Optical-fiber sensor networks in smart structures

Horst Baier, Uwe C. Mueller, and Stephan Rapp

Sensors not only monitor the health of a structure, but also provide feedback for adaptive systems that can actively respond to physical deformation.

Monitoring structures with embedded fiber-optic sensors (FOS) has found use in various applications, ranging from cryogenic fusion energy experiments over rotor blades of wind turbines to airplane and spacecraft structures. Such monitoring has multiple objectives, which include: observing manufacturing processes, especially curing (cross-linking of polymer chains) in fiber composite materials; structural testing prior to operation; or monitoring structural health and conditions during operation.

Intrinsic sensing techniques such as those that use fiber Bragg gratings (FBGs) allow the strain and temperature at many points along a single optical fiber to be measured, opening up the possibility of extensive FOS networks. Via proper transfer matrices, these networks produce measured discrete values that can be mapped into more-or-less continuously-represented displacement or temperature fields.

However, in order to make use of FOS networks in components and structural systems, a range of factors have to be taken into consideration. These include: whether the FOS are attached on or integrated into the component parts of the structure; the behavior of the full measurement chain; and data processing and evaluation, especially in the case of determining displacement or temperature fields from a finite set of discrete measurements.

Studies have shown that integrating FOS into fiber composite materials, such as wind turbine rotor blades, gives even more precise and reliable data than surface-bonded FOS. For sandwich-type structures, the FOS can be included at the interface between the face sheet and the core (see Figure 1).

Any time delay is usually of minor concern for structural health monitoring. But together with high acquisition frequency, this time delay becomes relevant when FOS is used to provide feedback signals in the control loops of adaptive systems. To overcome this problem a multi-channel processing system has been developed that uses a position-sensitive detector to interrogate different wavelengths. This leads to significant reductions in the time delay and a large bandwidth of up to several hundred kilohertz.

We have demonstrated the promise of this multi-channel processing system by applying it to a space telescope containing primary and secondary mirrors, with the latter supported by a tripod structure (see Figure 2). To determine thermal strains and deformations of the tripod, the FOS are integrated into the tripod’s carbon fiber reinforced plastic struts, as shown in Figure 3.

The FOS data provides a feedback control to compensate for any thermo-elastic deformation via piezo-actuators integrated into the struts. For the optical mirrors, measured strain data is used to determine quasi-continuous displacement fields, which are utilized for opto-mechanical data processing and mirror shape control. Required transfer matrices from strain to displacement vectors are established via modal data, Krylov

Figure 1. 3D model of a fiber-optic temperature sensor integrated between the face sheet and core of a sandwich panel.
vectors, and finite element (FE) displacement vectors. With certain filters, this procedure can also be used to recover lower vibration modes. Careful sensor and actuator positioning can limit the number of required sensors.2

Other potential applications for FOS networks include measuring temperatures in tank or satellite panel structures. This temperature information might then be used for the thermal control (see Figure 4).

Once attached to or integrated into structures, FOS can be employed from the manufacturing and testing phase through to operational conditioning and structural health monitoring in a wide range of terrestrial and aerospace applications. The collected signals can be used for structural health and condition monitoring, as well as to provide feedback signals for curing, vibration, or thermal control. Due to the relatively dense population of sensors that can be realized using FBGs, it is even possible to estimate deformation fields using collected strain data. This deformation information might allow structural shape control of airplane wings and control surfaces or of space reflectors.

Work still has to be done to further consolidate FOS performance and integration, as well as to improve data processing and interpretation for even better reliability, especially in health monitoring.

Author Information

Horst Baier, Uwe C. Mueller, and Stephan Rapp
Institute of Lightweight Structures
Technische Universität München
Munich, Bavaria, Germany

References

Figure 2. The tripod structure of a space telescope.

Figure 3. Integrated FOS in a fiber composite strut of the space telescope in Figure 2.

Figure 4. Fiber-optic temperature sensor network for the thermal control of structures.