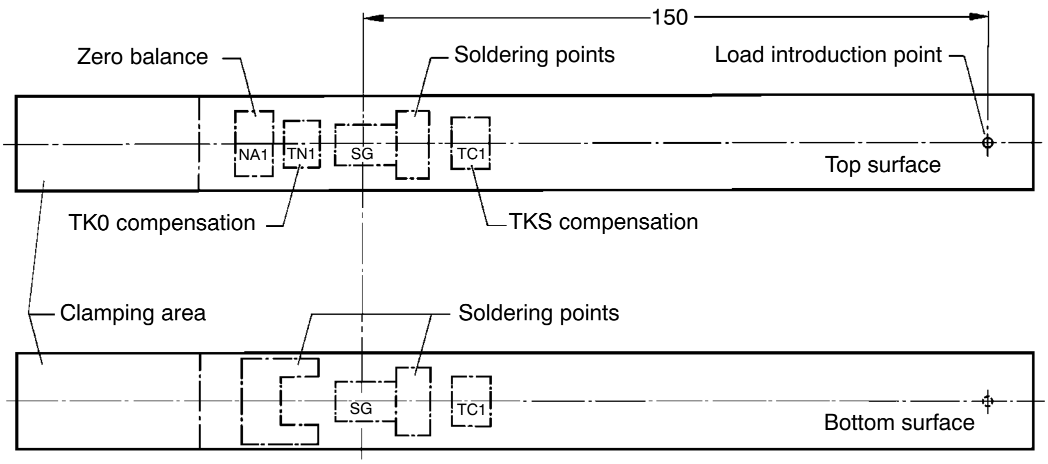


Fig. 3.19: Determination of the installation positions

The resulting effective lever arm of 150 mm and consequent mechanical strain level of approx. 600 µm/m at a nominal load of 1 kg are adequate for demonstration purposes. The recommended strain of 1000 µm/m occurs with this elastic element at a nominal load of approx. 2 kg, and is not achieved here because the effective shortening of the lever arm due to flexing would be relatively large.

q

3.2 The choice of strain gages

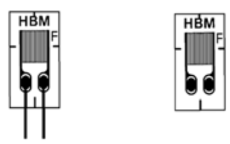
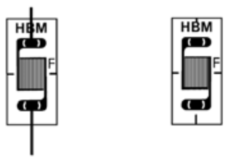
The “K” series forms a good basis for the choice of strain gage. These strain gages are tailored to the specific requirements of transducer construction.

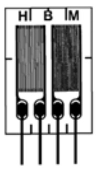
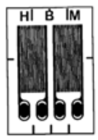
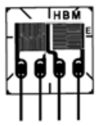
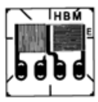
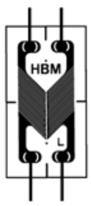
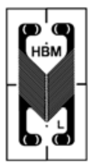
3.2.1 Geometry

The choice of SG geometry must take into account the measurement task and the form of the elastic element. In this case the term “geometry” is intended to apply to the actual geometry of the measuring grids, and to their number and relative positions.

The “K” series SG’s offer a suitable solution for present-day transducer designs. Tab. 3.2 summarizes the available basic types. The type most suitable for each measurement task can be selected, dependent upon the particular details of the installation.

Tab. 3.2: Basic “K” series SG’s and their suitability for different forms of transducer. Information and technical data is provided in HBM brochure “strain Gages and Accessories”.

Basic form/Type	Designation	Application
	Linear-SG	To detect strains in one direction. When single SG individually aligned in direction of principal strain basically usable for all transducer designs. Preferably where use of single SG’s is unavoidable, e.g., on narrow webs.
	Linear-SG	as above In special cases, different connection geometry to the basic form facilitates the shortest possible and symmetrical wiring within the bridge.

Basic form/Type	Designation	Application
 	Double-SG with parallel measuring grids	Specially suitable for simple bending beams to measure strains on the top and bottom surfaces with positive and negative strains respectively. Less expensive, since the half-bridge can be installed in a single working step.
 	SG-rosette T-form measuring grids at 90° to each other	Specially suitable for tensile and coin pression rods. The mutually perpendicular grids measure longitudinal strain(positive signal) and transverse strain (negative signal). Less expensive, since the half-bridge can be installed in a single working step.
 	SG-rosette V-form “Firtree”, measuring grids are each at 45° to axis of symmetry	Special for torsion shafts and shear beams. The measuring grids are aligned with the direction for principal strain. Less expensive, since the half-bridge can be installed in a single working step.
 	Diaphragm rosette	Specially designed for diaphragm-type pressure transducers. Less expensive, since the full bridge can be installed in a single working step.

3.2.2 Connection configuration

All basic types are available with two different connection configurations, namely.

1. Integral ribbon connections with covered measuring grid
2. Integral solder pads with open faced measuring grid

In general, the preferred type is the SG with integral ribbon connections. This version eliminates soldering on the SG itself, which in spite of the solder flow-stop “islands” is not without its risks (see Section 3.4.2.1). The cover makes the SG mechanically more stable and thus less sensitive to handling; moreover, the grid is protected against contamination and damage. Less extensive additional protection measures are required depending upon the operating circumstances. A further argument for the covered SG is its more reproducible creep behavior. This property, described in Section 3.2.6, is also influenced by the SG covering. Important here is the perfect “bedding” of the measuring grid. The glass-fiber reinforced cover applied at the factory naturally offers a more integral and consistent bond than any layer subsequently applied to an open faced measuring grid.

However, the versions with integral solder pads find their application where space limitations prohibit the use of separate soldering points. In this case the wiring can be connected directly onto the integrated solder pads.

3.2.3 Measuring grid length

All SG’s, with the exception of the diaphragm rosettes, are available with measuring grid lengths of 3 and 6 mm. These grid lengths have established themselves in transducer engineering.

The decision in favor of one or other of the two lengths depends upon the size of the elastic element and the strain path. When the installation surface permits and a sufficiently large uniform strain field is available, preference must be given to the 6 mm version. In such a case the strain is integrated over a large area and the effects of small, localized variations, e.g., inclusion of dirt particles during installation are reduced. If the transducer is to be operated with input voltages greater than >10 V, preference should again be given to the larger grid, since the heat generated can be dissipated over a larger surface area. The 3 mm version should be used where strictly limited strain fields and small installation surfaces occur. The basic rule is to have the grid as long as possible, but only as small as necessary.

Diaphragm-type rosettes are available in three different diameters. In this case the numerical data (in the type designation) refers to the outside diameter of the full bridge measuring grid. The choice depends upon the diameter of the pressure transducer diaphragm.

3.2.4 SG resistance

The strain gages in the “K” series have a nominal resistance of 350 Ω. This value has proven to be a good compromise when constructing transducers. On the one hand random effects of electrical interference signals should be kept as small as possible, a fact which calls for a low grid resistance. On the other hand is the need to aim at a higher resistance to minimize the energy absorbed in the SG, and thus to also minimize the self heating. In addition, the effects of contact and cable resistances are reduced.

To cope with circumstances in which the need for minimal energy consumption is the first priority, e.g., in battery-powered measuring chains, one can obtain special SG's with a higher nominal resistance. Alternatively, several SG's can be wired in series in one arm of the bridge.

3.2.5 Temperature compensation

Special measures taken during the production of the SG provide for subsequent automatic compensation of unrestricted thermal expansion in the elastic element material ("apparent strain") within a specified temperature range. Strain gages with this property are called self-temperature compensating SG's. The K series SG's are available with compensation to suit the most frequently used elastic element materials, these being steel with a thermal expansion coefficient $\alpha = 10.8 \cdot 10^{-6}/\mathrm{K}$ and aluminium with $\alpha = 23 \cdot 10^{-6}/\mathrm{K}$.

For other elastic element materials one would select a SG with the temperature compensation closest to the thermal expansion coefficient of the material concerned. Special SG's with other levels of temperature compensation can be produced for such cases.

Since aluminum is not generally used in diaphragm-type pressure transducers, temperature compensation of the diaphragm rosette is normally confined to steel.

3.2.6 Creep compensation

All spring materials exhibit the phenomena of creep to a greater or lesser extent. Following a sudden change in load the material will slowly continue to exhibit strain (positive or negative) for a period of time.

As the choice of material is strictly limited, other measures must be taken to compensate for this effect, or to minimize the error which it generates. Manipulation of the geometry of the SG grid is one method. Modern foil SG's provide the possibility to set the creep behavior of the SG such that it can be used to compensate for the creep effect in loaded elastic elements, and so to obtain greater accuracy. The view long expressed in many publications that creep in the SG is a significant disadvantage is thus not true!

Consequently K series SG's have an additional special feature over the normal SG: All types, with the exception of the diaphragm rosette, are available on request with different creep compensation. Since knowledge of the creep effect in the elastic elements forms the basis for the choice of creep compensation, we must examine this subject in more depth.

3.2.6.1 The creep effect in loaded spring materials

As a basic rule, the elastic elements of transducers must only be stressed in the area of high elastic deformation. Returning to the example in Fig. 2.1, if a rod is subjected to a tensile load in its elastic deformation area, it will exhibit spontaneous strain by an amount defined by Hooke's Law. When the material relaxes, this spontaneous strain will be followed by an additional strain which is time-related and asymptotic. When the load is removed from the rod it will spring back by the amount of the spontaneous strain under load. What remains is a small residual strain equal to the time related additional strain, which itself gradually reduces until the rod reverts to the original state. This is known as the "elastic creep" as opposed to irreversible material creep. Fig. 3.20 illustrates this elastic creep effect.

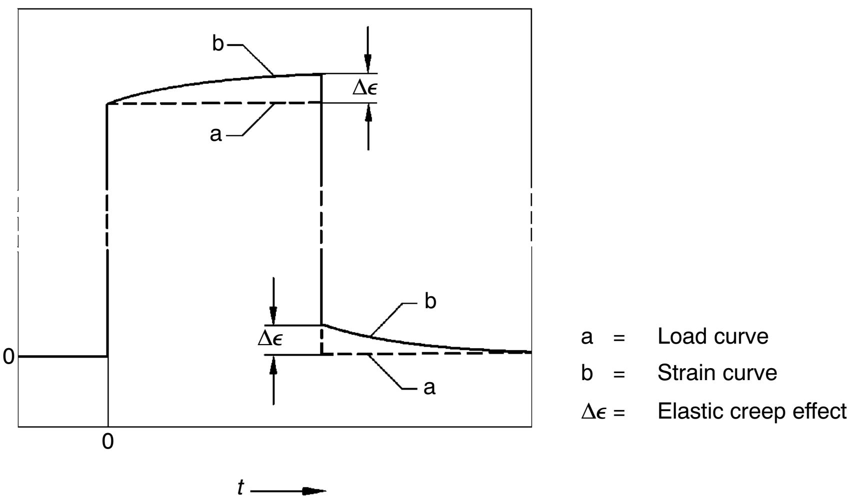


Fig. 3.20: Curve of strain of a component under constant load and after being completely unloaded

The spontaneous strain of a material is a measure of load both in the case of stress analysis and when measuring other physical variables involving force effects (force, weight, bending moment, torque, pressure and the like). The elastic creep generates a time related positive error (in the direction of deformation by the measured variable).

3.2.6.2 Creep in strain gages

If a SG is subjected to static strain then, in spite of the constant strain on the component, it will exhibit a time related change in its resistance. This change in the measurement signal in a SG under tension (or compression) happens very slowly ("creeping") and in the direction of "relief". The cause can be found in the purely rheological behavior of the strain transmitting layers of the adhesive and the carrier material. The elongated measuring grid acts in a manner which is similar to a tensioned spring. The spring tension generates shear stresses on the contact surfaces between the grid and the carrier, primarily around the grid end loops. These shear stresses are in addition to the direct stresses resulting from the strain. Under the influence of these stresses, the plastics in the SG and adhesive both relax, i.e., the counterforce weakens and the grid pulls itself back. A negative error occurs. This process is illustrated in Fig. 3.21.

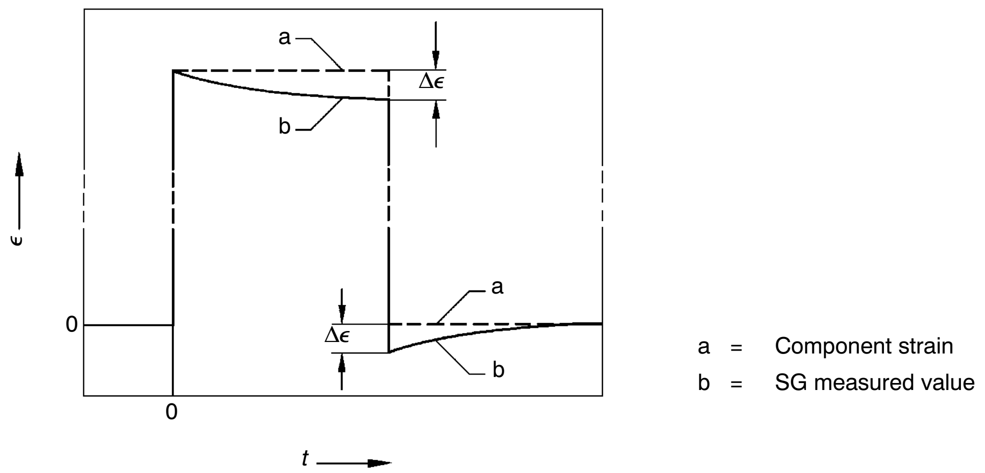


Fig. 3.21: Measured value of a SG after spontaneous loading of a component and after spontaneous removal of load (schematic)

As this process also occurs in the region of the grid ends, its effect is greater on short measuring grids than on long ones.

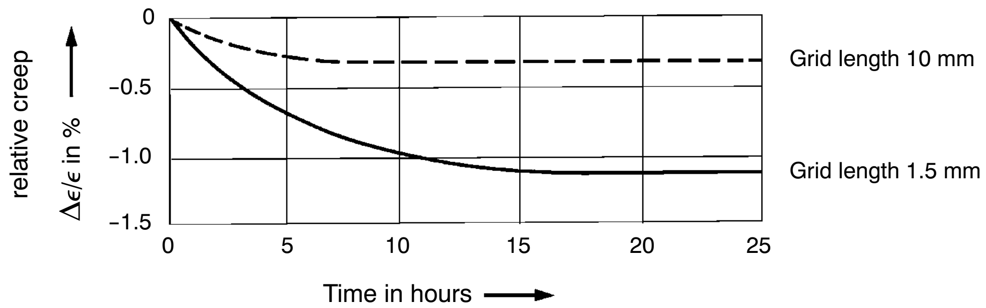


Fig. 3.22: Example of creep curves for two different length foil SG's

In comparison with the previously used types, foil strain gages have the advantage that the extended end loops are distributed over a larger area, thereby minimizing the shear stresses.

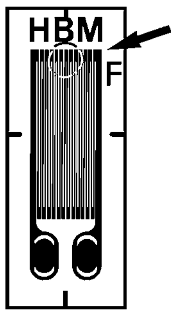


Fig. 3.23: Grid pattern of a foil SG, see Fig. 3.24 for detail

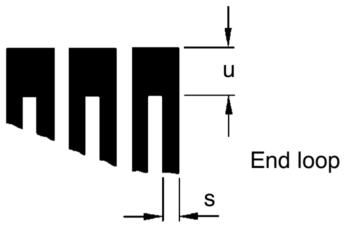


Fig. 3.24: Definition of end loops of a foil strain gage (detail from Fig. 3.23)

By appropriately modifying these end loops it is possible to influence the creep. This is achieved by making the end loops of different lengths. They are defined by quoting length “u” as a multiple of track width “s”.

When speaking of creep in the SG it must not be forgotten that, in addition to the actual SG properties, there are other important factors. The principal ones are criteria such as the nature and layer thickness of the adhesive, and the time or temperature effects. All effects taken together cause the creep, which is always a time-related reduction in the measurement signal, i.e., a time-related negative error, the greater or lesser magnitude of which depends upon the length of the end loops.

3.2.6.3 The compensation effect

It is shown how creep in the SG generates a negative error, whereas the creep in the elastic element material leads to a positive error. In the ideal case, the SG creep and the element creep compensate each other, as shown in Fig. 3.25.

Since it is not possible to influence the properties of the elastic element material, it is necessary to select the most suitable SG to approximate as closely as possible to the ideal case.

As a fundamental rule, shorter end loops cause negative creep in the transducer, whereas longer end loops cause positive creep.

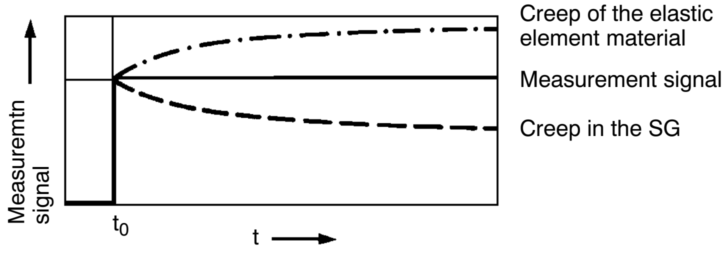


Fig. 3.25: Idealized diagram of creep compensation

3.2.6.4 The choice of creep compensation

All K series SG's, with the exception of the diaphragm rosettes, are offered with three different levels of creep compensation or end loop ratios. The end loop ratio concerned (definition, see Fig. 3.24) can be recognized from an identification letter on each SG. The series of end loop ratios commences with the letter A. This corresponds to an end loop length u = 1 s. Theoretically the series continues in alphabetical order in increments of 0.5 s. In actual practice it has made sense to limit it to round number ratios. Shown below is the legend to all standard end loop ratios:

A:	u = 1 s	M:	u = 7 s
C:	u = 2 s	O:	u = 8 s
E:	u = 3 s	Q:	u = 9 s
G:	u = 4 s	S:	u = 10 s
I:	u = 5 s	U:	u = 11 s
K:	u = 6 s	W:	u = 12 s

The strain gage brochure provides information on the allocation of the individual types of SG.

In addition to a mean, quasi neutral version, it is possible to choose between two other versions such as Example 1 shows.

Example 1 If there is no prior knowledge of the expected creep behavior of the transducer, it is recommended to first try the mid-range creep version. The magnitude and direction of the creep found during the subsequent measurement have an important bearing on the choice of another creep version, or in deciding to retain the originally tried type of SG. As already mentioned, the choice of a SG with shorter end loops influences the creep behavior of the transducer in the negative direction, and vice versa. After deciding upon another SG a new set of measurements must be made to check the effectiveness of the choice. This makes it clear that optimum creep

Available versions	End loop ratio	Transducer creep	SG creep
E	u = 3 s	more negative	more strongly negative
G	u = 4 s	smallest creep*	negative (quasi neutral)*
I	u = 5 s	more positive	less negative

* The data relates to the least creep (creep error measured in accordance with specification VDI/VDE 2637, 30 min) on a standardized transducer with uniform, constant strain field. Deviations in the creep behavior are possible with other forms of transducer. The difference in creep behavior between two adjacent creep versions (identification letters) is about 0.03 … 0.04 % of the measured sensitivity.

compensation can only be determined by empirical, experimental means. Because of the large number of sometimes imponderable influencing variables it is simply not possible to provide an all-embracing “recipe”.

With reference to the creep error it should be noted that, in many cases the creep behavior of the elastic element material varies from batch to batch. Thus, in extreme cases, new creep compensation may be necessary for each new material batch.

Each measurement of the creep error should be preceded by checking the zero signal stability in the unloaded state. Not until the zero signal is sufficiently stable is it possible to carry out the measurement under constant load conditions. It must also be ensured that the SG’s are installed under conditions identical to those which will later apply in the final version of the transducer. That is to say, the installation conditions (curing time, installation pressure, etc.), and the adhesive used must be the same as those for the production version.

The creep versions available as standard are designed such that the creep errors generally encountered in actual practice are largely compensated. Over and above this, for special measuring tasks or to meet particular accuracy requirements, special SG’s with individually designed end loops can be obtained subject to a minimum order quantity.

3.2.7 Carrier dimensions

The dimensions of the grid carrier are generally not a primary selection criterion, since they are in directly dependent on the previously specified grid length and grid configuration (see Sections 3.2.1 and 3.2.3). The only time that priority in SG selection is likely to be given to carrier dimensions over grid length is where the available space is very limited. If necessary, the carrier can be cut to match the actual requirements (subject to the observation of certain rules).

Parallel to the longitudinal axis of the grid the carrier can be cut to within a minimum distance 0.5 mm from the grid itself. A considerably greater carrier overhang is required on the ends, which are of more significance in introducing the strain. Here a minimum dimension of 1 mm at each end has proven practicable. No adverse effects on the SG properties need be feared if these dimensions are observed. Beyond this however, possible effects should be determined by conducting comparative tests with an untrimmed SG. Within the given limits special SG's with non standard carrier dimensions could also be considered.

3.2.8 Practical considerations concerning the choice of SG

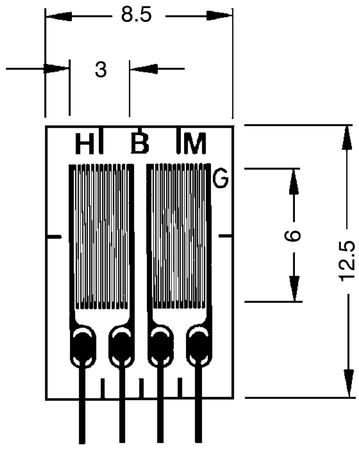
The previously mentioned example transducer is a simple bending beam. To measure the strain levels occurring on the top and bottom faces with opposite signs using a full bridge, it is necessary to install two SG's to each of these faces. In principle, all linear SG's are suitable. In this particular case it is possible to use double SG's. With these strain gages it is possible to apply a half-bridge in a single installation step. This considerably reduces the amount of work involved.

For the reasons given in Section 3.2.2, use should be made of covered SG's with integral ribbon connections. The dimensions of the elastic element as well as the strain curve shown in Fig. 3.18 permit the use of a SG with a grid length of 6 mm.

The elastic element material is a spring steel strip with a thermal expansion coefficient of $\alpha = 10.8 \cdot 10^{-6}/\mathrm{K}$. In order to utilize the self-temperature compensation effect of the foil strain gage, one with a suitable temperature compensation is chosen.

The transducer under discussion does not demand any special consideration of creep behavior. For this reason an average creep version of the appropriate strain gage type is chosen.

Since our example offers a sufficiently large installation surface, there is no need to trim the SG carrier. Taking into account all selection criteria finally leads to the choice of the type DK 11G 6/350, as shown in Fig. 3.26.



- Double SG with covered grid and integral ribbon connections
- Temperature compensated for steel ($\alpha = 10{,}8 \cdot 10^{-6}$ / K)
- Mid range creep compensation G: u = 4 s
- Grid length: 6 mm
- Grid resistance: 350 Ω

Fig. 3.26: The type DK11G 6/350 SG used for the practical example (enlarged drawing)

3.3 The SG installation process

In order to detect the mechanical strain and at the same time to “experience” the temperatures, the strain gages and the balancing and compensation elements must be bonded to the elastic element. Detailed information on this process of cementing—called installation—as well as the necessary preparations are contained in the instructions for use of the adhesive concerned, and in item [4] of the Bibliography. Nevertheless, at this stage it is worth mentioning a number of points to be observed.

A basic prerequisite for installation of the SG and all other elements is optimum preparation of the installation surfaces. Vital steps in this preparation are cleaning and roughening of the surface. To ensure that the SG is installed accurately, the elastic element must be provided with alignment marks. It is recommended to prepare a detailed installation plan before starting the work. This plan must show the positions of all elements and the corresponding alignment marks. The choice and determination of the installation points was already discussed in Section 3.1.3.

In the case of hot curing cements, the requirement for a clamping device with the same curvature as the elastic element must not be overlooked.

3.3.1 SG installation of the strain gages

K series SG’s can be installed with any adhesives which are suitable for use with foil strain gages. In transducer engineering special hot-curing adhesives are generally used, since they have been well proven particularly for the longterm use which is made of transducers.

The exposed grid in open faced SG’s should be covered by a thin layer of the same adhesive which is used to install them. Depending on the instructions for use of the adhesive concerned, this can be done together with the installation or else afterwards in an additional working and curing step. This “adhesive cover”, and thus the close bond, improves repeatability of the creep behavior (see Section 3.2.2), while at the same time the delicate measuring grid gets a first protective coat. Naturally, the integral solder pads must be excluded from this protection by covering them with adhesive tape. The covering layers additionally needed to protect the installation can be applied later to the layer of adhesive (see Section 3.6).

For SG’s with integral ribbon connections it is recommended to use separate soldering points. Where possible, these should be installed together with the SG. When mounted together (see Bibliography item [4]) the soldering points should be slid between the carrier foil and the connection ribbons. This can be assisted by lightly lifting the connection ribbons, which is best done by individually and carefully pulling the ribbons upwards (without kinking them) . At the same time the carrier must be pushed down onto a flat surface with a pair of blunt-nosed tweezers placed either side (to the left and right) of each connection ribbon.

To minimize the additional work resulting form faulty installation it is best to check the quality of the installation at the earliest possible stage. Simple but effective visual examinations, such as described in detail in item [4] of the Bibliography, the “eraser test”, as well as measurement of continuity and insulation resistance avoid the risk of delaying recognition of a faulty installation until after the transducer is “complete”.

3.3.2 SG installation of the balancing and compensation elements

Here it is intended to consider only those points which are important to the installation operation. A detailed description of the elements is given in Section 3.5. The installation operation is no different to that of the SG. Here too it is fundamentally possible to use all adhesives which are suitable for foil SG’s, including hot curing ones. However, the same extremely high requirements made on the quality of the bond of the SG are not necessary, since in this case the mechanical strain should, if possible, not be transmitted to the resistor network. For the same reason no great demands are made in respect of the positioning accuracy.

When making the installation care should be taken to avoid allowing adhesive to contaminate the connection surfaces or the exposed resistor networks. Particularly with adhesives containing a filler a covering layer can result, which makes it difficult to recognize the markings and printed circuit paths. This will adversely affect the subsequent balancing and compensation work.

3.3.3 SG installation of the soldering points

The soldering points are similarly installed using the same method as for the strain gages; for practical reasons it is also done at the same time, as already described above. All adhesives offered for installing foil SG's can be used. In order to avoid overstressing the relatively small adhesion surfaces, the soldering terminals should be installed in low strain areas if possible; strain relief measures should also be taken for the incoming leads. Here too no adhesive should be allowed on any surfaces still to be soldered, since this would detract from the ease of soldering.

3.3.4 Practical considerations concerning installation

Z70 cyano-acrylate based rapid adhesive is used on the example elastic element. The SG as well as the balancing and compensation-elements and soldering points are also installed with this adhesive. In this case there is no need for hot curing, as there are no special requirements concerning long-term stability or durability when exposed to high temperatures.

The installation areas are prepared in the same way as for installing foil SG's. Sand-blasting can be used to roughen the installation surfaces, although one must ensure that the blasting medium does not contain impurities from previous tasks. There is a risk that such impurities could be transferred to the surface of the elastic element, from which there is little chance of removing them.

When applying the markings for visual alignment as shown in Fig. 3.37, take care not to cause any damage to the surface of the material by scribing. If this happens, the resulting notch effect could lead to damage, or even fracture of the elastic element, especially if the transducer is subjected to dynamic loading.

Fig. 3.27: The elastic element prepared for installation. The roughened installation surface and the alignment markings can be clearly recognized.

When handling open faced versions of the strain gage (i.e., with exposed measuring grids) take care not to touch the region of the delicate measuring grid with the tweezers.

Fig. 3.28 and Fig. 3.29 show the top and bottom face of the elastic element with the already installed strain gages and other elements. The actual installation operation should commence with the strain gages and the associated soldering points, since the quality demanded for the adhesive bond calls for an absolutely clean installation surface. This requirement is easiest to fulfill at the beginning of work on the freshly prepared elastic element. Regardless of the adhesive used, before making the installation, one should fix masks around the SG's and the individual elements. This is to prevent exuding surplus adhesive from contaminating surfaces which are to be used later for installing other elements.

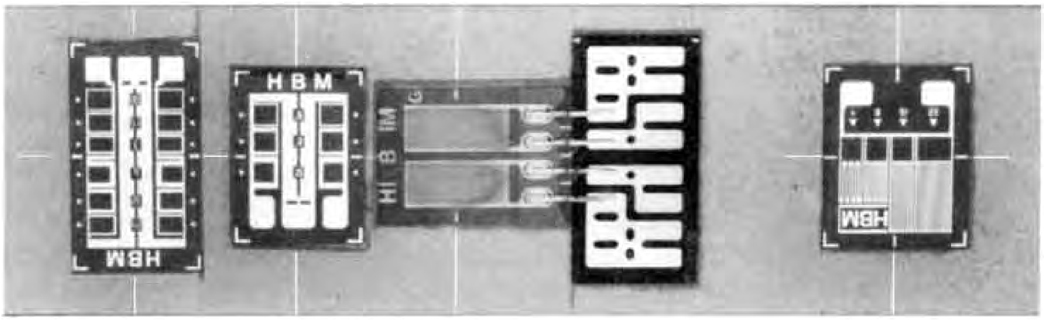


Fig. 3.28: The top face of the completed elastic element (for details of the balancing and compensation elements see Section 3.5.1).

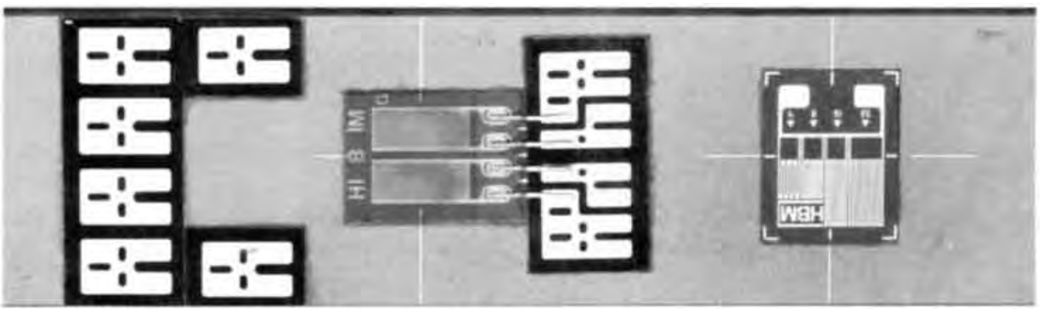


Fig. 3.29: The bottom face of the completed elastic element

3.4 The circuit arrangement

If higher accuracy than 1 to 2 % measurement uncertainty (at room temperature) is demanded of a transducer, it will be absolutely necessary to connect the strain gages in the form of a Wheatstone bridge. This circuit arrangement not only achieves a high degree of sensitivity; in conjunction with the use of self temperature compensating SG's, it very effectively compensates (amongst other things) thermal expansion of the elastic element. Detailed information concerning the effect and possible arrangements of the Wheatstone bridge is given in Bibliography item [2]. Note, however, that the circuit is not able to compensate for asymmetry of resistance such as can occur through resistance of wiring in the individual arms of the bridge. Consequently, in spite of the balancing and compensation measures to be taken later (see Section 3.5), attention should be paid to achieving a symmetrical layout and thus equal length for the connection leads within the bridge. Preparing a detailed wiring plan will prove to be helpful in this respect. These aspects should be considered at an early stage, since the necessary circuit arrangements often have to be taken into account at the design stage of the elastic element.

When diaphragm rosettes are used this problem with the internal wiring of the bridge does not arise because there is already an almost complete full bridge circuit. Fig. 3.30 shows how the connections are allocated.

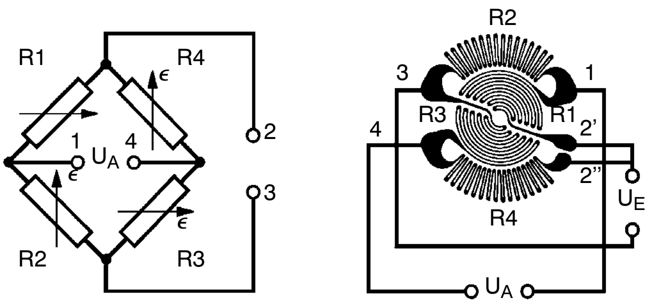


Fig. 3.30: Circuit arrangement of a diaphragm rosette. Connections 2′ and 2″ are normally interlinked. As described later, a temperature-sensitive resistor can be connected at this point to compensate for a temperature coefficient of zero point.

The choice of the appropriate wiring materials depends in the first instance on the design of the transducer and the conditions of use. When applying the wiring and soldering points care must be taken to prevent the input leads from applying a stress to the soldered connections. For the same reason strain relief measures must be taken at appropriate points. The individual connections or lead wires should be secured to prevent any relative motion with the transducer body or any oscillations. Stranded lead wires should be employed in certain cases where the use of unsupported connections is unavoidable. This applies particularly where the transducer is exposed to severe dynamic stresses.

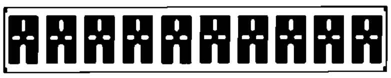
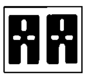
3.4.1 Wiring materials

The wiring materials listed here are included in the range of SG accessories in view of their particular suitability for the requirements of transducer engineering. Further tried and tested soldering points, cables and lead wires are listed in the HBM publication “Strain Gages and Accessories”.

3.4.1.1 Soldering points

Soldering points are important items for connecting the SG and the balancing and compensating elements to the Wheatstone bridge. This applies in particular to the use of SG’s with integral ribbon connections. In such cases soldering points should be installed together with the SG, so as to prevent short-circuits through possible contact between the connection ribbons and the electrically conductive elastic element. A further purpose of the soldering points is to act as the transition between the internal wiring of the transducer and the transducer connection leads. Depending upon the design of the transducer body and the positions of the individual elements, it may be advisable to apply additional soldering points. Tab. 3.3 shows the range of soldering points specially designed for transducers.

Tab. 3.3: Transducer-specific solder terminals; specifications see HBM brochure “Strain Gages and Accessories”

LS212		LS224
	Packaged form	
	Pair	
	Individual soldering points	

The spacing of the soldering points is matched to the connection spacing pattern of the SG. An advantageous feature here is that all connection surfaces branch out from one into two connection points. This special arrangement allows several connections (e.g., in a six-lead circuit) to be made without individual wires becoming loose when their neighboring wires are soldered. The decision in favor of one of the two types depends upon the prevailing circumstances. Fig. 3.31 shows examples of possible combinations.

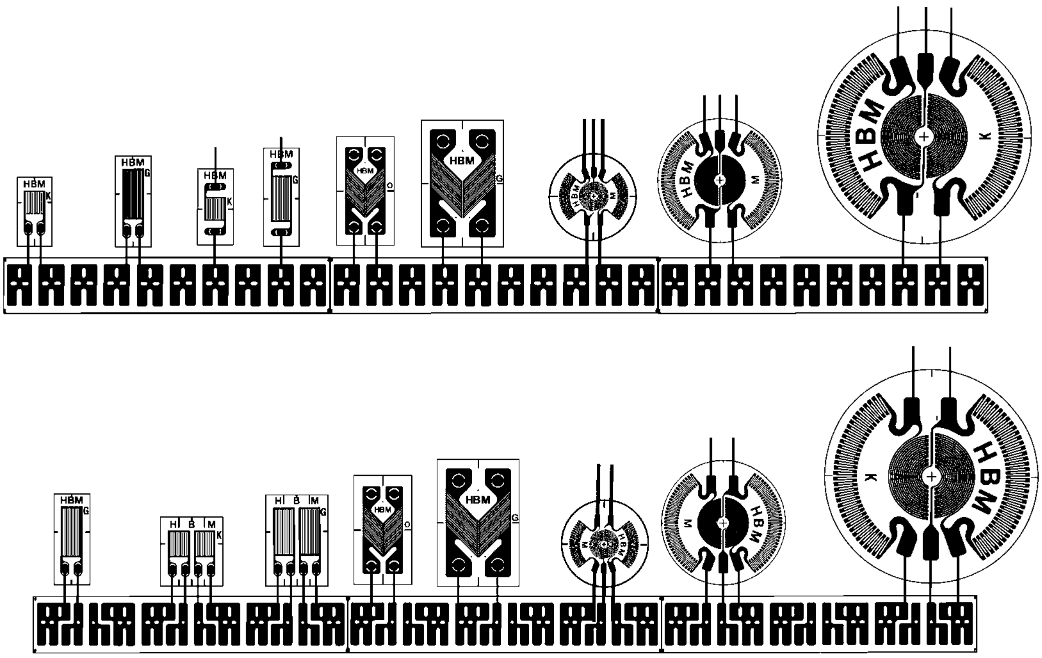


Fig. 3.31: Examples of combinations of soldering points LS 212 and LS 224 with K series SG's

3.4.1.2 Cables and lead wires

The HBM Program incorporates a series of cables and lead (i.e., stranded hook-up) wires suitable for SG's. Those described in Tab. 3.4 are particularly suitable for wiring of transducers.

Tab. 3.4: Material for internal wiring of transducers; additional cables, lead wires and connection cables for associated electronics equipment are contained in HBM publication "Strain Gages with Accessories".

	Enameled copper wire	**Stranded leads**
Type	Enamel insulated copper wire	PVC-insulated stranded copper wire
Conductor cross section/overall diameter	0.03 mm^2/0.2 mm^2	0.04 mm^2/0.6 mm^2 20 strands
	Matched to maximum permissible cross-section of 0.1 mm^2 when using SG with integrated connection surfaces	
Conductor resistance	0.549 Ω/m	0.417 Ω/m
Maximum permissible temperature (continuous)	130 °C	70 °C
Other features	2-layer insulation can be burnt off by the soldering iron at 350 °C. Eliminates time-consuming wire stripping; coloured insulation for better damage detection; clean and easy installation due to high ductility	Very high flexibility
Application	Internal wiring of transducers for static and dynamic use, when conductor can be bonded onto the elastic element	Internal wiring of transducers when constructional considerations necessitate exposed (unsupported) connections
	See also Sections 3.4 and 3.4.2	

3.4.2 Practical considerations concerning wiring

As already noted in Section 3.4, it is wise to make up a wiring diagram. Fig. 3.32 shows the wiring diagram for our example transducer. In addition to the position and number of elements, it should show the routing of the individual connection leads.

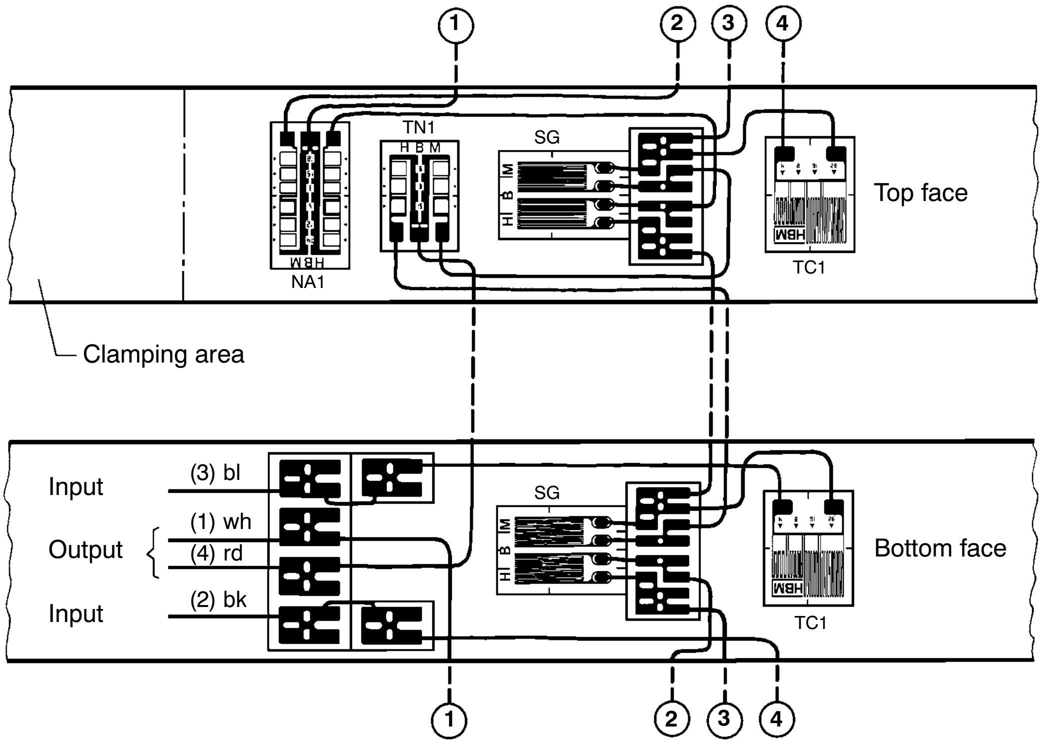


Fig. 3.32: Wiring diagram for the example transducer

Soldering points LS 212 and LS 224 are used. Type LS 224 is matched to the spacing pattern of the double SG and, together with its integral ribbon connections, simplifies the soldering procedure by eliminating direct soldering on the SG. Type LS 212 is used to link the transducer connection cable to the internal wiring. The geometry of this soldering terminal allows fixed resistors to be incorporated into the feed line to adjust the sensitivity, or parallel connection of a fixed resistor to the transducer input to set a specific input impedance.

The enameled copper wire described in Section 3.4.1.2 is used for the internal wiring of the transducer. The small conductor cross-section and the low stiffness of the copper reduce the inherent risk of influencing the transducer characteristics (force shunt).

This applies in particular to elastic elements designed for small measuring ranges. Due to its high malleability, this material can be adapted even to complicated contours.

The use of stranded lead wires is not necessary in our example transducer, since all connection leads can be fixed to the elastic element. In each case however, consideration must be given to the possible needs for using such lead wires.

The most suitable transducer connection cable is selected from the comprehensive range of HBM special cables which are available according to the particular requirements. The colors of the individual cores in these cables are matched to the widely used HBM color code for connections between transducers and associated electronic units.

The individual connections are made according to the wiring diagram. The connection wires in each arm of a bridge half (R1 and R2; R3 and R4) should be of equal length. In the case of the enameled copper wires the time-consuming job of stripping the insulation from the ends is not necessary as the insulation is “burned off” by the soldering iron when tinning, assuming a soldering temperature of 350 °C. The insulation on the stranded lead wires can be stripped by the usual mechanical means. When doing so take care not to produce any potential failure points by damaging the fine individual strands.

The enameled copper wire should not be routed over any sharp edges without additional protection, since otherwise in spite of the double layer of insulation there is a risk of damage and subsequent short circuiting. If this is not possible, one can use a steel wire with robust Teflon insulation (see HBM publication “Strain Gages and Accessories”).

The working steps described here are followed by soldering work on the SG’s and/or the soldering points. Information on this aspect is provided in Bibliography item [4]. Direct soldering onto the strain gages with integral solder pads calls for maximum care; also applicable are the general rules for soldering on electronic components. The next Section will deal again with this subject in greater detail.

The final wiring work generally concerns fixing the individual leads on the elastic element or on the housing (see Section 3.4). In addition to the possibility of fixing at intervals, the leads with small sheath cross-sections can also be fixed along their full length. Tab. 3.5 tabulates the different materials suitable for securing the wiring.

Tab. 3.5: Suitability of different materials for securing of cables and lead wires on elastic element; (●= well suited; ○= limited suited; — = not suitable)

	APPLICATION			
	Small sheath cross-section Sheath -∅ <0.6 mm e.g., enameled copper wire		Large sheath cross-section Sheath-∅ ≥0.6 mm e.g., Teflon wire	
Securing means	at intervals	full length	at intervals	full length
Textile-reinforced adhesive tape	●	○	●	○
Cold curing rapid adhesive X60	●	—	●	—
Cold curing rapid adhesive Z70	—	●	—	○*)
Transparent silicone rubber SG250	○	—	●	●
Polyurethan varnish PU120	—	●	—	—

*) not with Teflon insulation

The Z70 cold curing rapid adhesive is suitable for the enameled copper wires used in our example. The adhesive must be applied as thinly as possible along the route of the wire. Having done this, take the Teflon protective foil (included with the adhesive) and install it together with the wire under pressure from the thumb so that it cures in a thin layer. It should be noted again here that this adhesive only cures rapidly and reliably in very thin layers. For further information refer to the instructions for use.

This work must be completed before carrying out the following balancing and compensation measures. Fig. 3.33 and Fig. 3.34 show the wired top and bottom face of the elastic element of the transducer in their finished state.

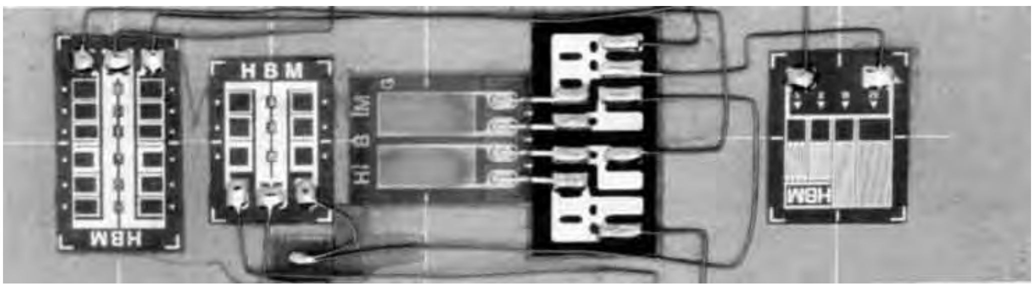


Fig. 3.33: The completely wired top face of the elastic element

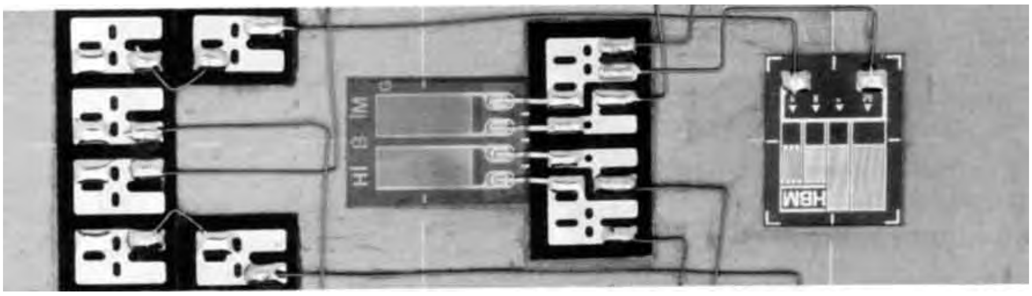


Fig. 3.34: The completely wired bottom face. The enameled copper wire used is secured along its full length with Z70 quick-acting adhesive.

3.4.2.1 Notes on soldering the connections to open faced SG's with integral solder pads

To ensure that the difficult soldered connections are properly made it is recommended to do the job under an illuminated magnifying glass. The soldering iron must have a fine tip, and must be temperature regulated (see HBM accessory range). The soldering temperature must be set to max. 350 °C. For soldering work on SG's it is recommended to use a DIN 1707 standard solder which is non-corrosive as per DIN 8511. HBM offers an appropriate type of solder (Elsold resin-cored soldering wire). Also listed is a soft solder 50 Pb-50 In, but this should not be used here, since the additional flux required can damage the open-faced measuring grid. This naturally also applies to every other corrosive flux. Careful work in the manner described here eliminates the need for any additional flux.

On leaving the factory, the integral solder pads shown in Fig. 3.35 are clean and can take solder. To further simplify soldering work and to assist the operation of the solder islands, it is recommended to locally roughen the solder pads. This can be done with a glass-fiber brush or the corner of a small abrasive cleaning stick (grain ≥320). Do this very carefully! The solder pad should be cleaned afterwards. For this we would recommend using a cotton bud soaked in SG cleaning agent (see HBM accessory range). The solvent saturated tip must be moved in one direction over the solder pad while simultaneously twisting the tip several times. The solder pad should be tinned immediately afterwards by applying a small quantity of solder without putting pressure on the connection surfaces. Fig. 3.36 shows the tinned solder pad. Special care must be taken to ensure that only a small amount of solder is applied, since otherwise the solder islands will be unable to perform their task (see Fig. 3.35).

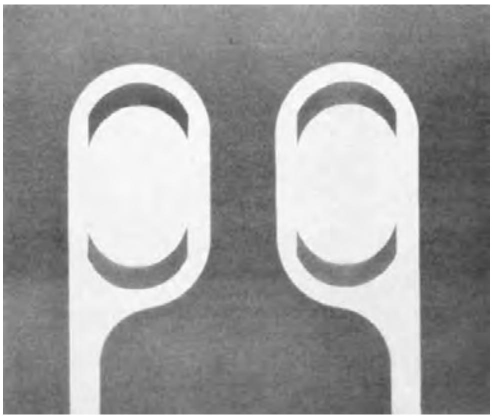


Fig. 3.35: The integral solder parts are designed for a maximum conductor cross-section of 0.1 mm (on diaphragm rosettes up to 0.17 mm). As can be seen in the enlarged diagram, the solder islands limit the soldering point and so also avoid any unwanted stiffening due to tinning. Solder cannot flow towards the measuring grid.

The max. soldering temperature of 350 °C must not be applied to the soldering point for longer than one second. Contact held for longer than this will adversely affect the adhesion between the solder pads and the carrier.

Before soldering on the cables or lead wires their ends must be stripped and tinned (except when using the enameled copper wire mentioned in Section 3.4.2). Soldering stranded lead wires must be done very quickly to prevent the PVC insulation from being "chased away" by the soldering heat. It is important not to tin the full length of the stripped section (see Fig. 3.38).

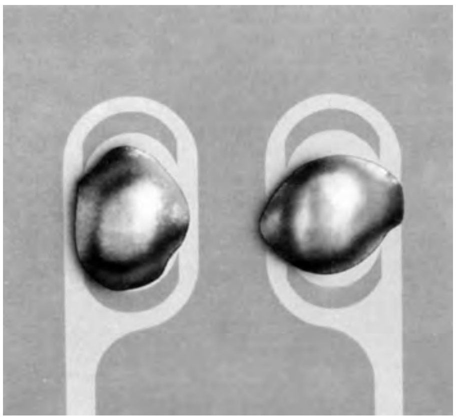


Fig. 3.36: The pre-tinned solder pads of the SG. Limitation of the soldering points by the solder islands can be clearly recognized.

The pre-tinned end of the conductor is now positioned over the soldering surface. Temporary fixing, e.g., with adhesive tape, simplifies the soldering operation and ensures that the solder pads will not be mechanically strained when aligning the connecting wires. After fixing, the wires are soldered on without adding more solder. The one second maximum limit on the soldering temperature naturally applies here too. Fig. 3.37 shows the finished soldering operation. The generally desired recognizable joint contour—that is, the formation of a concave curvature parallel to the conductor—cannot be achieved due to the very small soldering surface. But this does not mean that any concessions can be made in respect of the quality of the soldered joints.

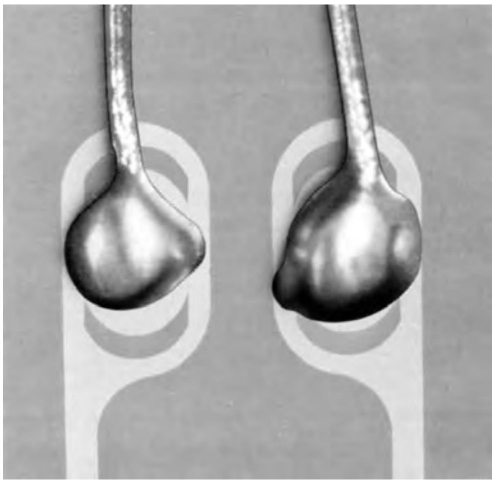


Fig. 3.37: Finished soldered joints between the connecting wires (enameled copper wire) and the integral solder pads of the SG

When using stranded lead wires pay attention to avoiding the formation of potential fracture points when stripping the insulation, tinning and subsequently soldering. These points can occur where the solder ceases to flow along the lead wire, so the aim must be to produce an arrangement as shown in Fig. 3.38.

After making the soldered connections, the solder pads and their surroundings must be thoroughly cleaned to remove all traces of flux. This is necessary to ensure high (≥20 000 MΩ) and consistent insulation resistance. Residual flux in any form (i.e., including colophony from the resin core of the solder) can, in conjunction with moisture, result in lower or variable insulation resistance. The problems associated with insulation resistance are covered in more detail in Section 3.6. A cotton bud soaked in SG cleaning agent is suitable for cleaning the soldering points. One is used to apply the solvent and another, dry cotton bud applied immediately afterwards to soak it up. This procedure must be repeated until no more residual flux can be seen on or around the soldering point.

At this point it is again worth remembering that great care must be exercised when doing this work on open faced SG's. It lies in the nature of the thing that, exposed very fine measuring grid structures are susceptible to mechanical stress and impurities (e.g., through splashes of solder). It is therefore recommendable prior to soldering and subsequent cleaning of the soldered points, to cover the measuring grid with adhesive tape until the final protective covering is applied.

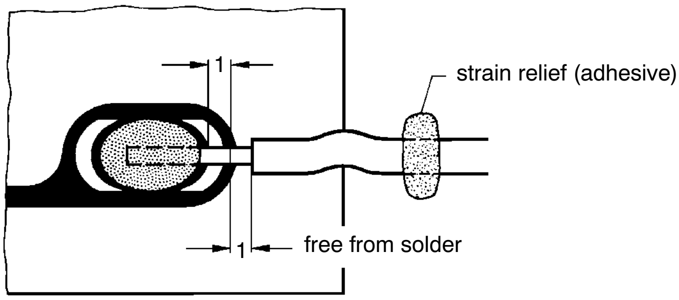


Fig. 3.38: Showing the ideal length relationship on the soldering point when using stranded lead wires

3.5 Balancing and compensation measures

A significant contribution towards achieving the intended technical specification of a transducer is made by the balancing and compensation measures described in detail in the following Sections. These include:

- Compensation of a temperature error in the Wheatstone bridge circuit, as well as temperature compensation of the zero point (TC0).
- Correction of unbalance in the Wheatstone bridge circuit, also bridge or zero point compensation.
- Compensation of temperature dependence of the transducer sensitivity, as well as temperature compensation of the sensitivity itself (TC_C).
- Sensitivity and nominal value balance.

In practice this means the introduction (described later) of fixed and temperature sensitive resistors in the Wheatstone bridge or in the input lines. Fig. 3.39 initially shows the basic circuit diagram of a SG transducer incorporating these resistors.

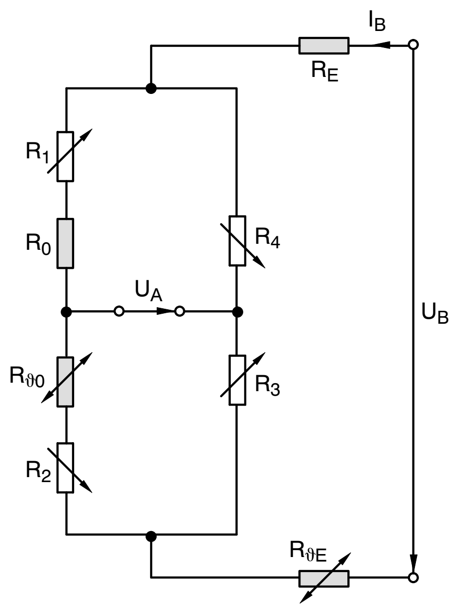


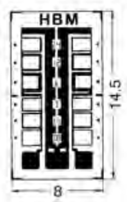
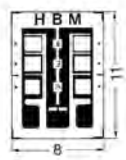
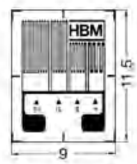
Fig. 3.39: Basic circuit diagram of a strain gage transducer

The individual tasks should be carried out in the sequence laid down here. This ensures that the individual measures supplement each other, and as far as possible avoids adverse interaction between them.

3.5.1 The balancing and compensation elements

These balancing and compensation elements are notable for their practical design. The resistance networks can be applied in a simple manner in the same way as the strain gages (see Section 3.3.2). The following Section covers setting of the necessary resistance values. Tab. 3.6 provides a summary of the available types, their technical specifications and application.

Tab. 3.6: Balancing and compensation elements for constructing balanced and temperature compensated transducer circuits. The number of resistance steps and the maximum adjustable resistance (per half) can be seen from the type designation.

Designation	Adjustable foil resistors		
	for zero point balancing	for temperature compensation of the zero point	for temperature compensation of sensitivity
Type	NA1 6/4, 73	TN1 3/1,05	TC 1 4/60
Design (magnified)			
Resistor material	Constantan alloy	Nickel	Nickel
Temp. coeff. of the resistor (+20 °C … +70 °C)	—	$5.0 \cdot 10^{-3}/°C$	$5.0 \cdot 10^{-3}/°C$
Maximum resistance [Ω]	4.73 (per half)	1.05 (per half)	60
No. of stages	6 (per half)	3 (per half)	4
Individual resistance in steps Resist. tolerance [Ω]	2.4 1.2 0.6 0.3 0.15 0.08 ±20 %	0.6 0.3 0.15 ±20 %	32 16 8 4 ±20 %
Special features	Resistance values can be set by cutting the conducting paths. Binary incrementing of the settable resistance values. Explicit marking of all resistance values on the elements.		
	Symmetrical, double structure with three connections to link onto bridge corner points, so allowing balancing or compensation in positive and negative direction.		

Designation	Adjustable foil resistors		
	for zero point balancing	for temperature compensation of the zero point	for temperature compensation of sensitivity
Achievable	Zero point balancing to approx. 0.0285 mV/V or 57 µm/m (smallest resistance step: 0.08 Ω ≙ 114 µm/m)	TC0 error can be compensated to approx. 0.15 %/10 K relative to 2 mV/V or 4000 µm/m (at smallest resistance step: 0.15 Ω ≙ 11 µm/m/10 K)	TC_C error in steel or aluminum elastic elements can be compensated to approx. 0.03 %/10 K (at smallest resistance step: 4 Ω ≙ 2.3 µm/m/10 K)

3.5.2 Setting the resistance values

The arrangement of the resistance networks allows simple and reliable setting of the necessary resistance values. The procedure is the same for all three elements. The individual resistors are bridged and are introduced into the circuit by mechanically cutting these bridges. The separation is made as shown in Fig. 3.40 at the points indicated by arrows.

Cutting several bridges permits any chosen combination of individual resistors.

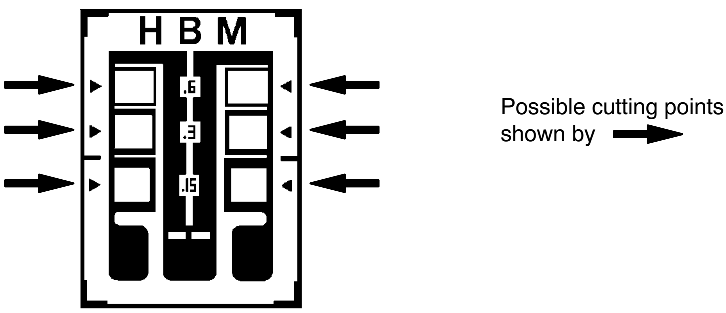


Fig. 3.40: Adjustable foil resistor TN1 3/1.05 for temperature compensation of zero point (enlarged diagram)

There are two different possible methods of cutting the conducting paths. These are described below. All work should be done under an illuminated magnifying glass.

The cutting is best made using a high-precision miniature milling tool (dental cutter, Fig. 3.41).

The cutter drive (hand-held with integral motor) should run at approx. 10 000 rpm. Before commencing work secure the elastic element together with the applied resistance networks to a firm base.

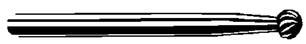


Fig. 3.41: Carbide dental burr (round-head milling cutter) for cutting PC-board conductors. The head should have a diameter of approx. 0.8 mm (shown enlarged)

To cut the conductor the cutter must be moved over the selected area without applying extra force, i.e., purely under its own weight. This procedure must be repeated until the conductor is interrupted over a length of at least 0.5 mm. Working without applying extra force is particularly important, since the object is to remove only the 0.5 µm thick conducting layer. Damage to the 40 µm thick plastic carrier material below must be only very slight. Under no circumstances should one penetrate this insulating layer down to the elastic element as this will introduce the risk of short circuiting.

A scalpel can be used as an alternative to the dental burr. With the scalpel make two parallel perpendicular incisions approx. 0.5 mm apart in the conductor. Here too work with as little pressure as possible. The segment between the two incisions must be completely removed using fine pointed tweezers. Fig. 3.42 and Fig. 3.43 show breaks made with the milling cutter and the scalpel respectively.

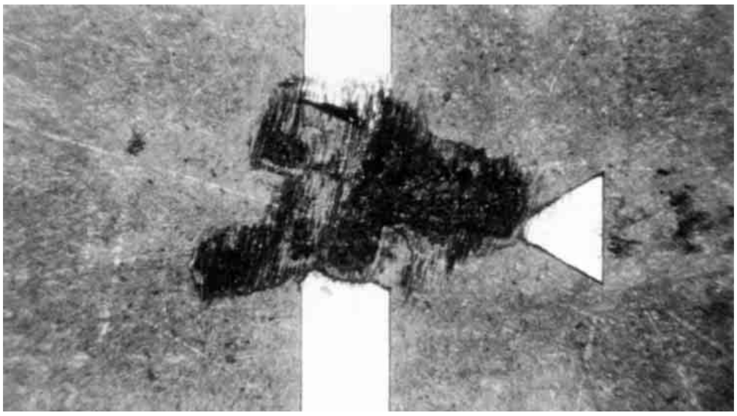


Fig. 3.42: Microscopic photograph of a break made in a conductor by a round-headed carbide milling cutter. The top surface of the plastic carrier layer is merely “scratched” by the cutter.

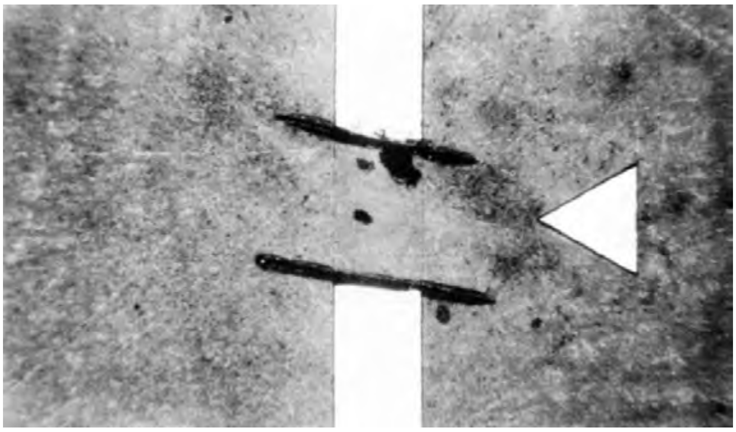


Fig. 3.43: Microscopic photograph of a break made in a conductor by a scalpel. The section of conductor remaining between the two incisions must be completely removed.

When working with the scalpel it is virtually impossible to avoid cutting through the plastic carrier layer even when exercising great care. However, since the damage to the insulating layer is only over the cutting width of the thin scalpel (see Fig. 3.43), there is practically no risk of short circuits. Nevertheless, if one can choose between either of these two methods, preference must be given to the milling cutter because, when used with care, it will not penetrate the insulating layer at any point. While making the break its effects should be monitored on an ohmmeter or directly on the amplifier. This will allow early recognition of any possible faults such as short-circuits or incorrectly set resistance values.

3.5.3 Compensation of a temperature error in the Wheatstone bridge circuit (temperature compensation of the zero point)

This temperature error has a direct effect on the stability of the zero point, hence its designation also as the “temperature coefficient of the zero point” (TC0). To counter this effect it is first necessary to look at its causes.

In contrast to the ideal, symmetrical Wheatstone bridge circuit with theoretically no temperature variation, actual practice shows that the zero signal is dependent to a greater or lesser extent upon temperature.

This temperature dependence is invariably due to unsymmetrical components of temperature sensitive resistances within the bridge. These asymmetries cannot be eliminated even by working very carefully. The reasons for this are:

- Unequal lengths of connection paths within the bridge.
- Within the tolerance range, even in high-quality strain gages, there can differences in the decisive parameter of temperature characteristic, i.e., their temperature behavior is not exactly equal. (To minimize this effect all the SG’s in a full bridge should come from the same pack).

When the specified measuring accuracy demands it, the above mentioned error can be largely compensated. This is done by introducing an additional temperature sensitive resistor in the bridge arm with the smaller temperature error (adjacent to the arm with the larger temperature error), which can be seen from the algebraic prefix of the measured temperature error. The resistor must have the same temperature dependence or change its value with temperature by the same amount as the asymmetries causing the temperature-dependent zero signal. In accordance with the theory of the Wheatstone bridge, whereby changes in adjacent arms of the bridge are deducted from each other when they have the same prefix, the effects cancel each other out (see basic equation (1) for the Wheatstone bridge circuit).

A simple method of compensation is offered by the “Adjustable foil resistance for temperature compensation of the zero point” in Section 3.5.1. Fig. 3.44 shows the arrangement of this element in the bridge circuit.

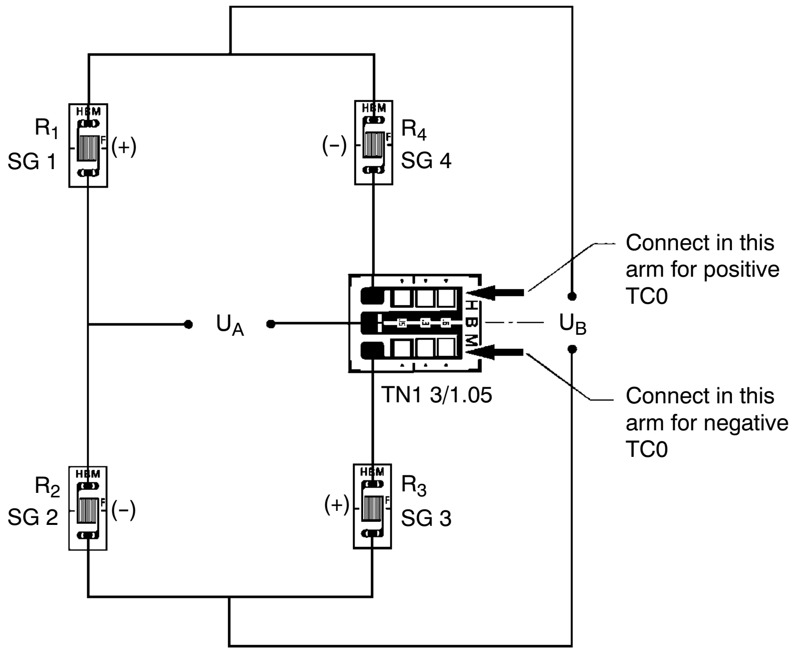


Fig. 3.44: Wheatstone bridge circuit with the “Adjustable foil resistor for temperature compensation of the zero point” (Conductor material: Nickel). The symmetrical design and thus the possibility of siting at the bridge corners allows compensation of positive or negative temperature signals.

If, say, lack of space prevents the use of the resistor network, a comparable effect can be obtained by using fine wire. This wire must also be made of a material with a significant resistance temperature coefficient. Copper or nickel wires are suitable. As a general rule, when using these materials the following resistance temperature coefficient values (applicable to the temperature range from +20 °C to +70 °C) should be applied:

$$\text{Copper:}\ \alpha = 4 \cdot 10^{-3}\frac{\Omega}{\Omega}/\mathrm{K}$$
$$\text{Nickel:}\ \alpha = 5 \cdot 10^{-3}\frac{\Omega}{\Omega}/\mathrm{K}$$

Shown below is the theoretical method of determining the necessary resistances.

Resistance value R_{TN1} for compensating TC_0 must be calculated when using the resistor network. The basis of this calculation is the temperature error measured over the operating temperature range.

Depending upon the associated electronic equipment, the temperature error is measured either in mV/V or in µm/m.

In the first case the R_{TN1} to be set is calculated from the following equation:

$$R_{TN1} = 4 \cdot \frac{U_O}{U_B} \cdot \frac{R_{SG}}{\Delta\vartheta \cdot TC_{TN1}} \tag{2}$$

Derivation of equation (2):

$$\frac{U_O}{U_B} = \frac{1}{4} \cdot \frac{\Delta R_\vartheta}{R_{SG}} \tag{3}$$

Equation (1) page 8, modified for the quarter bridge circuit:

$$\Delta R_\vartheta = \alpha \cdot R_0 \cdot \Delta\vartheta$$
$$\Delta R_\vartheta = TC_{TN1} \cdot R_{TN1} \cdot \Delta\vartheta \tag{4}$$

By substituting this equation—describing the temperature dependence of the electrical resistance—in (3), and expressing in terms of R_{TN1}, we obtain equation (2).

When the temperature error is given in µm/m resistance R_{TN1} is calculated according to the following equation:

$$R_{TN1} = 2 \cdot \frac{\epsilon \cdot R_{SG}}{\Delta\vartheta \cdot TC_{TN1}} \tag{5}$$

Derivation of equation (5):

$$\frac{\Delta R_\vartheta}{R_{SG}} = k \cdot \epsilon \approx 2 \cdot \epsilon$$
$$\Delta R_\vartheta = 2 \cdot \epsilon \cdot R_{SG} \tag{6}$$

Here too equation (4) is substituted for ΔR_ϑ nd then resolved according to R_{TN1}.

Where:

R_{TN1}:	The resistance value to be set on resistor network TN1 3/1.05 in [Ω]
R_{SG}:	Resistance of the strain gage used in [Ω]
R_0:	Original resistance at reference temperature in [Ω]
ΔR_ϑ:	Temperature dependent resistance change in [Ω]
TC_{TN1}:	Temperature coefficient α of compensation resistance in [(Ω/Ω)/K] TC of nickel resistor (+20 °C ... + 70 °C) to be set on resistor network TN1 3/1.05: $5.0 \cdot 10^{-3}$(Ω/Ω)/K
$\Delta\vartheta$:	Temperature change in [K]

Output signal due to the temperature:

$\frac{U_O}{U_B}$:	Relative bridge output voltage in [V/V]
ϵ:	Apparent strain in [m/m]

If the previously mentioned copper or nickel wires are to be used, the resistance of the wire and its length must be calculated, such that the resistance change in response to a given change in temperature is equal to the amount to be compensated.

If the temperature variation is measured in the form of bridge unbalance U_O/U_B, that is in mV/V, the following equations apply:

$$\frac{U_O}{U_B} = \frac{1}{4} \cdot \frac{\Delta R_\vartheta}{R_{SG}} \qquad \text{(Basic relationship (3))}$$

$$\Delta R_\vartheta = 4 \cdot R_{SG} \cdot \frac{U_O}{U_B}$$

$$\Delta R_\vartheta = R_{Wire} \cdot \alpha_{Wire} \cdot \Delta\vartheta$$

$$R_{Wire} = \frac{\Delta R_\vartheta}{\alpha_{Wire} \cdot \Delta\vartheta} \qquad (7)$$

Where resistance per unit of length is known:

$$L_{Wire} = \frac{R_{Wire}}{R_{LWire}} \qquad (8)$$

If the temperature range is measured in units of strain, µm/m, the following equations apply:

$$\frac{\Delta R_\vartheta}{R_{SG}} = k \cdot \epsilon \approx 2 \cdot \epsilon$$

$$\Delta R_\vartheta = 2 \cdot \epsilon \cdot R_{SG}$$

$$R_{Wire} = \frac{\Delta R_\vartheta}{\alpha_{Wire} \cdot \Delta\vartheta}$$

$$L_{Wire} = \frac{R_{Wire}}{R_{LWire}}$$

Where:

R_{Wire}: Resistance of inserted wire in [Ω]
α_{Wire}: Temperature coefficient of wire material in [(Ω/Ω)/K]
R_{LWire}: Resistance of wire per unit of length [Ω/mm]
L_{Wire}: Length of inserted wire in [mm]

Parameters not defined here are contained in the list on page 60.

3.5.3.1 Practical considerations concerning temperature compensation of zero point in the Wheatstone bridge circuit

Before carrying out the following balancing and compensation corrections on the example transducer or elastic element described in Section 3.1.1.4, note that this transducer together with the stand illustrated in Fig. 3.45 must be regarded as a single fixed unit.

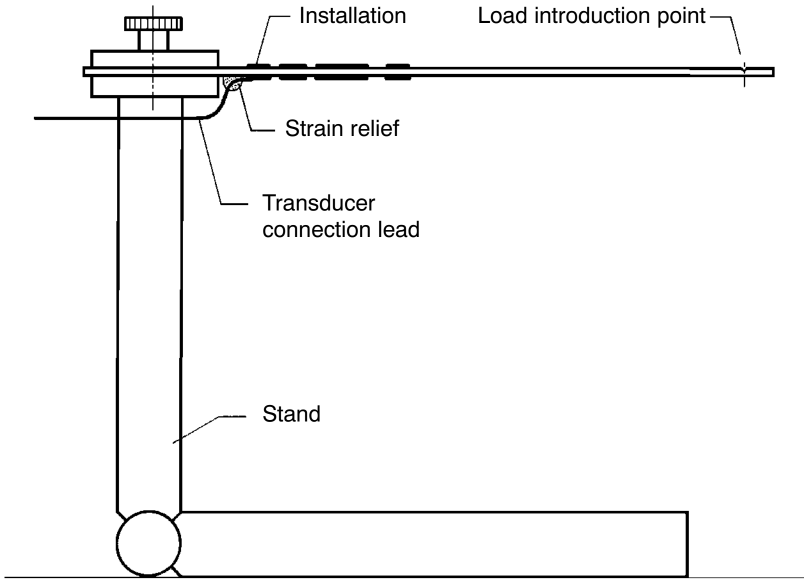


Fig. 3.45: Simple example transducer for practical illustration. In this type of transducer the defined distance between the point of load introduction, strain gages and clamping device is particularly important

This is the only way in which all measurements can be related to a defined, repeatable starting point. The signal caused by the inherent weight of the elastic element, which must not be neglected in this example, is reliably taken into account in the bridge and sensitivity balancing operation. Possible cable effects (force shunt) are minimized.

It lies in the nature of the thing that measurements to discover the temperature behavior and the necessary compensation measures are quite extensive. This is because, while the measurements are being taken the transducers must be maintained precisely at the specified temperatures. The chosen temperature range should depend upon the transducer's intended operating temperature. In this example the most effective range for most transducers is covered, namely, −10 °C to +70 °C. The temperature variation is measured at each end point and in between at +20 °C and +40 °C. In order to obtain exact results, temperature equilibrium is necessary at each individual temperature stage. The dwell time necessary for this depends upon the mass of the transducer or the elastic element, as the case may be.

On our example transducer a temperature error of ϵ = +30 µm/m is measured in the nominated temperature range.

measured: $\epsilon = +30\,\mu m/m = +30 \cdot 10^{-6} m/m$

$\Delta\vartheta = 80\,K$

given: $R_{SG} = 350\,\Omega$

$TC_{TN1} = 5 \cdot 10^{-3} \frac{\Omega}{\Omega}/K$

$k \approx 2$

required: R_{TN1}

$R_{TN1} = 2 \cdot \frac{\epsilon \cdot R_{SG}}{\Delta\vartheta \cdot TC_{TN1}}$ in accordance with equation (5)

$= 2 \cdot \frac{30 \cdot 10^{-6} \cdot 350\,\Omega}{80\,K \cdot 5 \cdot 10^{-3}}$

$R_{TN1} = \underline{\underline{0.053\,\Omega}}$

This calculated value of resistance should be set on the network. However, the smallest resistance step which can be set on network TN 1 3/1.05 is 0.15 Ω. This value is derived from the accuracy requirements generally applicable to the transducers specified in the introduction to this publication. With a nickel resistance of 0.15 Ω, a TC_0 offset of approx. 0.3 %/10 K is achieved relative to 4000 µm/m or 2 mV/V respectively. Accordingly, the TC_0 error can be compensated to about half this range, namely to about 0.15 %/10 K. In this example, however, a TC_0 error of 0.09 %/10 K relative to 4000 µm/m output signal is immediately achieved more or less by chance. The need to trim the network is therefore eliminated, or would lead to "over-compensation".

In certain instances some benefit may be derived from further reduction of the TC_0 error, in which case the necessary compensation can be achieved by inserting a wire, as described in the preceding Section.

To demonstrate on a practical example the effect of "over-compensation" and that of the inserted wire (in this case copper wire) the smallest stage (0.15 Ω) in the resistor network has been introduced into the bridge arm with the smaller temperature error (see Section 3.5.3). Fig. 3.46 shows the different curves for the temperature error before and after compensation.

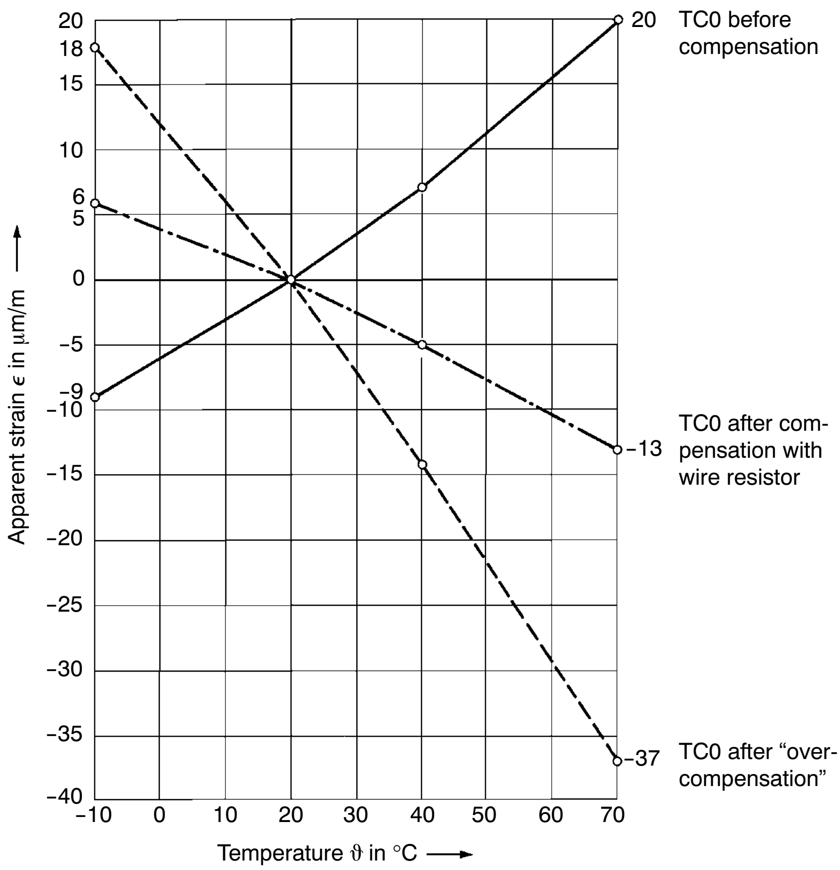


Fig. 3.46: Temperature errors in the example transducer before and after the various compensation measures. The risk of "over-compensation" existing in this case is avoided by using the copper wire.

Determined below is the required length of the copper wire.

measured: ϵ after over-compensation = $-55\,\mu m/m = -55 \cdot 10^{-6} m/m$

$\Delta\vartheta = 80\,K$

given: $R_{SG} = 350\,\Omega$

$k \approx 2$

$\alpha_{Copper} = 0.004\,\frac{\Omega}{\Omega}/K$

$R_{LWire} = 0.014\,\Omega/mm$ for copper wire 0.04 mm diameter required: $L_{Cu\ Wire}$

$$\Delta R_\vartheta = 2 \cdot \epsilon \cdot R_{SG}$$

$$= 2 \cdot 55 \cdot 10^{-6} \cdot 350\,\Omega$$

$$\Delta R_\vartheta = 0.0385\,\Omega$$

$$R_{Cu\ Wire} = \frac{\Delta R_\vartheta}{\alpha_{Wire} \cdot \Delta\vartheta}$$

$$= \frac{0.0385\,\Omega}{0.004\,\frac{\Omega}{\Omega}/\mathrm{K} \cdot 80\,\mathrm{K}}$$

$$R_{Cu\ Wire} = 0.120\,\Omega$$

$$L_{Cu\ Wire} = \frac{R_{Cu\ Wire}}{R_{LCu\ Wire}}$$

$$= \frac{0.1203\,\Omega}{0.013988\,\frac{\Omega}{\mathrm{mm}}}$$

$$L_{Cu\ Wire} = \underline{\underline{8.6\,\mathrm{mm}}}$$

After inserting the compensation resistance in the form of a copper wire (now in the adjacent arm of the bridge), re-checking the temperature error shows a value of –0.06 %/10 K. This residual temperature error meets very high requirements when achieved in the manner just described (i.e., with considerable effort). Experience has shown that, the residual errors of 0.15 %/10 K achieved by using the resistor network, and thus with comparatively little effort, is quite adequate.

3.5.4 Correcting an unbalance in the Wheatstone bridge (bridge or zero balance)

Although modern measurement amplifiers used with the transducer generally offer zero balancing facilities, in actual practice the design aim is for the transducer to generate practically no signal in the unloaded state. A prerequisite for this is that the Wheatstone bridge is symmetrical. If this is so, the bridge is balanced to zero.

The causes of signals from an unloaded transducer, i.e., a basic unbalance in the Wheatstone bridge circuit, are as follows:

- Asymmetries due to different lengths of connection paths within the bridge
- Asymmetries due to slight differences in the resistance of the strain gages
- Asymmetries caused by inserting a resistor during the previous zero point temperature compensation
- Asymmetries due to possible distortion of the strain gage during its installation

The basic unbalance generated in these ways can be balanced by introducing a non temperature sensitive resistor into the arm of the bridge with the smaller resistance, i.e., opposite to the already inserted network TN1 3/10.5. This bridge arm can be identified from the algebraic prefix of the signal from the unloaded transducer. Balancing is also carried out in accordance with the theoretical principles of a Wheatstone bridge circuit, as described in Section 3.5.3.

A simple facility for balancing the bridge is the "Adjustable foil resistor for zero point balancing". Fig. 3.47 shows the arrangement of this element in the bridge circuit opposite the TC_0 compensation element.

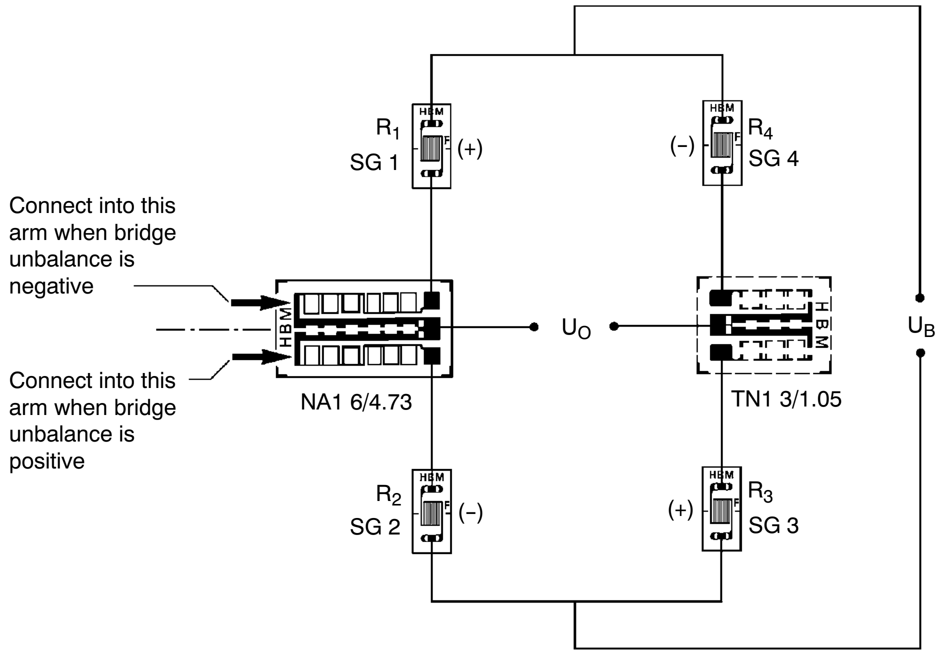


Fig. 3.47: Wheatstone bridge circuit with "Adjustable foil resistor for zero point balancing" (conductor material: Constantan alloy) and the opposite TC0 compensation element. The symmetrical design and thus the possibility of sitting at the bridge corner points allows a positive or negative bridge unbalance to be corrected.

In cases where the resistor network cannot be inserted, e.g., due to lack of space, a similar result can be obtained here too by using fine wire. The wire must have the lowest possible temperature coefficient analogue. Wire made of Constantan alloy offers a solution.

When using the resistor network it is necessary to calculate the value of the resistance R_{NA1} needed to balance the bridge. The basis for this calculation is the absolute bridge unbalance as measured at the reference temperature.

Dependent upon the associated electronics the bridge unbalance will be measured either a) in mV/V or b) in µm/m.

In case a) the resistance R_{NA1} to be set is calculated from the following equation:

$$R_{NA1} = 4 \cdot R_{SG} \cdot \frac{U_O}{U_B} \tag{9}$$

Derivation of equation (9):

$$\frac{U_O}{U_B} = \frac{1}{4} \cdot \frac{\Delta R}{R_{SG}}$$

Solving equation (1) modified for the quarter bridge circuit in terms of ΔR, $R_{NA1} = \Delta R$

When the bridge unbalance is measured in µm/m resistance R_{NA1} is calculated from the following equation:

$$R_{NA1} = 2 \cdot \epsilon \cdot R_{SG} \tag{10}$$

Derivation of equation (10):

$$\frac{\Delta R}{R_{SG}} = k \cdot \epsilon \approx 2 \cdot \epsilon$$

solved in terms of ΔR, $R_{NA1} = \Delta R$

Where:

R_{NA1}:	The required resistance value in [Ω] to be set on resistor network NA1 6/4.73
ΔR:	Resistive asymmetry leading to bridge unbalance corresponding to R_{NA1} in [Ω]
R_{SG}:	Resistance of single SG used, this corresponds to bridge arm resistance in [Ω]

measured bridge unbalance:

$\frac{U_O}{U_B}$:	Relative bridge output voltage in [V/V]
ϵ:	Strain in [m/m]

3.5.4.1 Practical considerations concerning correction of an unbalance in the Wheatstone bridge circuit

In the example transducer, a bridge unbalance of = −342 µm/m (reference temperature 20 °C) was measured after carrying out the TC_0 compensation measures.

measured: $\epsilon = -342\ \mu m/m = -342 \cdot 10^{-6}\ m/m$

given: $R_{SG} = 350\ \Omega$

required: $R_{NA1} = \Delta R$

$$R_{NA1} = 2 \cdot \epsilon \cdot R_{SG}$$

$$= 2 \cdot 342 \cdot 10^{-6} \cdot 350\ \Omega$$

$$R_{NA1} = \underline{\underline{0.24\ \Omega}}$$

This resistance value must now be set as closely as possible on resistor network NA1 6/4.73. This is achieved by combining or separating resistance stages 0.15 Ω and 0.08 Ω. The total balancing resistance thus obtained is 0.23 Ω.

The algebraic sign of the measured bridge unbalance determines the arm in which the resistor must be fitted, and which half of the symmetrical network must be activated, (see Fig. 3.47).

3.5.5 Compensation of the temperature dependence of the sensitivity of the transducer

Without suitable countermeasures, in addition to the zero signal, the output signal from a loaded transducer is similarly influenced by an unwanted temperature dependence. This is manifested in changes in the sensitivity of the transducer in response to varying operating temperatures. The following applies to all transducers supplied with a constant voltage:

$$\text{Nominal sensitivity} = \frac{\text{Bridge output voltage at nominal load – zero signal}}{\text{Bridge excitation voltage}}$$

$$C = \frac{U_O}{U_B} \tag{11}$$

The reasons for this dependence of the nominal sensitivity on the temperature are:

1. *The temperature dependence of Young's modulus of the elastic element material.* The Young's or elasticity modulus E of the elastic element material used in construction of transducers reduces with increasing temperature. The result is that, a constantly loaded elastic element experiences greater strain at a higher temperature than at a lower one. The strain consequently registered by the SG is not only dependent upon load but also upon temperature. A positive temperature coefficient this exists for the sensitivity. Published literature contains only relatively general information about the temperature dependence of Young's modulus of certain materials, because no account is taken of scatter due to alloying.

Tab. 3.7: Temperature dependence of Young's modulus in commonly used elastic element materials over the range 0 ... 100 °C

Material		$\Delta E/\Delta\vartheta[10^{-5}/K]$
Spring steel	51 CrV4	-26
Spring steel	X5 CrNi CuNb 1744	-19
Copper-beryllium	CuBe 2	-35
Aluminium	AlCuMg 2	-58

2. *The temperature dependence of the gage factor (k) of strain gages*
   The gage factor is a measure of the sensitivity of the strain gages.

$$k = \frac{\Delta R/R_0}{\Delta l/l_0}$$

$$\frac{\Delta l}{l_0} = \epsilon$$

$$k = \frac{\Delta R/R_0}{\epsilon} \tag{12}$$

The gage factor also exhibits temperature dependence. Fig. 3.48 shows the curve of typical gage factor against temperature.

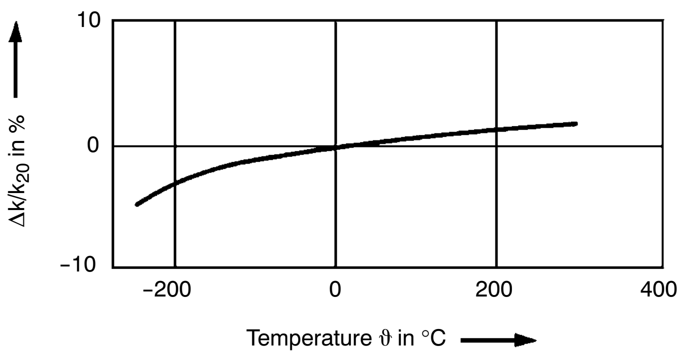


Fig. 3.48: Temperature dependence of gage factor. The example shows the curve for a SG with Constantan alloy measuring grid (CuNi 55/45)

In foil strain gages with a grid made of Constantan (a copper/nickel alloy) this dependence is positive and is approx. $0.8 \ldots 1 \cdot 10^{-4}/K$. Precise specifications are contained in the relevant SG data sheets.

From the preceding statements it can be seen that the temperature dependence of the sensitivity is influenced by both effects in the same direction.

For compensation purposes series resistors with large positive temperature coefficients must be inserted in the input leads of the Wheatstone bridge circuit. When the transducer is then exposed to heat the input voltage will be reduced by an amount equal to the increase in the output signal due to the previously mentioned temperature effects. The result is that, the ratio U_O/U_B and thus the sensitivity will remain almost constant.

A simple method of compensation with temperature sensitive resistors is offered by the "Adjustable foil resistor for temperature compensation of the sensitivity". Fig. 3.49 shows the arrangement of these elements in the input leads. The resistance values for the network are designed to balance the temperature dependent changes in Young's modulus for the most commonly used elastic element materials.

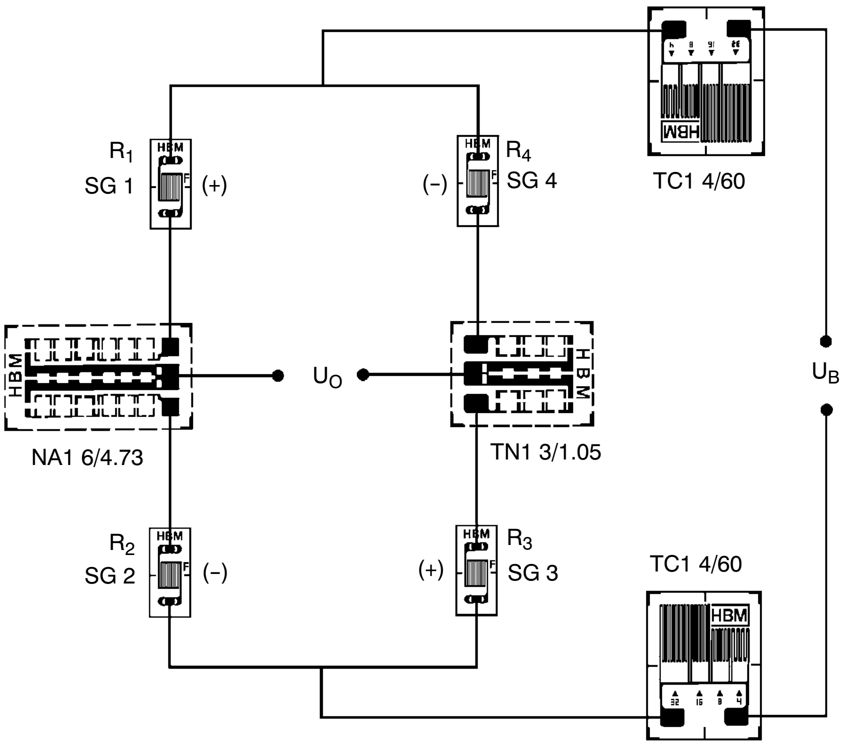


Fig. 3.49: Wheatstone bridge circuit with "Adjustable foil resistor for temperature compensation of sensitivity" (conductor material: Nickel). For symmetry reasons, the calculated resistance R_{TC1} should be equally distributed between the two input leads, i.e. one network per lead.

When using the resistance network the value of resistance R_{TC1} needed to compensate the TC_S must be calculated. The basis for this calculation is the output signal measured at nominal load over the necessary temperature range.

The value of resistance R_{TC1} to be set is calculated as follows:

$$\Delta R_\vartheta = \left(\frac{K_1}{K_2} - 1\right) \cdot R_B \tag{13}$$

$$R_{TC1} = \frac{\Delta R_\vartheta}{TC_{TC1} \cdot \Delta\vartheta} \tag{14}$$

Where:

ΔR_ϑ: Temperature dependent change in resistance in [Ω]
R_{TC1}: The required resistance value in [Ω] to be individually set on resistor network TC1 4/60
R_B: Bridge resistance in [Ω]
TC_{TC1}: Temperature coefficient a of the compensation resistance in the unit [Ω/Ω/K] to be set on resistor network TC1 4/60. TC of nickel resistor (+20 °C … + 70 °C) : $5.0 \cdot 10^{-3}$ Ω/Ω/K
K_1: Output signal from transducer carrying nominal load at maximum operating temperature in [mV/V] or [µm/m]. These units can be converted from one to the other using the ratio 4000 µm/m = 2 mV/V applicable to full bridges and strain gages with a gage factor of 2.
K_2: Output signal from transducer carrying nominal load at reference temperature in [mV/V] or [µm/m]

3.5.5.1 Practical considerations concerning compensation of the temperature dependence of sensitivity

Measurement of the temperature dependence of sensitivity in the example transducer gave the following results:

Output signal from transducer carrying the selected nominal load of 1 kg at reference temperature 20 °C:

$$2498\,\mu m/m = K_2$$

Output signal from transducer carrying a load of 1 kg at the maximum operating temperature of 70 °C:

$$2539\,\mu m/m = K_1$$

measured: $K_1 = 2539\ \mu m/m$

$K_2 = 2498\ \mu m/m$

$\Delta\vartheta = 50\ K$

given: $R_B = 350\ \Omega$

$TC_{TC1} = 5 \cdot 10^{-3}\ \frac{\Omega}{\Omega}/K$

required: R_{TC1}

in accordance with (13):

$$\Delta R_\vartheta = \left(\frac{K_1}{K_2} - 1\right) \cdot R_B$$

$$= \left(\frac{2539\ \mu m/m}{2498\ \mu m/m} - 1\right) \cdot 350\ \Omega$$

$$= 5.7\ \Omega$$

$$R_{TC1} = \frac{\Delta R_\vartheta}{TC_{TC1} \cdot \Delta\vartheta}$$

$$= \frac{5.7\ \Omega}{5.0 \cdot 10^{-3}\ \frac{\Omega}{\Omega}/K \cdot 50\ K}$$

$$\underline{\underline{22.8\ \Omega}} = \underline{\underline{(2 \cdot 11.4\ \Omega)}}$$

A value must now be set on the resistor network TC1 4/60; it must be as close as possible to the calculated value and be shared equally between the two input leads. This can be achieved by combining or separating the resistance stages 4 Ω and 8 Ω in both networks.

When structural aspects preclude measurement of the temperature coefficients (which frequently happens in practice), the TC_S can be approximated by following a standardized compensation procedure shown below.

This can be illustrated by an example:

R_B = 350 Ω (bridge resistance)
R_{TC1} = 30 Ω (estimated value for compensation resistance)

R_{Total} = 380 Ω (total resistance of input circuit)

Temperature-dependent due to	variable change in %/K
$\Delta\epsilon$ due to $\Delta E/\Delta E_{20°}$ (steel)	approx. +0.03
SG measured value due to $\Delta k/k_{20°}$	approx. +0.01
Transducer sensitivity $\Delta C/C_{20°}$	approx. +0.04

The resistance of the measuring circuit must therefore increase by 0.04 %/K.

In the selected example that is:

$$\Delta R_{Total} = \frac{380 \cdot 0.04}{100} = 0.152\,\Omega/K$$

Temperature coefficient of balancing element $TC_{TC1} = 5.0 \cdot 10^{-3}/K$

The basic resistance of TC1 at 20 °C is calculated from:

$$R_{TC1} = \frac{\Delta R_{TC1}}{TC_{TC1}} = \frac{0.152\,\Omega/K}{5 \cdot 10^{-3}/K} = \underline{\underline{30.4\,\Omega}}$$

The closest partial resistance of the TC1 is 32 Ω.

Compared to the result from measurements and calculation (see page 72), scatter of the variables concerned makes the above-mentioned procedure less accurate, although for many uses it is certainly still adequate.

3.5.6 Balancing the sensitivity of the transducer

SG transducers are normally designed to deliver an output signal of 2 mV at their nominal load ($\hat{=}$ 1000 µm/m component strain) and 1 V input. The sensitivity is therefore 2 mV/V. Achievement of a relatively tight tolerance on sensitivity is useful, e.g., when a transducer has to be exchanged because of a defect. It will then not be necessary to recalibrate the measuring system.

It is not possible to build transducers with exact round figure sensitivities. This is due to the unavoidable mechanical and electrical tolerances and the already mentioned balancing and compensation measures. The elastic element should therefore be dimensioned so that, in the unbalanced state under nominal load it provides a signal greater than 2 mV/V, e.g., 2.4 mV/V.

To trim the output signal to 2 mV/V we now insert a fixed resistor (with a low temperature coefficient) into the input leads. This resistor, designated as R_E, reduces the input voltage and so consequently the output voltage.

The market offers a large variety of high stability high precision resistors, so they are relatively easy to obtain. Alternatively, one can produce their own elements with appropriate resistance material.

The resistance R_E needed to trim the sensitivity can be calculated from the following equation:

$$R_E = R_B \cdot \left(\frac{K_1}{K_2} - 1 \right) \tag{15}$$

Where:

R_E: The required balancing resistance in [Ω] in the form of a fixed value resistance distributed equally between the two input leads
R_B: Bridge resistance in [Ω]
K_1: Transducer sensitivity prior to balancing in [mV/V]
K_2: Desired transducer sensitivity after balancing in [mV/V]

We will not consider a practical example at this point, since the design of our example transducer is aimed more at the preceding balancing and compensation measures, and less at setting a defined sensitivity.

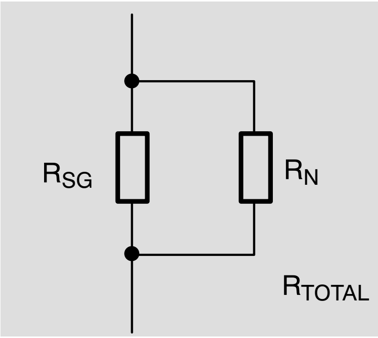
3.6 Measures to protect the SG installation

Protection of the SG installation is a further important step in the process toward the finished transducer. This measure is a significant factor in determining whether the properties of the manufactured transducer will be durable in the long term, and whether the transducer will resist external influences. Such external influences are primarily taken to mean mechanical effects and environmental influences. Of the environmental influences moisture is the most significant.

The effect of moisture on the measurement point can be, for example, to form a shunt resistance across the strain gages, i.e., the insulation resistance is reduced. These shunt resistances alter in response to changes in temperature and moisture, and manifest themselves as long-term drift in the output signal.

The following example is intended to give an impression of the magnitude of the possible error.

At a strain ϵ of 1000 µm/m and a SG resistance R_{SG} = 350 Ω with a gage factor of k = 2 we get an absolute resistance change of R = 0.7 Ω when the transducer is subjected to nominal load. If insulation resistance R_N is regarded as a shunt resistance across the SG, then the total resistance will be given by:



$$\frac{1}{R_{Total}} = \frac{1}{R_{SG}} + \frac{1}{R_N} \qquad (16)$$

$$R_{Total} = \frac{R_N \cdot R_{SG}}{R_{SG} + R_N} \qquad (17)$$

As already noted, the insulation value R_N should be equal to or greater than 20 000 MΩ. With a SG resistance of 350 Ω this would give the following total resistance:

$$R_{Total} = \frac{350\,\Omega \cdot 2 \cdot 10^{10}\,\Omega}{2 \cdot 10^{10}\,\Omega + 350\,\Omega}$$

$$\underline{\underline{R_{Total} = 349.999\,\Omega}}$$

As we can see, the minute change in resistance to be set can be safely disregarded. If the insulation resistance now decreases to, say, 2 MΩ (possibly due to the effects of moisture), we obtain the following equation:

$$R_{Total} = \frac{350\,\Omega \cdot 2 \cdot 10^{6}\,\Omega}{2 \cdot 10^{6}\,\Omega + 350\,\Omega}$$

$$\underline{\underline{R_{Total} = 349.94\,\Omega}}$$

This produces a difference in the total resistance for the two cases of ΔR = 0.06 Ω, i.e., the change in resistance simulates an strain or change in strain of 85.7 µm/m. At a nominal load of 1000 µm/m this would represent an error of almost 10 %.

This example shows in a striking manner the extent to which the accuracy of a transducer can be degraded by moisture. It is also clear that the effect of moisture increases with larger nominal resistance of the strain gages.

Protection of the installation is indispensable in order to counteract these problems. The SG accessory range contains a series of suitable covering agents. The HBM publication “Strain Gages and Accessories” and Bibliography item [4] assist any decision relating to the extent to which environmental conditions are allowed to influence the system.

Fig. 3.50 shows that, on our example transducer the SG and the balancing and compensation elements are initially covered with a thin coating of PU 120 polyurethane varnish, which in turn is covered with SG 250 silicone rubber. This standard form of protection has, amongst other things, been well proven on transducers used in laboratory environments where it provides adequate protection against the forms of moisture encountered in these areas, and against mechanical effects.

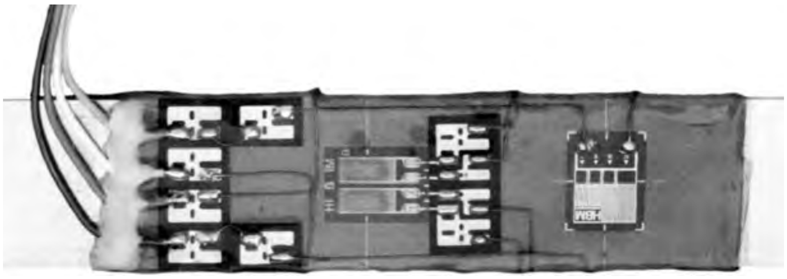


Fig. 3.50: Protection of the SG installation with PU 120 polyurethane varnish and SG 250 silicone rubber. The strain gages and the other elements remain recognizable through the transparent layers.

4 Bibliography

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