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FIBRE BRAGG SENSORS COMPARED WITH ELECTRICAL STRAIN GAUGES FOR USE IN FORCE MEASUREMENT - PROSPECTS AND POTENTIALS

Thomas Kleckers

Hottinger Baldwin Messtechnik GmbH, Darmstadt Germany, Thomas.Kleckers@HBM.com

Abstract − This article deals with the technical properties of fiber Bragg gratings with regard to their use as the strain-sensitive element in force transducers.

Electrical strain gages are widely used in modern, precise force transducers. The electrical strain gage provides both outstanding technical properties and cost-effectiveness.

Besides the electrical strain gage, the measurement principle of fiber Bragg-based sensors has recently become established. First applications in experimental mechanics have shown that this technology offers a lot of potential.

Optical strain gauges are available on the marked since one year and are proofed in many applications.

These sensors are mainly based on so-called fiber Bragg gratings. Such a Bragg grating uses a great many reflection points at regular spacing. At each of these points, part of the radiated light is reflected. The reflected light interferes (constructive interference) and generates a reflection peak. This peak shows a characteristic wavelength which is dependent on the spacing of the reflection points.

The following sketch shows a Bragg grating in a fibre and its influence on the spectrum of the transmitted and reflected light.

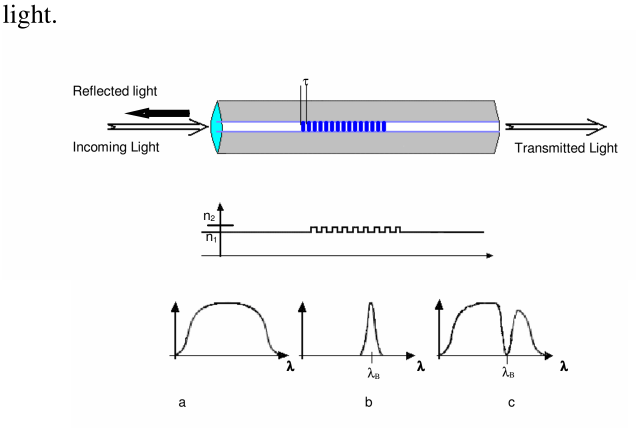

Fig. 1. Principle of a fibre Bragg Grating. Diagram a shows the spectrum of the light which is send into the fibre. The light at the Bragg wavelength is reflected (b). Diagram c shows the spectrum of a Bragg grating in transmission.

This article presents the properties relevant to use in the manufacture of transducers such as:

- Creep
- Temperature behaviour
- Drift
- Electromagnetic compatibility

and others and compares them with the properties of electrical strain gages.

Keywords: Optical strain measurement, Fibre-Bragg-Gratings, Optical Force measurement

1. THE METHOD OF STRAIN MEASUREMENT USING BRAGG-GRATINGS

The effect used for strain measurement now is the effect of positive-fit introduction of strain into the Bragg grating. Thus the spacing of reflection points changes as a result of the introduction of strain. This causes a change in wavelength of the reflected light. Analogously to the electrical strain gage, the relative change in wavelength is proportional to the introduced strain.

$$\frac{\Delta\lambda}{\lambda_B} = k \cdot \varepsilon \qquad (1)$$

Meanings are as follows:

$\Delta\lambda$:	Change in wavelength
λ:	Base wavelength
K:	Gage factor
ε:	Strain

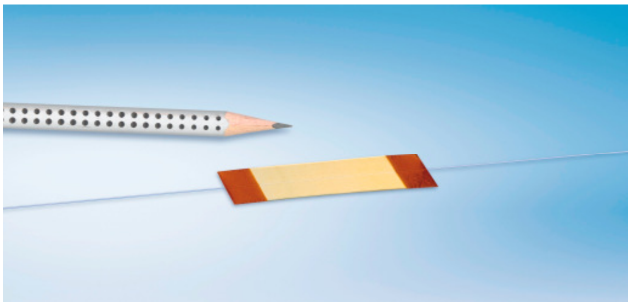

Fig. 2. Optical strain gage for use in experimental mechanics

Sensors based on Bragg gratings have the following advantages:

- Insensitivity to electromagnetic fields
- Suitable for use in highly explosive atmospheres
- No mechanical failure of the sensor material (glass) at high vibration loads
- Small mass of the connecting leads and thus small influence of this mass on the test object
- Reduced "wiring effort", because many sensors with different Bragg wavelengths can be accomodated in a single fiber

2. CHARACTERISTICS FOR STATIC MEASUREMENTS

Static measurements place very high demands on freedom from drift, creep characteristics and the insensitivity to temperature of the zero point.

2.1. Temperature dependency of the zero point

Every electrical strain gage shows an output signal dependent on temperature variation.
This output signal is due to two physical reasons:

- The electrical resistance of the measuring grid material is a temperature dependent quantity.
- The spring element material shows a thermal expansion coefficient.

With electrical strain gages, the temperature dependence of the measuring grid material can be adjusted, therefore the temperature signal of an electrical strain gage is very small. Despite this adaptation, the remaining temperature response of electrical strain gages must not be neglected.

This error is largely compensated using the Wheatstone bridge circuit. However, perfect error compensation requires that all strain gages used in a Wheatstone bridge behave exactly identical - this is not the case, the strain gages vary. The resulting remaining error is minimized by connecting additional temperature-dependent resistors in the Wheatstone bridge.

Optical fiber Bragg gratings too show a temperature output signal which is also based on two physical effects:

- The refractive index of the glass used is a function of temperature.
- The temperature dilatation of the spring element material is measured like mechanical strain.

Thus:

$$\frac{\Delta\lambda}{\lambda_0} = k \cdot \varepsilon + \alpha_\delta \cdot \Delta T \qquad (2)$$

Meanings are as follows:

ε: Thermally induced strain
K: Strain gage sensitivity of the Bragg sensor
α_δ : Temperature dependency of the zero point
ΔT: Temperature variation

The temperature output signal of the individual fiber Bragg grating cannot be modified and both of the above mentioned effects act in the same direction. Thus, a fiber Bragg grating has a substantially higher temperature dependency than an electrical strain gage.

Figure 2 shows the thermal output of single fibre-Bragg-grids mounted on different materials. The thermal output of a Bragg-grid mounted on aluminium is more than 500µm/m at 40°C where 20°C is the reference temperature. A compensation of this temperature effect is more necessary than in case of electrical strain gauges as the thermal output is less than one tenth at the same temperature difference. .

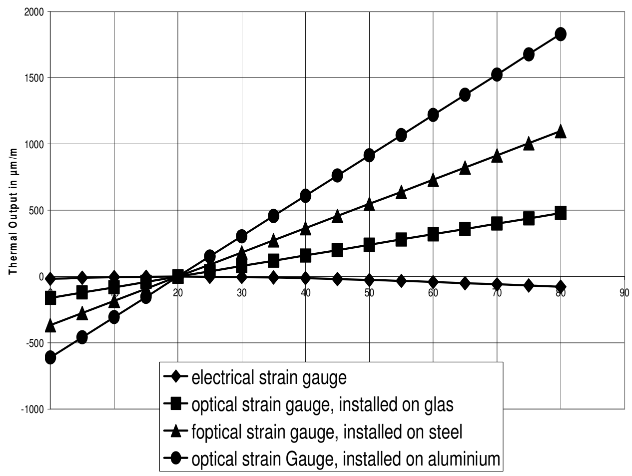

Fig 3. Comparison of the temperature output signals of optical and electrical strain gages.

Compensating optical fiber Bragg sensors in the same way as electrical strain gages is a suitable solution to the problem. Since when using optical Bragg sensors every grid requires a separate channel (connection in a measuring bridge similar to electrical strain gages is not possible), a suitable solution is to map the relationships in the Wheatstone bridge on a computer for mathematical compensation of the temperature effects.

Because of the high sensitivity to temperature effects, fiber Bragg grating-based sensors are very sensitive to temperature variations between the grids. Fast temperature variations and gradients strongly affect the zero point.

2.2. Drift

The drift of strain gages may be explained by oxidation effects in the strain gages. Oxidation is a temperature-dependent, chemical process, thus drift mainly occurs at higher temperatures.
Good electrical strain gages are subjected to artificial aging - therefore, a drift occurring within the operating temperature range is not possible.

Fiber Bragg gratings are made from glass, a material that is highly corrosion resistant. Since no electrical connections that might cause modifications are required, optical fiber Bragg gratings may be considered free from drift.

2.3. Creep

A transducer's creep behavior depends on the spring material's creep behavior which is always positive. This means that the absolute value of surface strain increases with invariable load.

Here, electrical strain gages have a compensating effect, because their absolute value shows a negative creep which is dependent on the strain gage's end tab length. This may be explained by the fact that the force is introduced into the measuring grid through the end tabs. Here, the plastic strain gage carrier is subjected to high shear stress, because the measuring grid on top is a spring. Due to viscoelastic processes the plastic material yields in the direction of load - the strain gage creeps.
If very long end tabs are used, creep occurs only around the end tabs, i.e. the measuring grid links' dimension remains unchanged and the electrical resistance and thus the measuring bridge output signal remains constant. With short end tabs, however, this process affects the length of the measuring grid links - the creep of the strain gage increases. Thus, the creep behavior of a strain gage can be adapted to the creep behavior of the spring material.

Electrical strain gages have made considerable progress in this field over the past years, especially through homogenization of carrier materials. Strain gages based on filled polyether ether ketone as well as strain gauges based on polyimide carriers have very homogeneous creep properties which enables the cost-efficient series production of high-precision transducers.

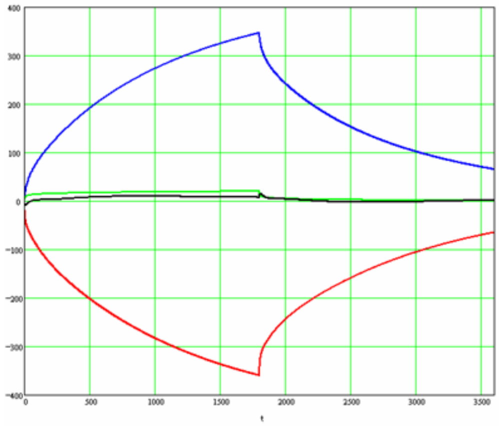

Fig. 4. Creep behavior of an electrical strain gage: upper curce (positive creep) is the electrical strain gage, lower curve (negative creep) is the transducer body. Total creep is zero (middle curve).

Force is introduced into a fiber Bragg grating by installing the Bragg grating on the base body. There are no force application surfaces that would correspond to the end tabs of a strain gage. Therefore, the creep of a fiber Bragg grating sensor cannot be adjusted.
At present, there are attempts being made to use other parameters of force introduction into the fiber to make sensor creep adustable. The following options are available:

- Configuring the viscoelastic properties of the plastics introducing strain into the fiber.
- Configuring the geometric properties of force introduction, e.g. the layer thickness.

Both options are potentially suitable for determining the creep of a fiber Bragg sensor; however, creep behavior will definitely vary widely because of the many material parameters involved.

3. OTHER RELEVANT SENSOR PROPERTIES

3.1. Temperature coefficient of sensitivity

Strain gages change their sensitivity in case of temperature variation. The elastic modulus of the spring material too is temperature-dependent; therefore, the absolute strain value in the area of the strain gages changes at a given load. The absolute strain value increases with higher temperature and decreases with falling temperature.

Electrical strain gages enable this effect to be compensated by connecting nickel resistors to the strain gages' excitation lead. If the temperature increases, the increasing resistance of the nickel elements results in a decreasing voltage on the strain gage bridge. Hence, the bridge circuit yields a reduced output voltage - the temperature dependency of sensitivity can be adjusted.

Moreover, strain gages featuring a sensitivity that decreases with temperature are available. These elements enable the behavior of the steel and aluminum alloys from which the measuring bodies are made to be compensated.

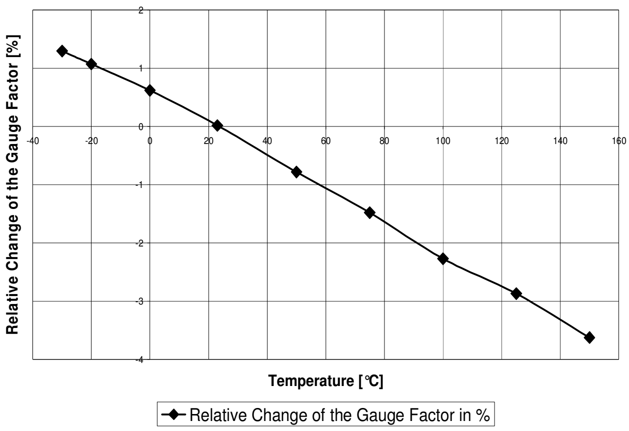

Fig. 5. Typically temperature-dependent change in sensitivity of electrical strain gages made of a Chrome–Nickel-Alloy. Sensitivity decreasing with temperature.

Changes in sensitivity of fibre Bragg sensors resulting from temperature variations have already been described in pertinent literature, however, no adjustment or compensation method has been found so far. It is important to note that the above described temperature-dependent change in elastic module affects measurement as an error.
The solution that suggests itself is to measure temperature and implement active compensation.

3.2. Electromagnetic fields

Electromagnetic fields of course cannot affect fiber Bragg-based sensors. Use in applications in potentially explosive atmospheres is also possible without restrictions.

3.3. Linearity

Strain gages attain a high linearity. An interesting study of the gage factor of fiber Bragg sensors shows a difference in sensitivity between positive and negative load.
This means that a force transducer has different sensitivities for tensile and compressive loads.

Table 1: Gage factors of optical strain gages of fiber Bragg sensors with tensile and compressive load

Sample	Gage Factor Positive Strain	Gage Factor Negative Strain
1	0,808	0,79
2	0,804	0,785
3	0,801	0,784
4	0,804	0,781
5	0,808	0,794
7	0,806	0,793
8	0,803	0,79
Mean Value	**0,805**	**0,788**

3.4. Force shunt

An electrical strain gages requires approx. 2 N for being strained by 1000 µm/m. A Bragg grating from HBM requires about 1 N.

Hence, fiber optics-based force transducers with small nominal forces too can be implemented at least theoretically.

4. CONCLUSIONS

This article shows that fiber optics-based force transducers are an interesting technology.

With fibre optics-based transducers, compensation requires active computation of the above mentioned characteristic quantities.

Fibre Bragg force transducers will take place in those applications where their advantages play a main rule and highest precision is not needed.
Areas with high electromagnetic fields or areas with highest voltages are examples. The wiring of optical sensors is much easier in many cases as the diameter of a fibre is much lower than the diameter of a electrical cable. More than this, many optical force transducers can be connected in a row, if the Bragg wavelength of the sensors is different to each other.
The optical fibre cannot be effected by humidity, this makes wiring also easier.

With static applications requiring high precision with regard to creep behavior and the temperature coefficient of zero point and sensitivity, the electrical strain gage will continue to be the first choice, because it can passively compensate for all these effects.

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