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Fiber Optic Sensors In Aircraft Manufacturing

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Fiber Optic Sensors In Aircraft Manufacturing

Fiber Bragg gratings increase the reliability of future Airbus generations

(Bob Grietens, XenICs, Leuven, Belgium and
Marc Voet, FOS&S, Geel, Belgium)

New fiber reinforced composite materials and integrated sensors are converging to form smart structural components. They excel by their higher reliability, lead to more economical maintenance procedures and contribute significantly to reducing the cost of operating air fleets.

The economics of aircraft operation

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Advanced aircraft construction and design tends to be guided ever stronger by the expected cost of flight operation. Accordingly, the development objective of new ultra-wide body Airbus planes was not just increased passenger payloads but also a reduction of the plane's specific operating cost per person and miles traveled. Compared to other modern passenger planes, these costs were to be lowered by 15 %. To reach this ambitious goal, the weight of the plane had to be minimized – of course without compromising its safety and reliability.

Such a design objective is feasible primarily through large-scale utilization of plastics and sandwich construction as well as novel composite materials: up to 40 % of all structural components of modern Airbus types are made of CFRP (carbon fiber reinforced plastic) and GLARE (glass fiber reinforced aluminum), a combination of materials structured as multiple layers of aluminum and glass fiber reinforced plastic just tens of a millimeter thick which are bonded together under pressure (Figure 1).

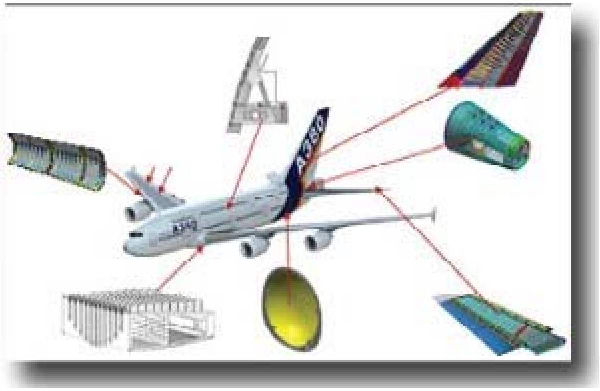


Figure 1:
Advanced aircraft are more and more built of fiber composite materials.

Source: http://www.unistuttgart.de/aktuelles/science/2004/02/text.html

Since fiber reinforced composite materials are up to 25 % lighter than aluminum, the current standard material for aircraft construction, their usage saves a considerable amount of weight. In the end this yields higher payloads. Yet beyond saving on weight there is another significant advantage that the new fiber composite materials contribute: increased reliability. Take GLARE: It definitely performs better in terms of crack prevention, because any developing cracks are "bridged" by glass fiber layers so that crack velocity decreases with crack length. This is in contrast to aluminum structures, in which crack velocity significantly increases with length.

The economics of maintenance

Besides the structural measures described above, it is regular maintenance work that contributes considerably to flight safety and reliability. Up to now it was a mandatory maintenance procedure to dismantle an airplane's safety-critical parts, check them, then reassemble or replace them. These are procedures that add heavily to an air fleet's cost of ownership. It would be much better to gather the internal condition of important structural elements continually, in-flight, and then, if necessary, take timely and appropriate preventive measures. This would ensure highest reliability at minimum cost.

To this purpose, two Belgian-based high-tech firms, FOS&S and XenICs, have jointly developed a novel IFSA (In-Flight Aircraft Structural Analysis) system which continuously monitors the internal health of important structural elements in a modern airframe. For those critical parts, the system acquires the actual distribution of mechanical tension and compression as well as temperature data – statically and dynamically - and the structure's reactions to the prevailing loads. Any reaction exceeding the permitted variance (such as excessive vibrations and internal damage due to crack forming) is recognized so that appropriate countermeasures can be taken right away.

This way, the IFSA system can lower the flight operator's cost of ownership by reducing the maintenance budget of a commercial air fleet, and so extend the usability of airframe structures beyond their projected life cycles, which in most cases include a large safety margin.

Fatigue test serving as a model

The fatigue test performed in Dresden on a modern Airbus type can serve as a model for such a novel monitoring concept. Between September 2005 and November 2007, this test will simulate a total of 47,500 flights. The results, together with FEM analyses performed during the plane's development, will determine the conditions for in-flight monitoring of specific critical components and problem zones. This, in turn, will enable the placement of monitoring sensors exactly where early indications of excessive wear and tear are to be expected. However, the measurement technology currently deployed at Dresden is not quite appropriate for regular flight operations: it is much too heavy and voluminous for this purpose, making it virtually impossible to embed its wiring harness inside the structures to be tested. Here, novel measurement methodologies and architectures are required.

Fiber optic sensors

It is quite obvious that fiber-based sensors and sensor arrays are a good choice to monitor fiber composites. Fiber optic sensors, in contrast to traditional electrical sensors, offer significant advantages which suit them for component monitoring in vehicles of all types:

. They are robust and corrosion-free passive components, and excel by a high life expectancy of more than 20 years.
. Their measurement function is based on a special location-based property of glass fibers, which enables signal transmission over more than a several kilometers.
. Fiber optic sensors are not impacted by electromagnetic radiation. They function under extremely harsh usage conditions, which regular sensors would not survive.
. Neither sensor function nor data transmission require electrical signals or metallic conductors. They are intrinsically safe and suited for EX applications.
. Multiple fiber optic sensors can be operated within one fiber as a multiplex configuration.
. They can be made thinner than a human hair and thus functionally embedded in multi-layer

structures (Figure 2).
. Light as a feather, they enable very flexible sensor arrays for monitoring large surfaces.

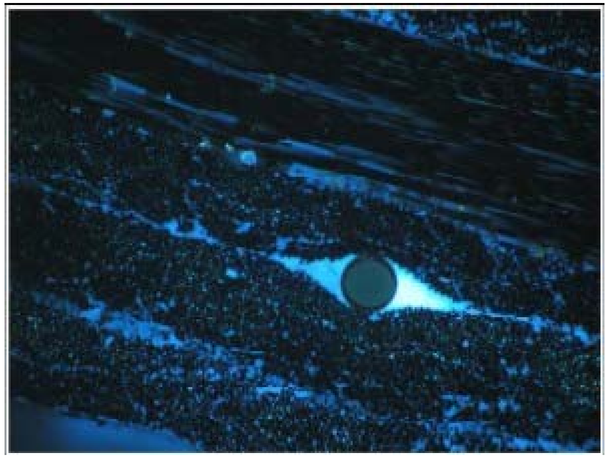


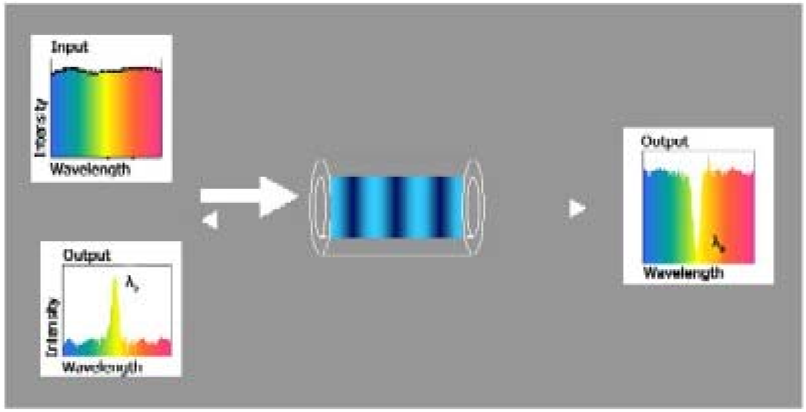
Figure 2:
Optical fiber embedded in an 8-ply carbon-epoxy laminate
(Courtesy of Ghent University)

Fiber Bragg grating as a sensor base

Among the currently most important fiber optic sensors are fiber Bragg gratings. They have a refraction index that periodically varies over a certain fiber length. Bragg gratings are made by exposing a fiber to UV light through a micro-lithographic mask that carries a specific bar pattern: the UV-exposed areas show a lowered refraction index, while unexposed areas retain the fiber's original refraction index. Thus, within the fiber core, multiple areas with lower index are followed periodically by ones with higher index. Any light coupled into the fiber is partly reflected at each of those boundaries. The reflected waves superimpose each other. At a certain wavelength, called Bragg wavelength and dependent on grid period as well as refraction index, all of them are in sync and therefore get amplified.

This effect, called Bragg condition, is shown in Figure 3. At the Bragg wavelength, the reflected spectrum is at a maximum, whereas, in the transmission spectrum, it disappears. Since the grid can be made with high precision and repeatability and, most importantly, it doesn't change over time, this enables the production of sensors which show no offset or zero-point drift.

Figure 3: The principle of a fiber Bragg grating.



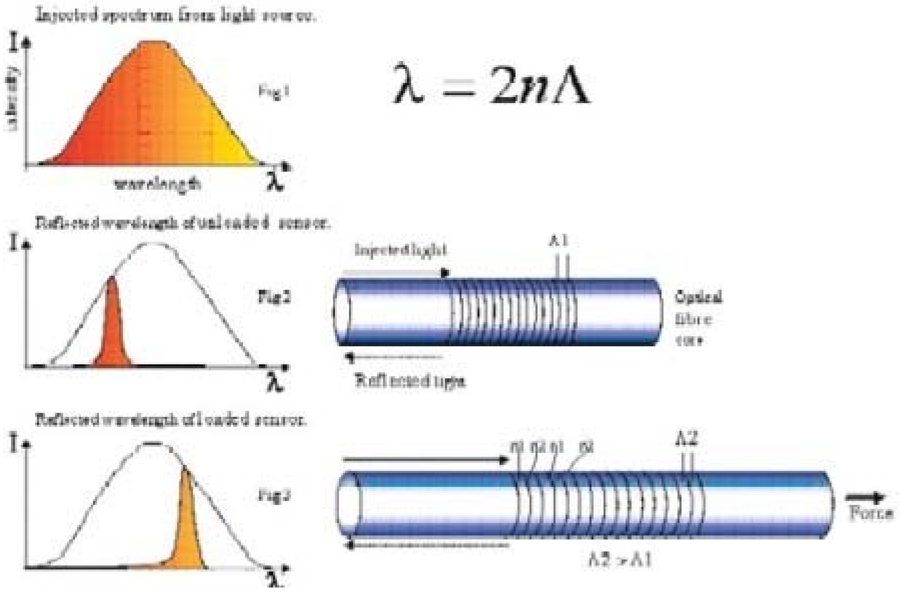
Fiber Bragg gratings function as sensors

Fiber Bragg gratings can be used for sensor functions in two different ways: reflection or transmission modes. Reflection mode, among others, has the advantage that the fiber must be accessible only from one end, where it is illuminated by a sufficiently broad-band, near-infrared light source (Figure 4), usually in the C- (1530 to 1570 nm) and L- (1570 to 1610 nm) bands, or a combination of both. The medium wavelength of the reflected component according to the Bragg condition is

$$\lambda Refl = 2 n \Lambda$$

with n being the refraction index, and Λ the grid period. Since both these values are a function of temperature and tension force acting on the fiber, the wavelength of the reflected light will vary in accordance with its temperature and/or elongation. As shown in Figure 4, a tension force will enlarge the grid period Λ and thereby shift the reflected radiation maximum towards larger wavelengths. Since the dependency of refraction index and grid period on both temperature and force are exactly known, either temperature or elongation can be determined through measuring the wavelength of the reflected light. Typical temperature sensitivity is
$d\lambda/dT \sim 12$ pm/K, and elongation sensitivity is
$d\lambda/(dL/L) \sim 1{,}2$ pm/(µm/m).

Figure 4:
Elongating the fiber shifts the Bragg wavelength – which is used as sensor function.



Wavelength multiplexing for sensor chains and arrays

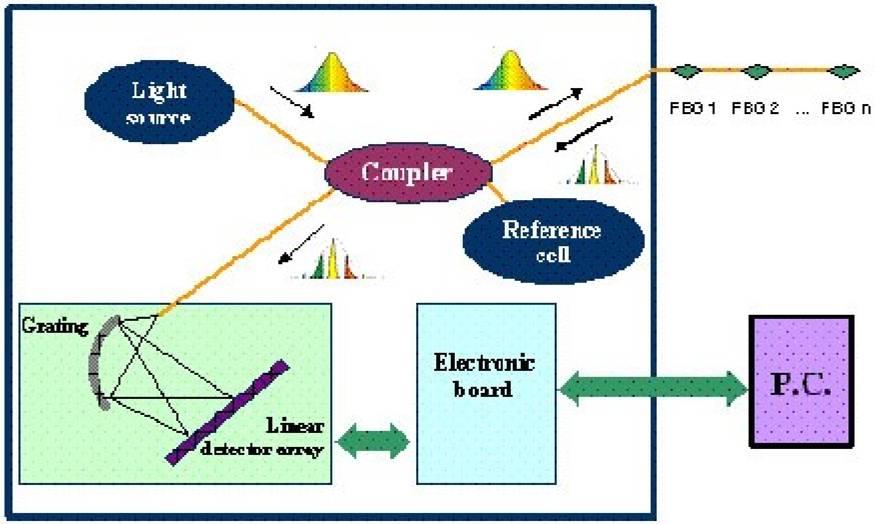
Since fiber Bragg gratings appear transparent to other wavelengths outside their own Bragg condition, it is feasible to establish fiber Bragg gratings with different Bragg wavelengths at several locations along a fiber. Without any wiring harness, just by the common fiber, they are connected to the system's measuring unit. There they are separated by wavelength demultiplexing and independently processed. This way, sensor chains can be realized, which serve as a sensor line, for example in the longitudinal expansion of an aircraft wing. Likewise, by forming meander patterns, sensor chains can cover an entire surface with a sensor array.

Evaluation of sensor data

For the utilization of these novel sensor designs it is crucial to have application-friendly measurement methods and appropriate equipment on hand. Figure 5 shows the DynoSense 300 evaluation unit jointly developed by FOS&S and XenICs as a block diagram: the energy of a broad-band light source is fed to the sensor fiber via an optical 2 x 2-coupler. The coupler takes the reflected light to a poly-chromator, which projects, through its concave mirror, the received spectrum onto a highly sensitive line sensor. This sensor is from XenICs, Europe’s leading developer of innovative infrared image sensors.

It enabled the wavelength resolution of the measuring range to be refined from 1520 – 1580 nm to below 1 pm. Thanks to this high precision, DynoSense 300 can monitor up to 40 sensors on one fiber: a good prerequisite for two-dimensional sensor arrays for close-meshed monitoring of expanded structures in aircraft. A further advantage in this respect is the flexibility of the infrared detectors from XenICs: With the DynoSense 300, for example, the dynamic range of the sensor can be optimally adjusted to the measured light intensity by controlling the integration time.

Figure 5:
A high-resolution IR-spectrometer in the DynoSense System of FOS&S and XenICs measures spectrum shift and, thereby, tension and compression forces at several measurement points.



The unit's three operational modes cover wide applications: in wavelength mode, it acquires the sensors' wavelengths as a function of time, at a scan rate of 3.3 kHz. This lets it safely detect higher-frequency mechanical vibrations. Second, in spectral mode, the entire optical spectrum is visualized – which is especially valuable in a self test of the sensor network. Third, in FFT mode, the unit performs a Fast Fourier Transform of the acquired wavelength signals – which greatly expands the system's diagnostic functionality.

Outlook

In a close cooperation between FOS&S and XenICs, the ground was laid out for fiber-optic sensor systems to monitor structural elements made of fiber composites used in aircraft building. The work of integrating the sensors in carbon-reinforced materials is done together with the Netherlands-based materials manufacturer Ten Cate Advanced Composites. Another cooperative with Netherlands-based Stork Fokker as the structural designer will lead to a novel front-edge design for airplane wings yielding improved flight properties and higher reliability.

Reference: Article "High dynamic strain measurements and aliasing suppression capability using a PDA-based spectrometer design," (Fig. 1)

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