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Fiber Optic Sensing: the challenges of miniaturization, ruggedization and integration to enhance flight test instrumentation capabilities

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Abstract

One of the main challenges encountered by flight test instrumentation is to offer the adequate means to deliver accurately the continuously increasing number of data requested by design offices while minimizing the intrusiveness on the test vehicles. This contradictory trend applies to all stages of the instrumentation chain: sensing part, cabling, data acquisition units and communication.

Nowadays, new fiberoptic sensors are gaining ground in various industries due to their unique characteristics. However, their optical interrogation has been very challenging, particularly for the demanding environment in aerospace applications.

To overcome requirements interlinked between performance and miniaturization, a new innovative fiber-integrated approach is presented, with a focus on the reduction and optimization of all necessary materials and components.

This paper aims at highlighting the benefits of Fiber Optic Sensing technology compared to legacy sensing methods as well as sharing an initiative to integrate this technology in an existing compact and modular data acquisition unit compliant with harsh environments

Key words: Instrumentation, Flight Test, Fiber Optic Sensing, Fiber Bragg Grating, Spectrometer, Interrogation system

High-end aerospace instrumentation

In the aerospace domain, instrumentation, telemetry and data processing are key components to support the flight test campaign of a test vehicle whatever the type: civil or military aircrafts, rotorcrafts, UAV, eVTOL, HAPS, space launchers, missiles,…

Safran Data Systems (SDS) aims at developing solutions, such as devices, but also complete turnkey systems, combining high performances (accuracy, synchronization,…), low intrusiveness, ease of use, versatility and high level of reliability and ruggedization against shocks, vibrations, EMI/EMC, temperature, fluids, dust, pressure, vacuum and even radiations for space applications.

The more than 60-year experience of SDS in instrumentation has shown that each test vehicle brings its own unique set of functional and environmental requirements. SDS has developed and maintains a comprehensive toolbox in order to always be able to propose a tailored solution based on COTS bricks. These functional bricks are data acquisition units (DAUs), recorders (airborne & ground), data routers (e.g. Ethernet switches), data links (e.g. short and long distance transmitters, antennas, receivers and transceivers), data processing units, data display units and data replay units,…

Modular data acquisition unit

Whether they are hardware or software based, the functional bricks are most of the time attached to a modular architecture open to the final user. It is especially the case with the XMA data acquisition unit designed by SDS, which has been selected by major aircraft and rotorcraft manufacturers for more than a decade. The modules that compose this device can be of different types:

- Analog acquisition modules: intended to acquire electrical quantities (voltages, currents, charges, resistances, etc.) from sensors measuring different physical phenomena (temperature, acceleration, pressure, mechanical stress, displacement, position, etc…).
- Digital acquisition modules: intended to acquire digital information from sensors integrating signal digitization or from control/command systems and test vehicle avionics. The data can be conveyed under different standards (RS232/422/485, Ethernet, ARINC429, MIL-STD1553,…)
- Video (analog or digital)
- Data Storage
- Data transmission (wired or wireless)
- Customization :
    - In terms of software, by hosting and running user defined algorithms
    - In terms of hardware, by hosting and powering user defined electronics

Fig. 1: Example of XMA modular Data Acquisition Unit with 6 modules and a power supply

Analyzing technological trends and taking into account the news expectations expressed by the flight test community are definitely key factors when managing an instrumentation product line. As such, it appeared natural for SDS to explore the possibility to add Fiber Optic Sensing (FOS) capability to the XMA product. A fruitful teaming with Safran Tech and FiSens paved the way towards this goal and is described here after.

Safran Tech activities – Sensors Research unit

Safran Tech is the corporate Research and Technology center of Safran. It is responsible for developing and building innovative technology bricks for the aeronautics of the future. As part of its activities, S3AR (Safran Sensing Systems Application and Research) focuses on sensing technologies. FOS is part of S3AR activities.

Activities deal with all the building blocks of a fiber optic system. From the sensing element to the interrogation system. As well as methods and means for fiber optic integration.

To characterize these different blocks, tests are carried out in both laboratory conditions (To assess nominal performances) and on test rigs conditions (To get in line with real life applications).

Origins of Fiber Optic Sensing

Fiber optics are well known in the field of telecommunications as they made it possible to reach higher and higher data transmission rates over longer and longer distances.

In parallel, fiber optics found rapidly growing use in the field of sensing for various applications:

- Energy: Oil and Gas, dams, wind energy, nuclear plants…
- Civil engineering: Bridges, structures and tunnels monitoring…
- Transportation: Railway, Aerospatiale…
- Many others such as smart factories, biomedical…

Fiber optic sensing systems play an important role in SHM (Structural Health Monitoring), process control, predictive maintenance and smart structures.

The integration of fiber optic sensing systems in an increasing number of fields is made possible thanks to intrinsic characteristics of fiber optics. These specifications allow fiber optics to reach environments where conventional sensors cannot operate and densify the sensing capacity.

The main advantages of fiber optic sensors are listed below (Non-exhaustive list):

- Reduced weight and size.
- Immunity to Radio Frequency Interference and no emitted Radio Frequency.
- Compatibility with ATEX environments and harsh environments (high temperature and/or irradiated environments).

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- High density of sensing points along the fiber optic and good metrological performances (Precision, sampling rate, measuring range…).
- Plurality of technologies/suppliers as most of the components come from the telecom field.

Fiber Optic sensing Technologies:

Many fiber optic sensing technologies are currently available in the market for industrial applications. Each one having its own pros and cons and its relevance for a given application. Fiber optic sensing technologies share a common architecture. The “brain” of the system is the interrogator, it consists of the active components that generate and collect light and the necessary electronics for data processing and transmission. The interrogator is coupled to the sensing fiber optic which will reach the DUT (Device Under Test).

The schematic architecture of a fiber optic sensing system is shown below:

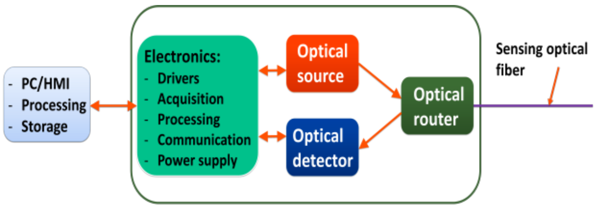

Fig. 2: Block diagram of fiber optic sensor interrogators

FOS technologies can be classified into three main families:

- **Distributed sensing systems**:

These systems allow to measure a high number (up to tens of thousands) of sensing points along the optical fiber. They are based on different backscattered phenomena (Rayleigh, Raman and Brillouin). Both OTDR (Optical Time Domain Reflectometry) and OFDR (Optical Frequency Domain Reflectometry) principles can be used to perform distributed fiber optic sensing. The drawback of these systems is the sampling rate which is quite low (in the order of the second) regarding the massive quantity of processed data.

The distributed sensing systems perform various types of physical measurements such as vibrations measurement using DAS (Distributed Acoustic Sensing) or temperature using DTS (Distributed Temperature Sensing).

- **Quasi-distributed sensing systems:**

These systems allow to measure a moderate number (up to approx. 100) of sensing points along the fiber optic. They are mostly based on FBGs (Fiber Bragg Gratings) which mainly utilize Wavelength Division Multiplexing (WDM).

These systems can reach sampling rates up to tens of kilohertz.

The Quasi-distributed sensing systems perform various types of physical measurements such as temperature, strain and displacement.

- **Point (Punctual) sensing systems:**

These systems allow to measure a single sensing point generally located at the tip of the fiber. They are based on several techniques (Interferometric cavities such as Fabry-Perot, power modulation…). They are often used for dynamic and static pressure measurement. The sampling rate can exceed 100kHz.

Fiber Optic sensing in the field of aeronautics

The field of aeronautics noticed many evolutions throughout the years. Among the evolutions, the number of sensing points inside the aircraft kept increasing in order to ensure reliability, improve safety and optimize performances. The field of aeronautics also noticed an increasing use of composite materials in order to reduce weight and thus consumption. New generations of engines tend to reach higher core temperature in order to increase thrust and optimize efficiency.

These new features benefited from the advantages of fiber optic sensors. A few examples of applications are listed below:

- Multiplexed temperature sensing for fire and overheat detection [1].
- Multiplexed strain sensing for various structural elements (Wings, landing gears, fuselage…) [2].
- Composite material process and lifetime monitoring to assess mechanical properties [3].
- FOD (Foreign Object Detection) in various aeronautical structures [4].

Challenges

Fiber optic sensors technology is already widely used in different fields of application. For the aeronautic field, its use implies to take into account specific challenges related to harsh environments:

- Interrogator: Capacity to be embarked (weight, volume), environmental stress (temperature, vibration, sealing…).
- Reliability: Due to the long lifetime of the devices, strong environmental constraints (thermal cycling…) and metrology (drift, hysteresis…).
- Metrology: Maintain the performance targeted by the application (acquisition frequency, number of sensors and measurement channels, accuracy, noise and stability ...).
- Integration: Ensure the integration of sensors, routing fibers along different paths and in harsh environments (Curvature radius, how to fix fibers, mechanical protection, maintenance…).
- Costs: Systems must be at an affordable price to be considered for deployment on a larger scale.

Focus on Fiber Bragg Grating technology

Fiber Bragg gratings (FBG) are known for more than 40 years [5] and consist in general of periodic changes of the refractive index within an optical waveguide leading to the reflection of a certain wavelength resonant to this refractive index pattern (fig. 3).

Fig. 3: Basic principle of fiber Bragg gratings: a periodic refractive index modification leads to a reflection of a specific resonant wavelength.

Spectroscopic techniques are obviously some of the most common tools to analyze reflected wavelengths of light. However, for about one hundred years the construction of dispersive high-resolution spectrometers has been following the same pattern: light enters the spectrometer through a narrow slit, a mirror or lens is used to collimate the light on a diffractive grating and finally a second imaging optic is used to create the wavelength resolved light distribution on a detector (e.g. [6]).

A precise interrogation of FBG wavelengths by means of a spectrum analysis requires a high optical resolution in the order of 0.1-1.0nm. To date this parameter can only be achieved by extending the overall optical path within a common spectrometer expanding the light cone essentially illuminating more lines or grooves of a diffraction grating. Unfortunately, this leads to bulky, heavy, and expensive devices with low light and energy efficiency.

In [7] and [8] FiSens first presented a fiber-integrated spectrometer which overcomes these limitations.

FiSens is a young company founded by a team of the Fraunhofer Heinrich-Hertz Institute in 2018. For more than 10 years the team has been focusing on the development of a Point-by-Point (PbP) femtosecond laser process for the inscription of FBG and other grating structures within optical fibers.
Utilizing this proprietary process FiSens also creates a precise periodic formation of ellipsoid nanostructures within the core of an optical fiber. By this patented apparatus [8] FiSens can encode all components for optical imaging usually needed for a common spectrometer (slit, lens or mirror, diffraction grating, lens) directly into the core of an optical fiber (Fig. 5). The resulting spectrometer requires only a second component: a detector (e.g., CMOS) to be placed in a lateral focal plane next to the fiber to capture all outcoupled and diffracted light with high intensities.

Fiber-Integrated Spectrometer:

To obtain an actual optical image at a predefined lateral focal distance to an optical fiber it is necessary to chirp the spacings between each point of the fiber-integrated diffraction grating. For instance, for a spectrometer in the visible region the required spacings between the grating points for the most efficient first order diffraction grating is in the range of 0.5µm with a change of the period of only slightly more than 10nm. Therefore, an extremely precise and reproducible setup for the PbP fs-laser inscription is required.
In the example shown below a diffraction grating has been simulated to support the simplest geometry for an actual visible spectrometer: a parallel positioning of detector and fiber and a wavelength sensitivity over the entire visible spectrum between 400 nm and 800 nm.

Figure 4 depicts simulated directions of constructive interference for different wavelengths: the Bragg angles for the first, the last and one pair of neighboring points in the middle of the grating are visualized. Additionally, the resulting focal position for each wavelength is marked. In this case the combined image appears quite symmetrically curved to the waveguide and the overall error for a parallel placed detector is minimized.

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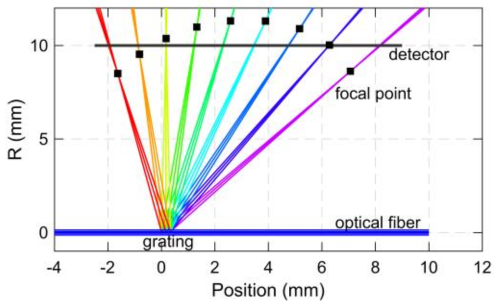

Fig. 4: Simulated directions of constructive interference of two neighboring points at the beginning, the middle and the end of an aspheric chirped grating

Applying the results of these brief simulations a fiber integrated spectrometer for the visible range has been created and no pre- or postprocessing has been performed on a polyimide coated standard single mode fiber.

Fig. 5 shows the fiber-integrated diffraction grating positioned above a simple sheet of paper, first illuminated by a red diode laser of 650 nm (a) and afterwards by a white light LED (b).

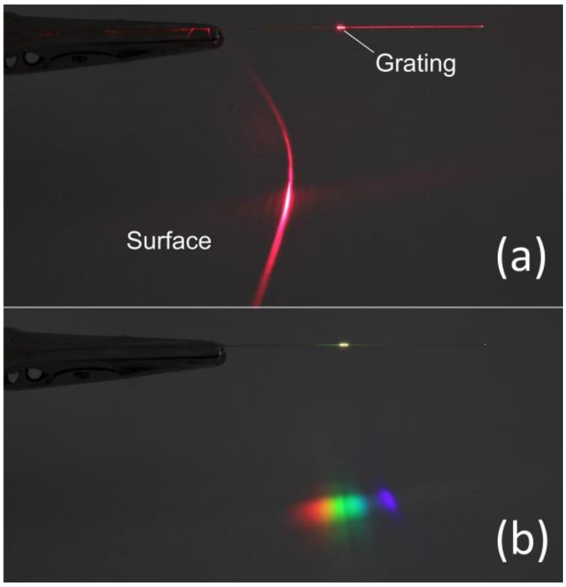

Fig. 5: a) red diode laser, b) white light LED imaged on a flat surface from a chirped first order PbP processed fiber-integrated diffraction grating by femtosecond laser pulses.

The laser light shows one singular bright red line, which focuses on the targeted distance from the core of the fiber at approx. 13 mm. For this wavelength a second order scattering occurs at a too small angle to leave the fiber due to total internal reflection. This second order is coupled to the cladding and coating of the fiber and results in an additional reddish glow beyond the grating. The white light leads to a clearly resolved rainbow including the LED-typical gap before the blue-UV region.

This fiber-integrated spectrometer represents the main building block for the analysis of reflected FBG wavelengths and can detect them with high optical resolution and light intensity.

Ultra-compact FBG-Interrogator

To accomplish the construction of an ultra-compact and high-performance FBG-Interrogator it is mandatory to inject high optical power into the waveguide, routing it to the FBG sensors and back to the spectrometer.

One highly space-consuming optical component within FBG-Interrogators is the routing of the optical fiber itself by means of optical circulators, couplers, switches, or fiber loops. By introducing the spectrometer into the optical fiber, the whole routing of it can be drastically reduced.

As seen in Fig 6. FiSens uses a bi-directional approach around a single monolithic optical fiber. The optical power of the light source is directly guided through the fiber-integrated spectrometer a first time while being routed to the FBG sensors. Since the fs-laser induced grating diffracts light at different angles dependent on the direction of light impinging on it, the light guided from the light source is outcoupled into an adverse direction and eliminated in a stray light trap. Only the light back reflected from the FBG sensors are directly imaged on the CMOS detector.

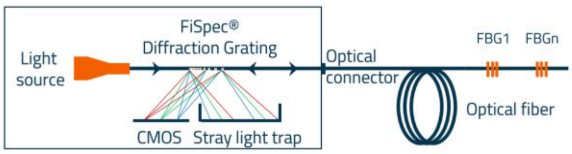

Fig. 6: Schematic illustration of a patented [4] FBG Interrogator around a single monolithic optical fiber.

Furthermore, the choice of operating wavelength for light source, detector and optical fiber plays a critical role. It is advantageous using 850nm over 1550nm due to the detector being silicon-based and only half the size. The higher attenuation at this wavelength can be neglected for applications of fiber lengths ranging up to 500m. The advantages of 850nm over 1550nm are:

- FBG sensor length of only 1-3mm for pin-point spatial resolution

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- Critical fiber bending radius of only 5-6mm for tight routing
- Highly reduced costs and proven availability of CMOS detector
- CMOS detector with pixel-to-pixel pitch down to 5,5µm enabling high resolution

One of the key challenges with optical spectrometers and FBG-Interrogators are their ambient temperature dependent wavelength-drift. This effect occurs due the thermal expansion of detector and optical components. By shrinking the spectrometer build-up to only two very narrowly spaced components (i.e. fiber-integrated diffraction grating and detector) this effect can be reduced by several factors. Utilizing advanced materials like Invar36 around these two components can further minimize this effect. However, this alone will not be sufficient for a robust and stable sensor signal.

To overcome the full problem and stabilize the base line of the FBG sensor signal over the full operating temperature one can either actively thermally control the spectrometer (e.g., Peltier element) or passively compensate any base line drifts of the spectrometer using reference sensors inside the spectrometer. Hence, the most obvious solution is to use one FBG sensor of the available spectrum inside the single monolithic fiber of the FBG-Interrogator itself. This internal reference FBG sensor measures any changes in the device temperature and compensates against it.

Adding Fiber Sensing capability to the XMA

Among all the challenges anticipated, the mechanical integration has been the first roadblock encountered. As a modular product, it was mandatory to comply with the mechanical interface standard in order to keep hosting various type of modules in a single stack. This constrain would allow add-on capability to the thousands of XMA stacks currently in use and extend the combination of hardware configuration to meet future needs. Leveraging the mature mechanical design of the XMA, qualified and flight proven on numerous kind of test vehicles would be of great help to succeed in hosting and protecting the ultra-compact FBG Interrogator technology designed by FiSens. However, the volume offered by an XMA module housing is rather limited (50x80x11mm) as originally designed to high-end fine pitch electronics parts and not optical components.

The other challenges are the electrical interfacing (powering and data communication) and the synchronization / time stamping in order to provide consistent time aligned measurements that can be correlated with the other types of measurements.

Applying an agile methodology, SDS, Safran Tech and FiSens have decided to follow an iterative roadmap to integrate and ruggedize the FBG interrogator in the XMA product. Such approach has been eased thanks to the XMA-PRO and EXT modules which are off-the-shelf modules dedicated to host custom third party electronics in a standard XMA module housing.

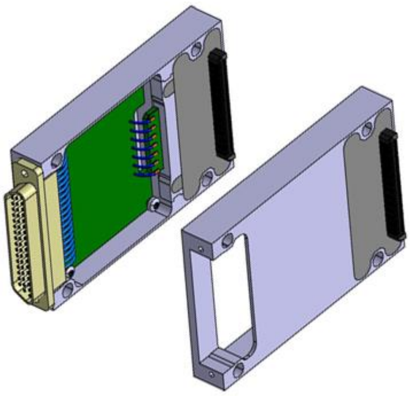

Fig. 7: XMA-PRO & EXT showing the surface allocated to host 3rd party components (in green)

This way of working allows focusing on the main challenges first, maximizing the probability to achieve a first flight capable version of the XMA-FBG interrogator module and minimizing the development effort. The counter part of this approach is that an additional module is required for the digital communication as the PRO&EXT modules only provide power supply voltages from the backplane. However, this additional module, which can be of different kinds (XMA-RSX, XMA-RSD, XMA-OBP,…), can be used to acquire the measurements coming from several XMA-FBG interrogators hosted in the stack or other serial and discrete signals needed for the application.

Thanks to the novel approach brought by FiSens and design simplification an ultra-compact FBG-Interrogator has successfully been integrated into the XMA form factor. (see Fig. 8). This first prototype of XMA-FBG combines a set of beneficiary properties:

- Dimensions of only 50x80x20mm
- Reduced weight of only 160g
- Low power consumption ~1W
- Simultaneous detection of all sensors (up to 30 FBG) without dead times
- High Precision of 1µe (@100hz, σ)

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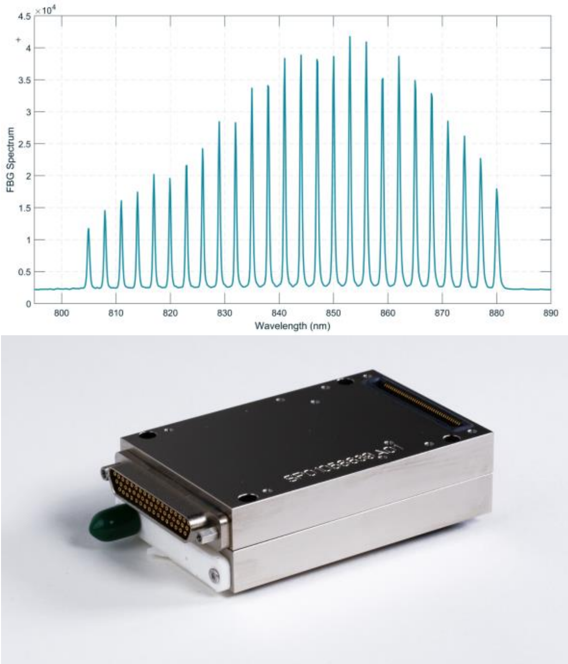

Fig. 8: 1st aerospace grade FBG-Interrogator prototype with availabe FBG spectrum at 808-880nm

The next steps will be to characterize the design in temperature, vibration/shocks and to run a first set of EMI/EMC testing. If needed, the design will be adapted following the same agile methodology.

Then, if all these test runs well, the target is to fly this first version of the XMA-FBG module on various test vehicles (fixed-wing and rotary-wing aircrafts) in order to meet quickly real flight conditions and to assess the benefits of this highly integrated FBG interrogator in a mature DAU.

Benefits of miniaturization and integration

Compared to stand-alone FBG interrogators, the miniaturization and modular approach offers the following benefits:

- **Mechanical installation in the test vehicle**: whatever the content of the XMA stack, only four mounting screws are required. External stand-alone interrogator would require additional mounting brackets or plate. This leads to time and cost savings. The high level of integration extends installation capabilities and offers more instrumentation channels for a given available volume.
- **Scalability**: one or several FBG modules can be hosted in a single stack whatever the form factor: XMA-CORE8, XMA-CORE16 or XMA-ROTOR

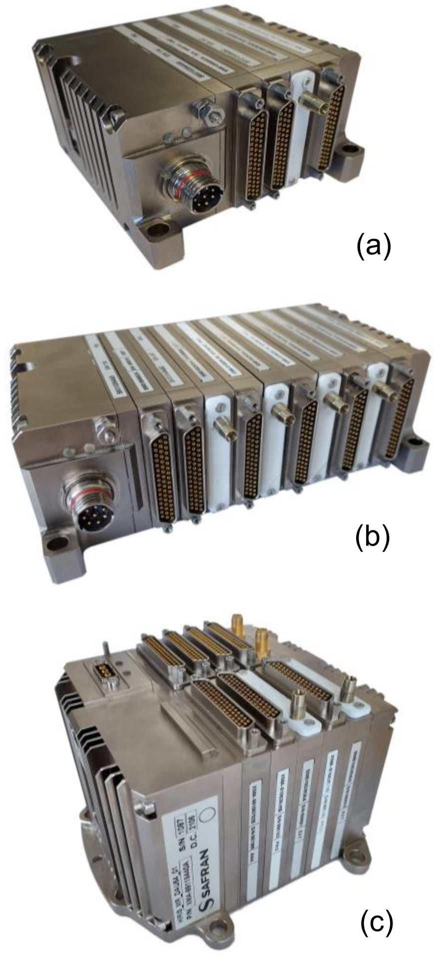

Fig. 9: a) XMA-CORE8 with 1 FBG interrogator + 2 other modules (top); b) XMA-CORE16 with 4 FBG interrogators + 2 other modules (middle); c) XMA-ROTOR with 2 FGB interrogators + 5 other modules (bottom)

- **Versatility**: capability to mix fiber sensing measurements with heterogeneous data types in the same data acquisition unit: legacy analog sensors (resistive strain gages, accelerometers, RTDs, thermocouples, pressure sensors,…), digital (avionic buses), discretes, video acquisitions,…
- **Homogeneous connectors**: obviously, the interface with the optical fiber implement a specific connector but data communication of the XMA-FBG module uses standard XMA microComp D-type connector.

- Electrical powering of the XMA-FBG modules comes from the XMA power supply module (XMA PSI / PSS) through the backplane and therefore take benefits of a fully isolated, DO-160 / MIL-STD704 qualified design.
- **Full integration** in SDS instrumentation system: configuration, synchronization, stand-alone or distributed architecture, wired or wireless network capability, standard compliant data stream (IRIG-106, IENA, …), on board recording, processing or telemetry,…
- **Ruggedization**: the ultra-compact FBG Interrogator will take benefits of the flight proven mechanical architecture of the XMA in order to be compliant with the demanding environments of flight-testing.

Conclusion and future perspectives

The collaboration between FiSens, Safran Tech and Safran Data Systems has led to a first successful integration of a downscaled FBG interrogator. The results obtained are promising but more developments are necessary in order to:

- Adapt the technical specifications for the targeted applications.
- Adapt the integration (mechanical and electrical) to be compatible with the standards and specifications.
- Reduce the cost.

However, the low intrusiveness, the high level of immunity, the compatibility with high temperature,… open promising perspectives in flight testing, but also in operations for health and usage monitoring (HUM) applications. As such, helicopter rotor blade monitoring appears definitely as a use case that could take benefits of such technology maturation and development effort.

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