Low-cost fiber-optic strain sensor for structural monitoring

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A new polymer-based device possesses all the advantages of standard optical fiber strain sensors and is also rugged, easy to handle, and much less expensive.

The trend toward building ever larger structures from lightweight materials is driving a growing need to constantly monitor the forces experienced by these structures. This online monitoring is required not only for bridges and roof constructions but increasingly also for the rotor blades of helicopters and wind power generators, and the wings of planes. In most cases, strain gauges are used to monitor these forces. Traditional strain gauges produce a change in electrical resistance when stretched. The newer optical varieties include the so-called fiber Bragg grating (FBG) sensors, which comprise an optical fiber with diffraction gratings incorporated into its core. Stretching these optical fibers affects the passage of light through them. Electrical strain gauges suffer from sensitivity to electromagnetic interference, whereas FBG sensors do not. FBG sensors also have excellent sensitivity and versatility, though they are comparatively expensive and not very mechanically robust. There is thus a general need for less expensive optical sensors for strain monitoring.

We have recently developed just such a sensor. It is based on a polymer optical fiber (POF), which is much more rugged than FBG sensors and extremely easy to handle. Typically, this kind of fiber is made out of acrylic glass and has a diameter of 1mm. The sensor system described here works on the basis of the well-known principle of phase shift,\textsuperscript{1,2} which occurs when two sinusoidally modulated signals take different amounts of time to travel through the same optical fiber (see Figure 1). In this case, the phase shift is caused by the optical fiber being stretched and is measured by an electronic phase-shift detector. Figure 2 shows a schematic of the complete system. The system also includes a reference optical fiber to help compensate for any thermal expansion. This reference fiber is mounted such that it does not experience the stretching force, but is exposed to the same temperature as the measurement POF.

We conducted a first test using a 1m-long POF that was stretched to various lengths at a range of modulation frequencies. Figure 3 shows the results for a modulation frequency of 2.2GHz and step changes in the fiber length of 50µm. The steps can be seen very clearly. Indeed, using these parameters and configuration, step changes in length of only 10µm can easily be detected. In a second test, two fiber loops 1m long were glued to a 10mm-thick wooden board (see Figure 4). We then fixed this board on one side and bent the opposite side down by 10mm. This downward deflection caused the upper side of the fiber loop to stretch and the lower side to compress. If the characteristics of the phase-shift detector are known, one can easily cal-
To calculate the phase difference from the output voltage, based on the modulation frequency and the propagation speed of the light along the optical fiber, the length change can then be determined. The measurement results are shown in Figure 5.

In addition to these tests, we have used this system to measure the strains on a real rotor blade to show its potential for online measurements. We have also written software to display the output voltage of the phase-shift detector on a PC monitor (see Figure 6). Furthermore, to check the functional capability of our temperature compensation approach, we tested the reference fiber in a climate chamber. We first put the measurement fiber in the chamber on its own. As expected, the temperature in the climate chamber had a strong influence on the output signal (see Figure 7). We then added the reference fiber to the chamber and found that it was able to compensate for the effects of temperatures between −20 and 60°C (see Figure 8).

We have made a very promising first step toward developing a fiber-optic sensor that is able to measure length changes down to the micron level. Our POF is able to combine all the benefits of fiber-optic sensors, such as immunity to electromagnetic interference, with robustness, ease of handling, and a huge potential for much lower production costs. With this sensor, strain monitoring in structures such as the rotor blades of wind power generators should become much more affordable.

Next steps include gaining experience with the setup by installing the sensor in test facilities parallel to other sensors, for

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example, in a 40m-long wind turbine blade, the roof of an ice hockey gymnasium, and possibly an experimental bridge made out of fiber-reinforced material. We will work on improving the electronics by using modulation schemes that are more sophisticated than primitive sinusoidal approaches. Examples include switching between frequencies or using bit patterns based on sequences of pulses that optimize the range and resolution of measurements. Finally, we aim to enhance the baseline stability with an additional reference.

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After several years working in industry on fiber-optic sensors, Hans Poisel joined the Ohm University of Applied Sciences in Nuremberg as a lecturer in applied photonics. In 2000, he founded the POF-AC and remains its director.

References