Optical strain gauge extremely stable in thin plate

Taking measurements using an optical fibre (fibre optic sensing) offers unprecedented possibilities when compared to conventional electronic measuring. This is mainly due to the wave characteristic of light: think of aspects such as resolution and multiplexing, with a good example being the 'optical strain gauge'. TNO Science and Industry has developed the principle for a high-frequency multi-channel measuring system based on Fibre Bragg Grating. This system can measure any quantity that can be translated into thermal or mechanical strain on the fibre. Technobis has now developed it into a product that is ready for the market, the Fibre Bragg Grating Interrogator. The greatest challenge, however, was to make the system extremely stable.

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During a project at TNO Science and Industry, the need was felt for a measuring system for fibre optic sensors that could read out several channels in parallel and at high speed. This led to the initiation of the development of Deminsys (Demultiplexing Interrogator System). Current commercially available systems have only one channel with a sample frequency of 3 kHz. In comparison, TNO's functional model of Deminsys is unique: it has a sample frequency of 19,3 kHz for all 32 sensors simultaneously (four channels, each with eight sensors); see Figure 1. Market research has shown that there is interest from, amongst others, the aviation, medical, offshore, maritime and space industries. In order to develop the functional model into a working product, TNO decided to engage an external party to take care of the project development. After some investigation, it was decided that Technobis be selected, a company with extensive experience in opto-mechanics and in developing functional models into market-ready products. Technobis Mechatronics has been established for ten years, has its offices in Uitgeest, the Netherlands, and recently formed sister companies in Eindhoven, Technobis Optronics and Technobis Fibre Technologies.

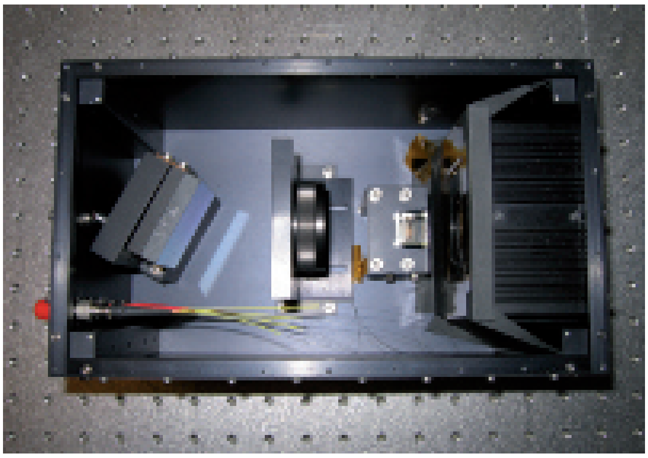

Figure 1. A view of the insides of TNO's functional model of Deminsys with, from left to right, a grating under which there are four fibre entrances, a lens, a spectrometer and a line scan camera.

Fibre Bragg Grating

The technique of Fibre Bragg Grating (FBG) is suitable for measuring any quantity of which a change in value can be translated into a variation of the strain on a glass fibre. For example, temperature, pressure and acoustic vibrations but also concentrations (by applying a layer of deuterium to the fibre which expands when absorbing hydrogen, a H_2 detector is created) or EM (electromagnetic) fields caused by high-voltage currents. In this way, fibres of tens or hundreds of metres in length can measure the stress loads inside the wing of a JSF fighter plane during test flights. It is also possible to continuously monitor the stress loads on the sails of windmills so that overload or fatigue can be detected on time. The same goes for bridges: see Figure 2.

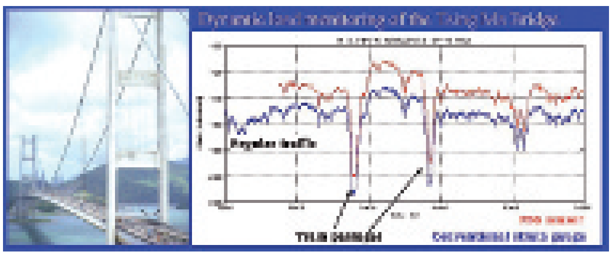

Figure 2. An example of the sensitivity of a FBG sensor: monitoring of the dynamic load on the Tsing Ma Bridge in Hong Kong. The optical strain gauge compared with its conventional counterpart.

Optical versus conventional strain gauge

The first advantage of replacing electrical measuring with optical measuring is that it is intrinsically safe: there is no risk of explosion as a result of sparks (relevant in, for example, the offshore extraction of oil and gas). Above all, there is no problem with electromagnetic compatibility. Furthermore, multiplexing is easy using optical techniques. In principle, one glass fibre can be used to carry out 128 measurements. Conventionally, this would require 128 strain gauges with four wires each, in other words, a complete cable tree. Strain gauges have a range of up to 100 Hz; above this threshold, the adhesive layer between the strain gauge and the object being measured will wrinkle. The optical strain gauge can measure at frequencies up to 20-80 kHz, which means that the measurement capabilities are not restricted to slow variations due to, for example, temperature swings. Acoustic vibrations, those found for example under water (whales, submarines) or used in MRI machines to communicate with patients because normal electric microphones do not work, are also within range. In the future, tsunami warnings will come from a sensor network based on fibre optics. Because of its high sample frequency, a FBG system is pre-eminently suitable for studying the dynamic behaviour of motion control systems such as stages or air bearings

It is possible to conduct measurements from a distance of up to 10-20 km without significant power – and therefore signal – loss. If measurements need to be conducted from a larger distance, there is always the possibility of boosting the signal by optical amplification. Finally, there is redundancy. If there is a single break in the cable, measurements can still be taken up to the fracture point or even on both sides of the fracture (i.e. the whole cable) if the cable runs in a loop.

Principle

The principle of Fibre Bragg Grating is shown in Figure 3. Broadband light (typically $\Delta\lambda = 40 \sim 80$ nm) enters the optical fibre. In a number of places, a grating is applied, a longitudinal periodic variation in the refractive index of the core of the fibre. Each grating has a unique spacing that determines the wavelength to be reflected by the grating, which can then be detected at the end of the fibre where measurements are taken. Thermal or mechanical stresses cause strain variations in the fibre; the variations cause a varying period and with that a variation in the reflected wavelength. The principle is based on the Bragg condition, which is calculated from both energy and momentum conservation:

$$\lambda_B = 2L\, n_{eff}$$

in which L is the period of the grating and n_{eff} is the effective refractive index. The measured wavelength varies linearly with temperature and/or strain. By giving each grating its own period and thereby a unique reflection wavelength, every measuring point on the fibre can be distinguished in the detection process. This is one of the properties that make multiplexing simple.

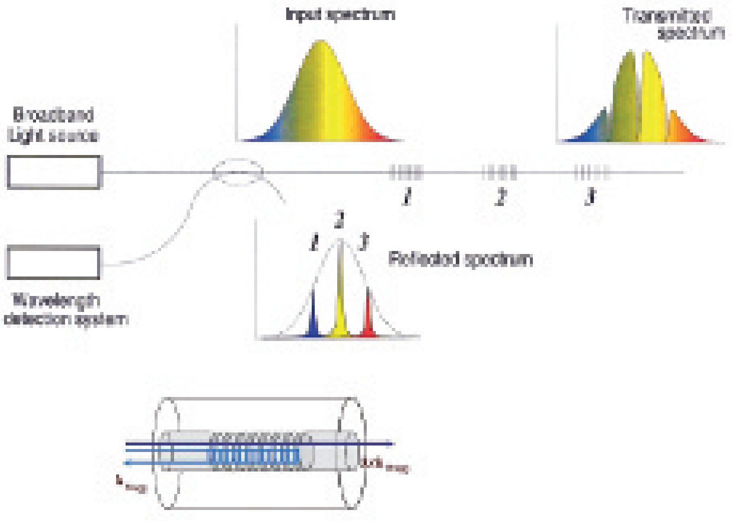

Figure 3. The principle of Fibre Bragg Grating. Specific wavelengths (1, 2 and 3) are reflected by different gratings. Below is shown how the wavelength that meets the Bragg condition is reflected and how other wavelengths pass through a grating.

Detection

The exiting reflected bundle is a compound of the reflections from FBGs in the fibre. Because each reflection has its own wavelength (colour), the signals can be resolved by means of a reflection grating; see Figure 4. This reflection grating spatially resolves the signals and projects them onto a CCD array of 256 pixels. Each signal is a spot which falls onto two adjacent pixels, that form a duo-detection cell, as it were. The exact position of the spot can be determined with a resolution of 50 nm through the relative signals of the two pixels. This corresponds to 2 pm wavelength resolution. The shift of a spot on the two pixels is a measure for the induced strain on the corresponding FBG. The high bandwidth of the system, i.e. a high sample frequency for the read out of the CCD array and the subsequent calculation of a measurement value, is the result of a 'trick': only the bits/pixels that catch the light of a spot are measured after initialisation. Because of the high frequency, it is impossible to 'lose' a spot between two samples
In order to be able to resolve the spots on the array, a difference in wavelength (read difference in period) of 4 nm is maintained between successive FBGs. This is a trade-off between the number of sensors, or FBGs, and the movement of the signal on the array (measuring range). The larger the signals to be measured (meaning large position shifts), the further apart the spots have to be (a greater difference in period) and the lesser the number of spots that fit on the array.
If fitted with a memory, the detection system can operate stand-alone. This is used in, amongst other things, crash-test dummies. The data is then downloaded to the 'real world' at a later point in time. In most cases, however, this system will be linked directly to a pc if continuous measurement is required.

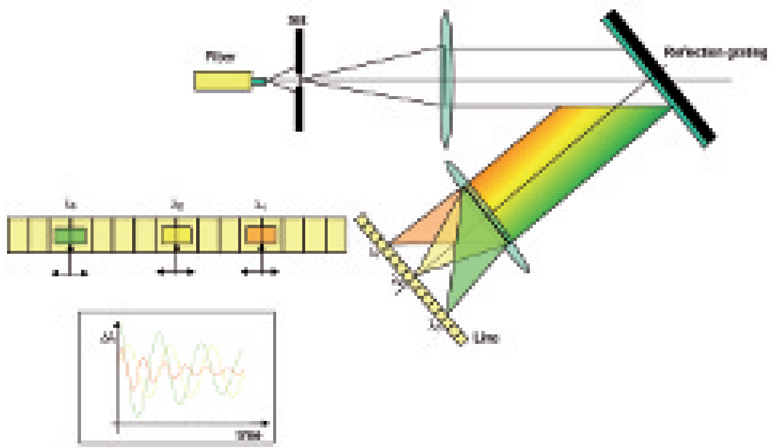

Figure 4. The detection principle, with the beam path drawn in: lenses, grating for resolving the different reflection signals, the CCD array.
On the left spots on the CCD array.

Construction

The greatest challenge when realising a market-ready product, is optimising the design of the construction. The stability, or the insensitivity to external influences, must be great. For crash-test measurements, the system has to be able to withstand up to 200 g. The functional model built by TNO did not have great stability however: a bang, a voice, the air conditioning, everything was reflected in the signal because those disturbances led to small displacements of the optical components.
The final construction cannot be shown in detail. It comes down to, amongst other things, kinematic design, correctly defining the degrees of freedom, maintaining as good a (rotational) symmetry as possible and introducing a thermal centre. As a result of these measures, the stiffness and stability of the construction increases to the point where accelerations of 200 g no longer cause noticeable relative displacements of the optical components.
It is also important to select the proper materials so that the expansion coefficients match, and to cleverly use thin plate materials. On the one hand this ensures a high stiffness of the base structure (the inner casing) while on the other it offers the possibility to compensate for expansion differences between the built-in components perpendicularly to the plate surface. The concept is derived from the ideas of prof. ing. W. van der Hoek, who, between 1962 and 1984, laid the foundations for the way of thinking as demonstrated in [1].

Stiffness

The detection system itself is housed in a thin-walled box of 25 x 25 x 100 mm^3. This constitutes the base casing fitted tightly around the optics; see Figure 5. This thin-walled casing ensures a high intrinsic stiffness. The maximum load at 200 g is very limited due to the small mass of the optical components. The rectangular base casing only becomes stiff when stiff end pieces are fitted at the ends of the base and define the shape of its cross-section. The construction provides for this by means of stiff optical components which keep the rectangular cross-section of the case in shape. It is necessary to define four degrees of freedom in the circumferential direction of the casing (see [1]). The same applies to the outer casing. A positive aspect is that the rectangular outer casing takes its stiffness from the ends of the base casing (one degree of freedom at one case end) whilst on the other side making use of the four screw connections to the solid world to define the other end. Seven degrees of freedom are required to define the position of the now stiff base casing inside the outer case. Besides, one extra degree of freedom is defined to make the outer casing stiff as a fixed rectangle at one end. Lips that stick through the outer casing transfer the seven defined degrees of freedom between the base casing and the protection casing. In this way, the connection is simple and extra stress being introduced into the base casing is avoided.

Insulation

The optical components sit tightly in the middle of the thin plate surfaces of the casing. The difference in expansion of optical components with respect to the casing leads to parts of the plating being forced a few microns inwards or outwards in places. The middle of the components, however, remains in the middle with respect to the heart of the casing, while the optical components' expansion behaviour only has the effect of pushing the plate walls outwards

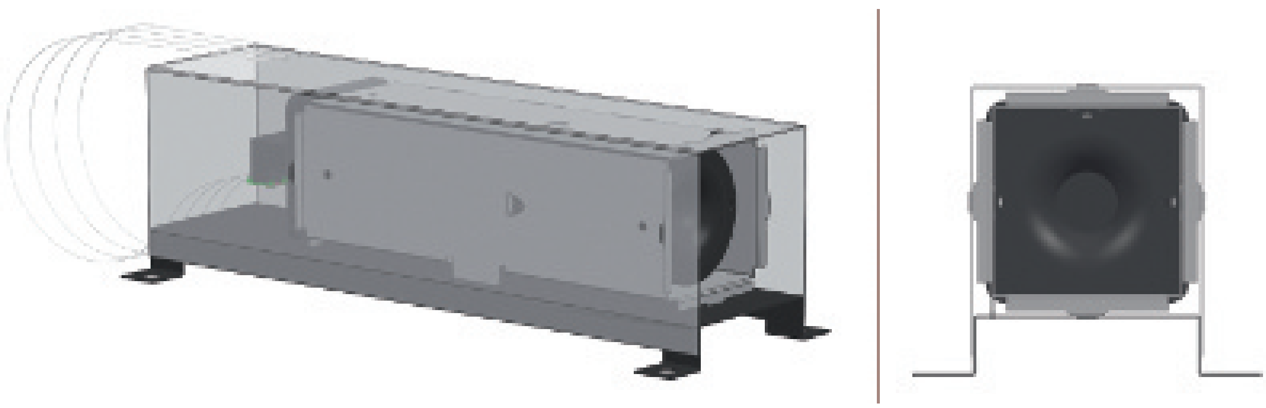

Figure 5. Front and side elevations of the construction.

locally. The optical design has been chosen so that it is not very sensitive to changes in the base casing's length. The second casing that surrounds the base casing will prevent localised thermal radiation from the latter, and because the temperature difference between the two casings is very limited, the heat transfer by radiation will be limited while relatively the conduction is much better. In this way, the outer casing ensures thermal and mechanical insulation of the base casing, as well as containment of the base casing and provision of pull relief for the fibres. Moreover, this casing prevents undesirable external forces from directly affecting the base casing.

Joining techniques

Spot welding of the plating is used as the main joining technique. A hysteresis-free technique is especially important for the sensitive base casing; [1]. After all, permanent deformation as a result of acceleration forces caused by drops or jolts must be avoided. Spot welds appear to show much less hysteresis than bolts or staples.
The glass components are glued into the casing. The shrinkage of the glue creates a slight pre-stressing of the glass components against small bumps in the casing wall.
The introduction of forces into the base casing plating has been carefully constructed [1], in order to maintain a sufficiently high level of suspension stiffness. If forces are not neatly introduced into the plating, it will quickly result in a lower level of stiffness. After all, the plating surfaces easily are subject to moments out of the plane and these result in a major distortion of thin plating.
Of course, a number of measures have been incorporated into the design to keep 'false light' out of the system. Enclosing the optics in a casing is also helpful in this respect.

Business

In autumn last year, a prototype of Deminsys was realised and Technobis is now building the systems; no high technology is involved in this production. Figure 6 shows the final system. In the meantime, the first orders have come in. If interest proves to be overwhelming, Technobis will find a solution in the form of production elsewhere. TNO and Technobis have signed a licensing agreement concerning Technobis' application of TNO's knowledge. TNO will invest proceeds generated by this agreement into new research into optical sensing technology in order to be able to answer, amongst other things, additional questions from Technobis and/or their customers.

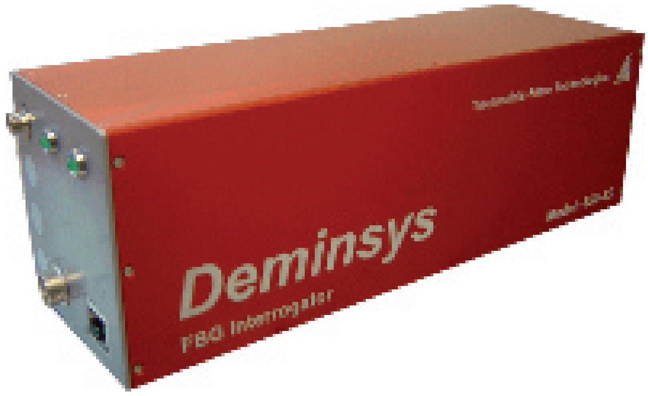

Figure 6. The world's first high-speed FBG Interrogator, having a sample frequency of 19,3 kHz and a total of 32 sensors.

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[1] M.P. Koster, *Constructieprincipes voor het nauwkeurig bewegen en positioneren* (in Dutch), edition 2005, ISBN 90-78249-01-3. Publisher PrintPartners Ipskamp, Enschede, the Netherlands. Specifically V1.3.10 and V6.3.

Information

www.technobis.nl
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