Measuring forces in the force shunt:
Three methods used in practice

Using force transducers to measure forces offers many benefits, for example high accuracy. Sometimes, however, it is of advantage to measure force in the force shunt. Special sensors, precisely matched to the application, are available for these cases. This article presents three methods used for measurement in the force shunt.

Calibrated force transducers offer the benefit that the characteristic curve determined during calibration - i.e. the ratio of applied force and output signal - can easily be reproduced even after installation on site. It is prerequisite that the force transducer is mounted in the force flow and that there is no force shunt. It must be ensured that the entire force to be measured flows through the transducer.

This also means that the force transducer's characteristic features - for example, stiffness and dynamic behavior - affect the overall design. In addition, force transducers for high forces are very large structures.

Alternatively, a force measurement can be carried out based on the deformation of the structure in which forces are to be measured. Three different methods are available.

The following three methods can be used:

- Installation of strain gauges
- Utilization of screw-on type strain transducers, sometimes even with integrated electronics
- Utilization of force washers, based on strain gauge or piezo technology

The table shows the key advantages and disadvantages of the methods presented:

Installation of strain gauges	Utilization of strain transducers	Utilization of force washers
Advantages		
• Well suited for **highly filigree structures** with a **small force** applied which do not enable the other methods to be used because of **excessive force shunt** • **Minimum space required**	• **Easy installation** by screwing onto existing structures, rapidly deployable • **Compensation of the effects of strain** that are to be suppressed when connecting several sensors in parallel • Versions with **integrated electronics** can be directly **calibrated in the application**	• Ideal for use on **bolts** or **screws** • **High degree of protection** • Delivered **ready for installation**
Disadvantages		
• **Installation effort** (bonding, wiring, protective coating) • **Calibration in the force shunt** required	• **Calibration in the force shunt** required (reduced effort with variants with integrated electronics)	• **Calibration in the force shunt** required

Utilization of strain gauges to measure forces on structures

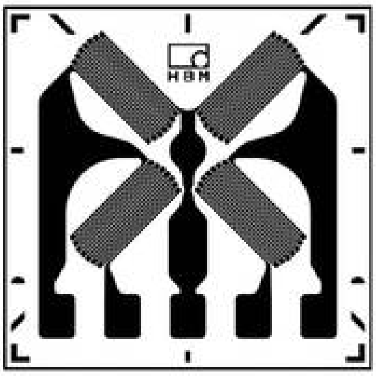

Fig. 1: VY41 strain gauge. The strain gauge is ready for connection in a full bridge circuit to minimize wiring effort. Observe the 45 degree alignment marks that are essential for installation in this case.

Directly installing strain gauges to measure force has several advantages.

Bonded strain gauges (SG) have practically no influence on the structure of the object under test. The stiffness and dynamic behavior of the structure as a whole remain unchanged. Strain gauges offer clear advantages when filigree structures are involved, because they require only very small forces to be deformed.

In this installation, strain gauge full bridges are used which, when carefully selected, compensate for parasitic effects (e.g. bending moments or torsion) or, alternatively, measure these effects [1], [2].

Assuming tensile/compressive loading without any bending moments acting on the workpiece, strain gauge full bridges are the ideal solution, for example VY41 from HBM which have to installed at an angle of 45 degree.

The output signal of such a measuring bridge is only dependent on the gauge factor of the strain gauge that is used and on the strain level as well as the material's Poisson's ratio; it can be calculated as follows:

$$\left(\frac{U}{U_0}\right) = k \cdot \varepsilon(1+\mu)$$

In this:

U/U0	Output signal of the measuring bridge
k	Gauge factor of the strain gauge
ε	Strain level on the strain gauge
μ	Poisson's ratio

Fig. 2: *Strain gauge-based SLB700 strain transducer*

Assuming 20 MPa mechanical stress in a steel structure with a resulting strain of 100 μm/m and a gauge factor of 2, the formula above enables an output signal of 0.13 mV/V to be calculated.

This calculation also shows the disadvantage of bonded strain gauges. To enable the structure to attain a defined stiffness, the output signal that can be attained is very small.

Moreover, the strain gauge needs to be installed on site. A protective coating is required. Furthermore, the strain gauges need to be connected with great care which increases the time required for installation. The installation of strain gauges is described in detail in the instructions supplied with the adhesives and covering agents as well as in HBM articles and seminars.

Controlled weakening of the component provides an easy means to increase the measuring bridge's output signal. However, this affects the object's stiffness. Which, in turn, affects dynamic behavior and stability.

Utilization of strain transducers to measure forces

Fig. 3: SLB spring element: The picture clearly shows the area of strain where the strain gauge has been installed

Strain transducers are sensors that can be installed on an existing structure. These transducers are based on a spring element onto which a strain gauge full bridge has been installed.

As shown in the picture, these strain transducers come with a silicone coating (white area on the transducer) which, in addition to moisture protection offers some degree of mechanical protection.

Strain transducers are based on the principle of strain transformers. Strain in the area of the installed strain gauges is bigger than the strain value between the two screwed connections.

Figure 3 shows the SLB spring element. Strain applied to the transducer is centered on the zone where the strain gauge has been installed. The reason: Here, a significantly reduced stiffness is used. The approximate excessive increase in strain can be calculated as follows:

$$\varepsilon_{SG} = \frac{\varepsilon_{Object} \cdot l_{Strain\ sensor}}{l_{Strain\ zone}}$$

Where:

ε_{SG}	Strain present under the strain gauge
ε_{Object}	Strain between the screwed connections
$l_{Strain\ sensor}$	Distance between the screwed connections
$l_{Strain\ zone}$	Length of the area of structural weakening

This view includes some idealizations.

It is assumed that the zone of strain application is strain-free. Of course, this is not true - strictly speaking. It becomes apparent that the strain transducer's sensitivity can be adjusted by means of the length ratio of strain zone and distance between the two screwed connections. In principle, a very high sensitivity can be attained, however, in practical use, an output signal of 1.5 mV/V at 500 µm/m has proved favorable. This results in a sensitivity increase of 230 % compared with a strain gauge full bridge as described above.

The temperature dilatation of components has been compensated for by taking appropriate circuitry measures.

In addition, strain transducers with integrated electronics are available that can be calibrated in the application, therefore providing an extremely efficient measuring chain.

The sensors without electronics have a high bridge resistance of 700 Ω. This enables several strain transducers to be connected in parallel without requiring an excessively high amplifier supply current.

This measure enables strain effects that need to be suppressed to be compensated for. For example, for monitoring press forces on a column the only proportion of strain that is relevant is the one resulting from tensile/compressive loading.

Let us assume that two strain transducers are connected in parallel and mounted on a column at the same height, opposite from each other. Under a bending load, one transducer will experience higher strain, the other one will be loaded with strain that is lower by the same amount. On the whole, only the proportion of strain resulting from tensile or compressive loading is measured. Bending is compensated for.

SLB strain transducers from HBM can be mounted on structures using 4 M6 screws. This only requires a plane surface, free from paint or other coatings. Upon screw-mounting of the strain transducer with the recommended torque, we recommend applying corrosion protection, for example ABM75 foil. Then, the sensor is immediately ready for use.

Utilization of force washers to measure forces

Force washers can be based on both strain gauge or piezo technology. Regardless of the principle selected:

Force washers can be used on both bolts or screws. Therefore, the force washers' internal diameter matches commonly used outside diameters of metric threads. The data sheets for KMR force washers also specify dimensions in inches.

The force shunt results from the bolt or screw on which the force washer has been installed functioning as a parallel spring element and thus reducing the measurement system's sensitivity. In this case, a value of approximately 10% has to be expected.

As a result, force washers cannot be calibrated at the factory; in this case, similar to the other two methods described above, calibration in the force shunt is always required.

To ensure good reproducibility, it is essential that a pre-stress is applied to the force washer. The magnitude of this force is dependent on the sensor's nominal (rated) force and the force to be measured - the highest bending moments may act on a force washer when it is loaded at 50 %. Ideally, the pre-stress should be rated such that the sum of pre-stressing force and working force is 50% of the force washer's nominal (rated) force on average. This recommendation applies to piezoelectric force washers in particular [3].

Force washers provide a high degree of protection and are delivered ready for mounting; in this respect, they offer the same advantages as strain transducers. Force washers, too, provide sufficient sensitivity that, with piezoelectric transducers, even is independent of the nominal (rated) force.

The scope of supply of HBM products includes the washers for force application with strain gauge-based transducers that ensure uniform distribution of forces over the entire circumference. If these washers cannot be used, the surface coming into contact with the transducers must be hardened (43 HRC) and ground; material unevenness must not exceed 20 µm.

Fig. 4: KMR force washer, smallest design, 20 kN nominal (rated) force

Fig. 5: CFW piezoelectric force washers, available with 20 to 700 kN. Here: 330 and 700 kN

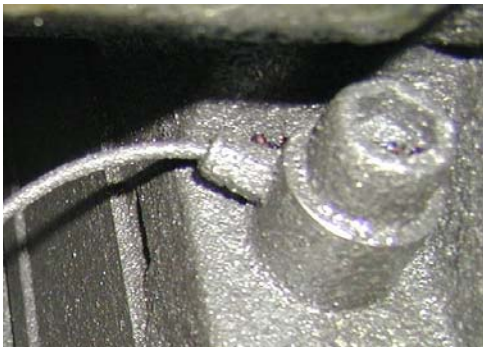

Fig. 6: For tool monitoring, a force washer measures the forces acting on a screwed connection.

Calibrating measuring chains in the force shunt

All three methods presented have in common that the measuring chain requires calibration after installation. This means that measurements have to be taken at two known points of force at least. The sensor output signal is then assigned to the forces. Due to the fact that the sensors' behavior is linear within tightly defined error limits and that these methods cannot be used for high-precision measurements, two-point calibration is sufficient in general.

The strain transducer's integrated electronics follows this line of reasoning. Calibration only requires measurement at the zero position and a control impulse sent to the electronics. When the maximum force has been applied another control impulse is required. Then the electronics is automatically adjusted. Zeroing is, of course, separately possible, without changing the gain factor.

Zero strain corresponds to 1 V, the maximum strain is converted to 9 V, however, the output range is set from 0 to 10 V to provide 10 % measuring range each for overload or negative strain. The electronics also enables negative input strain to be converted into positive output voltages. Current versions are available that work accordingly and offer an output range of 4...20 mA.

Measuring forces in the force shunt: Conclusions

This paper shows: Various useful methods are available for measuring forces in the force shunt. All methods have in common that they only marginally - if at all - affect the mechanical behavior of the structure as a whole.

However, SG or piezo technology-based force transducers remain the first choice, when high accuracy is essential. For the following reasons:

- Adjusting the force transducer after installation is not required, because the transducers already have been calibrated with high precision. When measuring forces in the force shunt, calibration directly on the object is always required.
- The measurement uncertainty of force transducers is known and can be influenced through the choice of force transducer model.
- Utilizing high-quality transducers (e.g. HBM's S9M providing 0.02 accuracy) enables very high accuracy to be attained that cannot be attained when measuring in the force shunt.

References

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