Distributed measurements unlock the future of design

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The next generations of materials and design will require sensing technologies that can monitor beyond the scope of point sensors such as thermocouples and strain gauges. New sensing platforms based on optical fibers can obtain spatially continuous, real time data, giving developers detailed insight across broad areas into how their materials and designs behave. Such systems also can sense multiple parameters simultaneously, offering easier installation with a single platform.

For decades, point sensing solutions like strain gauges and thermocouples have been good enough for most applications of thermomechanical measurement. However, the mindset of ‘good enough’ often blocks innovation, especially in the use of new materials and new design approaches. The limitations of point sensors are not about accuracy or reliability, however. Rather it is about insight. Many organizations have innovated beyond their ability to test and monitor their designs using point sensors.

Take for example the proliferation of composite materials in the aerospace and automotive industries. Designing with new materials creates a number of design challenges and legacy technologies cannot always provide the data necessary to efficiently understand how composite components and assemblies behave under real world conditions. Strain gauges cannot collect data about how forces are distributed throughout a structure; they only give information about specific areas. The same is true of thermocouples. Increasing the number of points sensed adds cost and complexity to the test effort and can quickly become impractical.

In contrast, fiber optic sensing systems can obtain spatially continuous data (distributed data) and are able to monitor full strain fields and temperature gradients with a single sensor. By monitoring both critical points and everywhere in between, distributed strain and temperature measurements give engineers unprecedented insight into the behaviors of their designs that legacy technologies simply cannot accomplish.

Fiber optic sensing basics
Navigating the fiber optic sensing technology landscape can be intimidating since there is such great diversity of capabilities within the industry. In order to properly discuss distributed fiber optic sensing it is important to understand, at a high level, the distinctions between technologies. (For a more in depth discussion of the fiber optic sensing landscape, see the article [Look Inside Fiber Optic Sensing](http://www.csrengineers.com/strain-gage-testing/).)

Fiber optic sensors can be divided into two types: extrinsic and intrinsic. With extrinsic sensors, the light leaves the fiber and gets modulated in a medium. With intrinsic fiber optic sensing technology, the light is kept within the waveguide and the fiber optic cable itself is the sensor. Light returning from a signal sent down the fiber provides information about conditions along the fiber.

Within the division of intrinsic fiber optic sensors, there are, generally speaking, three generations of technologies: scattering based sensors, point fiber Bragg grating (FBG) based sensors, and spatially continuous FBG-based sensors. In these systems, light returning from a signal sent down the fiber provides information about conditions around the fiber. The measurement system recognizes changes in the returning signal and interprets them as strain and temperature readings.

Scattering techniques depend on imperfections in the fiber optic cable to generate the return signal. There are three different types of scattering technologies used in sensing systems today and each has different capabilities. Generally speaking, scattering based fiber optic sensing systems benefit from distributed data and long sensing lengths. They are, however, subject to low data fidelity, very slow data acquisition rates on the order of minutes, and are susceptible to vibration, limiting them to static environments.

Point FBG sensors use gratings that are manufactured into the fiber's core at a series of points along the fiber's length. These gratings act as miniscule mirrors, so as light travels down the fiber, each grating reflects a portion of the signal back to the system. Some strengths of point FBG sensors include precision, the ability to perform dynamic tests, and high-speed data acquisition. However, the approach cannot provide the sensor density required for monitoring continuous distributions. Most FBG based systems have only a handful of sensing points along each fiber.

Some fiber optic sensors using FBGs as the sensing element in the fiber, however, inscribe them continuously along the fiber's entire length. This continuous grating, along with the technique used to interpret the signal, enables these platforms to take spatially continuous data while retaining the precision, dynamic testing, and high acquisition rates afforded by using FBGs. This spatial continuity allows engineers to obtain precise measurements of full strain fields, temperature gradients, and other parameters in either static or dynamic environments. Using the distributed strain data provided by the fiber, engineers can also measure such things as internal and applied loads, deflection, 3D shape, and liquid level.

**Benefits of distributed data**
Validate models -- One of the core benefits of distributed strain and temperature data is that with the data engineers can more efficiently and confidently validate their FEA and thermal models. By monitoring full strain fields, such sensing systems are able to determine how loads are distributed throughout a structure. This information can help engineers refine their models to avoid costly failures later in the development process or after the product has launched.

As a concrete example, NASA Armstrong used fiber optic sensing for a variety of tests during the Adaptive Compliant Trailing Edge project. The project, in conjunction with FlexSys and the US Air Force Research Laboratory, was aimed at developing and validating a design to replace traditional wing flaps with malleable monolithic structures that can change shape while maintaining a smooth surface. These new wings are estimated to reduce drag by 3-4 percent and when installed on an aircraft, could save an estimated 12 percent in fuel costs and reduce noise by 4-6 decibels.

The first step to realizing a commercially available adaptive wing is by gaining an understanding of how the structure behaves in flight. NASA engineers used a fiber optic sensing platform to provide real time strain data and information about how loads were redistributed throughout the wing during flight. In addition to using the strain and load data to validate the FEA model, this data can then be fed into a flight control feedback system so that the control system can optimize the shape of the flap in real time in order to optimize efficiency. As a result, fuel consumption and the overall operating cost of the aircraft can both be reduced.

Improving process and accelerating development

In the automotive industry, organizations are implementing distributed fiber optic sensing technology to validate thermal models for various critical components, routing fiber around the engine block, battery, radiator, and exhaust system. With temperature ranges from cryogenic temperatures up to 400 degrees Celsius, fiber optic systems offer the greatest range and flexibility of any sensing technology on the market.

Improve processes -- Distributed fiber optic sensing has also been used to conduct tests in conditions where other sensors cannot operate. For example, the fiber, which is itself the sensor, has been embedded in a composite structure during the layup process. As a result of monitoring residual strain throughout the entire component, the fiber optic sensing system detected the presence of defects caused by objects that were accidentally embedded in the material. Strain gauges would not have detected the foreign objects unless the gauges happened to be placed directly above the defect. In addition to helping the engineers validate their structural models for the composite part, the data from the sensor helped them improve the manufacturing process of the composite materials.

Fiber optic sensing technology can also be used to create thermal profiles of molds during the injection molding process or dies during die-casting. Having distributed temperature data helps manufacturers understand how their molds and casts perform under different conditions and can allow them to improve their processes to avoid defects like blistering, flow lines, stringing, warping and more.

Ensure the safety of structures -- One challenge facing Structural Health Monitoring (SHM) systems today is a lack of fine spatial resolution from sensors. Some fiber optic sensing systems help overcome this challenge by providing spatial resolution on the order of millimeters. The distributed data provided by these systems as well as their real time monitoring capabilities provide a continuous monitoring solution for SHM using global vibration information.

As an example, using strain data from a fiber optics sensing platform and Ensyso’s nondestructive damage evaluation software yielded a continuous health monitoring system that detects, localizes,
and characterizes damage to a structure. Rather than using point sensors like accelerometers or vibration wire strain gauges that only collect points of information, asset management organizations can deploy fiber optic sensing to ensure that their infrastructure is structurally sound.

**Figure 2** The top image shows the distributed strain data from a demonstration beam instrumented with approximately 10 m of fiber. The spike inside the red circle corresponds to a strain concentration around a crack in the beam. The bottom image is a diagram, illustrating in blue, the sensing fiber layout on the beam.

**Accelerate development** -- Model validation and improving processes both contribute to accelerating development, but the ability to monitor multiple parameters at the same time can significantly speed up the development process. Existing data acquisition hardware is capable of supporting multiple sensor types, however, the weight of the cables and tedious installation of sensors make legacy solutions cumbersome to deploy in multiple kinds of tests. Fiber optic technologies can provide a multi-sensing platform.

Multi-sensing platforms, simply put, are sensor technologies that can monitor multiple parameters (strain, temperature, deflection, etc.) simultaneously. It’s not just about being able to monitor different parameters using the same data acquisition hardware. More than that, a multi-sensing platform can consolidate sensing technology so the same hardware, with minor changes in application techniques and sensor packaging, can adapt to cover multiple testing and monitoring needs of an organization. In order to accomplish this, a sensing platform must be able to do more than just sensing more than one parameter. The sensing system must obtain spatially continuous information in real time, be capable of taking dynamic measurements, be able to easily integrate with a network, and must perform well in the lab or harsh environments. These features allow multi-sensing platforms to be deployed in lifecycle monitoring applications from design validation to providing operational data for critical components and equipment.

One organization, for instance, uses fiber optic sensing technology to validate the performance of a monitoring system that will be deployed in harsh environments. Due to the flexibility and ease of deployment of the multi-sensing platform, the customer was able to conduct validation tests at a much more rapid pace than if they had used legacy sensing technologies. The increased rate of
testing coupled with the distributed strain and temperature data provided by the system enabled the project to be completed an estimated two years earlier than if the test had been conducted with point sensing technologies.

Armed with distributed strain and temperature data, engineers can better validate their models, improve processes, ensure the safety of structures, and accelerate development. With the pace of technology advancement accelerating, many organizations discover that they have innovated beyond their ability to test with legacy technologies. New technologies, like fiber optic sensing, that obtain spatially continuous measurements offer one solution to overcome the testing and monitoring hurdles organizations face today.

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