On-line structural health and fire monitoring of a composite personal aircraft using an FBG sensing system

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ABSTRACT

We report in this paper on the design and development of a novel on-line structural health monitoring and fire detection system based on an array of optical fiber Bragg grating (FBG) sensors and interrogation system installed on a new, pre-commercial compact aircraft. A combined total of 17 FBG sensors—strain, temperature and high-temperature—were installed at critical locations in an around the wings, fuselage and engine compartment of a prototype, Comp Air CA 12 all-composite, ten-passenger personal airplane powered by a 1,650 hp turbine engine. The sensors are interrogated on-line and in real time by a swept laser FBG interrogator (Micron Optics sm125-700) mounted on board the plane. Sensors readings are then combined with the plane's avionics system and displayed on the pilot's aviation control panel. This system represents the first of its kind in commercial, small frame, airplanes and a first for optical fiber sensors.

Keywords: Fiber grating, FBG, strain sensor, temperature sensor, aerospace, structural monitoring.

1. INTRODUCTION

Over the last few years, optical fiber sensors have seen an increased acceptance as well as a widespread use for structural sensing and monitoring in civil engineering, aerospace, marine, oil & gas, composites and smart structure applications. Optical fiber sensor operation and instrumentation have become well understood and developed and a variety of commercial sensors and sensing systems are now readily available. However, their historical implementation and actual adoption in real life and commercial platforms has tended to be limited and slow moving.

In sharp contrast to this reality, we report in this paper on the design and development of a novel on-line structural health monitoring and fire detection system based on an array of optical fiber Bragg grating (FBG) sensors and interrogation system installed on a new, pre-commercial compact aircraft. This system represents the first of its kind in commercial, small frame, airplanes and a first for optical fiber sensors. Pertinent details on the sensor design, packaging, installation, data analysis and processing will be presented in the sections to follow, along with the experiences and lessons learned from this exciting application.

2. IMPORTANCE AND VALUE OF PLANE HEALTH MONITORING

The driver behind aircraft monitoring is the use of composite materials. Due to this construction and logistical uses in larger multiple passenger aircraft the need to inspect the aircraft properly is essential due to the fact the majority of shapes are molded and hand worked. Once the aircraft is assembled areas of the aircraft structure are not visible and cannot be removed for inspection. Although the aircraft is easily repairable should any damage occur knowing what needs to be repaired drives the practical use of fiber optic sensing.

Some other factors is insurance of aircraft which can include, pilot error , miss use, surpassing aircraft specifications and weather effects while in flight. This is also key for customer ownership or multiple owners of private aircraft understanding what events the aircraft has been exposed to and having a record of its lifetime history. The insurance companies would know how to treat each event and analyze what liabilities they may have according to the circumstance presented. Essentially this is another type of black box information that would hold extremely valuable information for any type of event.

Using fiber optic technology on aircraft and FAA regulations for safety assurances is one of many reasons for this application. This would add another level of compliance to safety issues which the FAA is looking for.

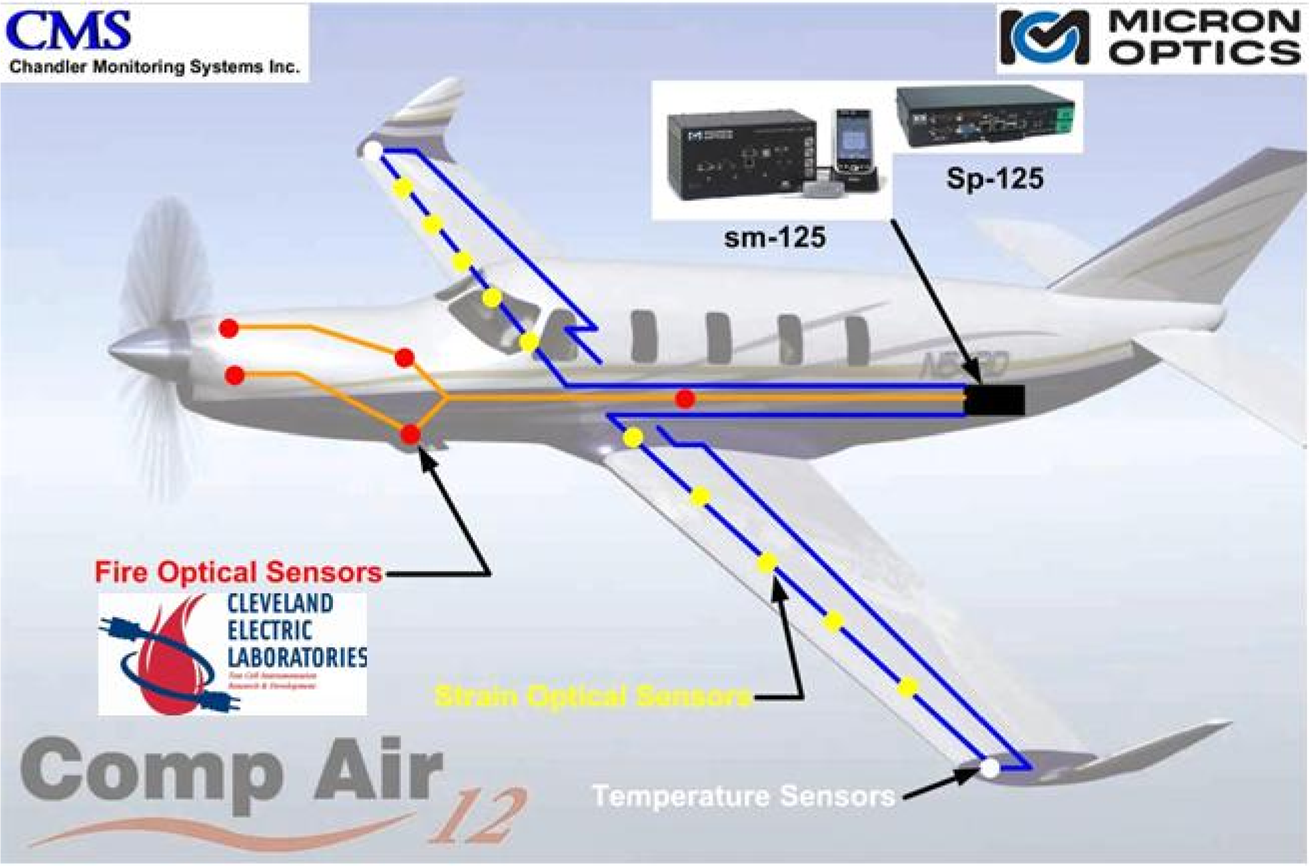

Fig. 1 Schematic of instrumented Com Air 12 plane with FBG sensors

3. COMP AIR COMPOSITE PLANE

Comp Air Aviation is manufacturing the CA12 through the strategic use of composite manufacturing technologies. This is an important opportunity to forever change the way composites are used in aircraft manufacturing, leading to lighter, less expensive, more durable aircraft that are easier to maintain.

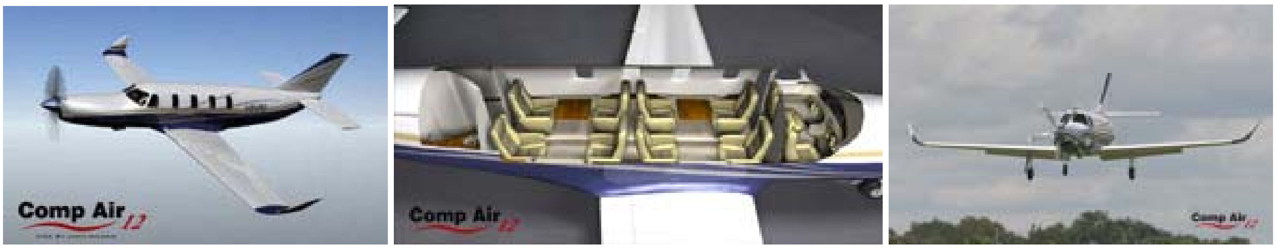

Fig. 2 Schematic view of aircraft Comp Air 12

Comp Air's integration of advanced composites on the CA12 prototype will enable a reduction of 80-90 percent in parts count and a dramatic reduction in corrosion and fatigue issues compared to conventional aircraft manufacturing approaches. Planned growth provisions will allow it to be used well into the future as a technology workhorse for a broad

spectrum of next generation aircraft. The use of composite materials in the aeronautic industry has been increasing since the 70s. The reason for their move was largely because of capacity to reinforce in preferential directions, their high rigidity, specific resistance and their enhanced fatigue and corrosion behavior. Comp Air Aviation's goal is to reduce the structural weight of the aircraft, the reduction in the number of parts needed in its assembly and, finally, the reduction of maintenance operations over the useful lifespan of the aircraft.
Composites are the most important materials to be adapted for aviation since the use of aluminum in the 1920s. Composites are materials that are combinations of two or more organic or inorganic components. One material serves as a "matrix," which is the material that holds everything together, while the other material serves as reinforcement, in the form of fibers embedded in the matrix.
The most common matrix materials were "thermosetting" materials such as epoxy, bismaleimide, or polyimide. The reinforcing materials can be glass fiber, boron fiber, carbon fiber, or other more exotic mixtures.

The following pictures Fig. 3 a-i show the aircraft in production.


a)


b)


c)


d)


e)


f)


g)


h)


i)

Fig. 3 a-i Production steps of aircraft Comp Air 12

Shown above Comp Air Aviation is using Carbon Fiber which is biaxial. This process is known as a wet lay-up process. This means Comp Air 12 is a Carbon Fiber but in a prepreg form which give consistency to the whole aircraft. It will be vacuumed bagged and placed in an oven to release the resin and in ensure a consistency throughout the design.

4. FBG SENSORS & MONITORING SYSTEM

Chandler Monitoring Systems, a designer and integrator of fiber optic sensing solutions, uses a system comprised of optical instruments developed by Micron Optics. The Micron interrogator equipment is the heart that operates the optical sensing systems on the CA12 utilizing the sm125-700 a 4 channel system and a sp125 Industrial PC to gather wavelength information. The sp125 communicates directly to the aviation displays giving the pilot a visual check of temperature in the engine compartment and structural information from the optical stress sensors. This information is gathered by using a combination of packed Cleveland high temperature optical sensors and Micron os410 temperature compensating (FBG) and os120 FBG array sensors for structural monitoring.
Cleveland Electric Laboratories (CEL) provided the five fiber optic temperature sensors that were installed in the engine compartment of the aircraft to monitor Temperatures and detect over-temperature conditions and fires. Each stainless Steel-enclosed sensor contains a silica fiber Bragg grating (FBG) with a working Temperature of up to 1100°F.

Since 1920 CEL has produced innovative extreme temperature and process control solutions. From over 40 years of combined aircraft and turbine engineering instrumentation, design, manufacturing, fabrication and repair service experience, CEL today is at the forefront of fiber optic high temperature sensor application development.
The system currently monitors the structural integrity of the aircraft with fiber optic sensors mounted on the composite structure of the plane. Optical temperature sensors installed in the engine compartment monitor temperature and provide fire protection. The optical sensing interrogator will give the pilot an automatic weight, balance, and center of gravity check in the near future. The fiber optic sensing system is expandable for other aircraft monitoring needs as they surface and is adaptable to any environment.

5. SENSOR INSTALLATION

The fiber optic strain and temperature sensors for the CA12 prototype was developed and installed on the forward wings and fire protection sensors in the engine compartment.

The wing sensors shown in Fig. 4a consist of 5 os120 sensors on a fiber optic array using epoxy on each wing for mounting and one os410 for temperature compensation. This is typical on both left and right wing and the sensors follow the main support spar in each wing.
The optical interrogator equipment in Fig. 4b is mounted in the rear compartment of the aircraft for easy access. This optical equipment is tied directly into the pilot avionic displays. Future aircraft will house the equipment in the avionics compartment.
The engine compartment containing the temperature optical sensors are shown in Fig. 4c. The yellow arrow is pointing to a typical sensor mounting technique using a vibration isolating clamps. These optical sensors are monitoring engine temperature, exhaust region, and fuel pump locations.
The optical cable routing is shown in Fig. 4d. Behind the aviation instrument panel the optical connections are routed from engine compartment to a cable chase for routing to the optical equipment.
The wing sensors are transitioned in to the landing gear wheel well and routed through the same common cable chase. Junction boxes are also mounted in three locations for maintenance access and future optical sensor expansions.

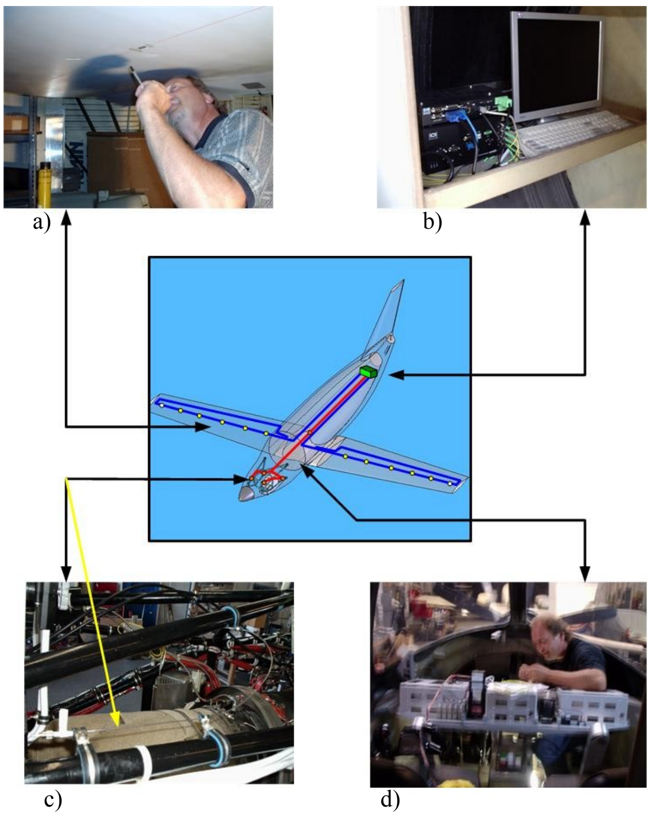

Fig. 4 a-d Details of sensor installation

The second prototype to be built for FAA certification in 2008 will contain 30 to 40 optical sensors for structural and fire protection. Other sensors that are to be developed are automatic center of gravity indicators, smart pilot windows, and optical fuel gage monitoring and brake system maintenance indicators.
Aircraft monitoring using optical sensors is well suited in this industry. The use of composite and existing metal materials gives a new level of safety to new and aged aircraft.
After the current installation techniques and for all future applications special FAA regulatory guide lines can be developed. The aircraft will be in FAA certification in 2008 with a new CA12 prototype to be built with new solutions being applied to meet these regulations. This will apply to optical connections, optical cable requirements and certification of the optical equipment.

6. TEST RESULTS

Conducting stress analyses of the prototype aircraft and the ability to understand the static, dynamics, and thermal loads to determine strength of the total airframe and expand to other areas will build a total solution package for the additional certification aircraft.
The installation has shown value and reliability of the optical sensing system on composites. The values shown in Table 1, column A, are the recorded wavelengths after curing the optical sensor array, surface prep process and painting of the aircraft in a stable ambient hanger environment. Also in Table 1, column B1, an example is shown for an in-flight snap shot of FBG sensor characteristics.
A diagram in Fig. 5 shows optical sensor locations to compare areas to Table 1 for the examples given.

Flight log data will be fully compared to optical system data through out 2008. The information is not complete but gives an example of two conditions. By using Graphite base Carbon Fiber with very little coefficient of expansion / modulus of elasticity under normal operating conditions due to imposed temperature or seen stress there is very little movement. The additional prototypes will be designed to have additional flexure to gain a smoother flight, but the goal of the optical sensing system is to sense damage should a circumstance out of ordinary occur. This also gives a safety margin throughout the life of the aircraft for FAA inspections. The fire protection gives real time values with all the advantages of optical sensors in response time and endurance over a long life with high reliability and the ease of installation of these systems.
Another reason for mounting optical sensors on the main spar is FAA has required as mandatory checks because spar fractures in other company aircraft has happened. So FAA requires an expensive non-destructive test for these manufactures.

Table 1 FBG sensor wavelengths

Location	A1 ground July 2007 typ. 32° C [nm]	B1 12,000 ft Feb 2008 typ. 14° C 270 knots	A2 ground [nm]	B2 12,000 ft	A3 ground [nm]	B3 12,000 ft	A4 ground [nm]	B4 12,000 ft
Port Wing Strain all positive for spar direction	1526.183	132.75 με	1536.304	138.66 με	1546.173	138.32 με	1556.056	160.66 με
Starboard Wing Strain All positive for spar direction	1526.045	135.64 με	1536.227	134.75 με	1546.177	136.62 με	1556.040	140.66 με
Engine Cowling Temperature	1531.104 Fuel distribution area	93°C	1532.001 Fuel distribution area	95°C	1541.815 Exhaust area insulated	162.7°C	1542.112 Exhaust area insulated	168.89°C
Fuel Pump and Electrical Chase Temperature	1555.562 exposed	1553.723	"	"	"	"	"	"
Temperature Compensating Port Wing	1534.834	1532.990	"	"	"	"	"	"
Temperature Compensation Starboard Wing	1534.611	1532.772	"	"	"	"	"	"

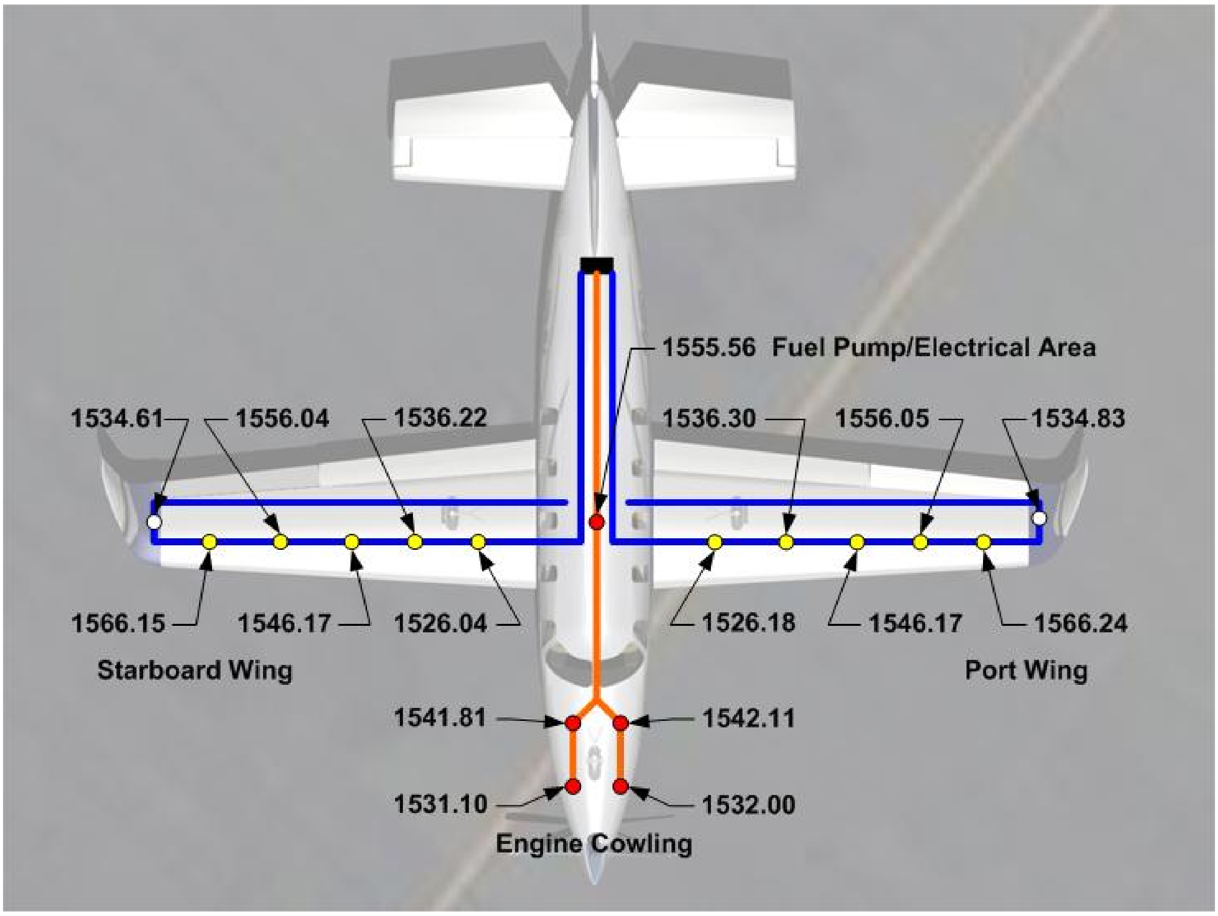

Fig. 5 Schematic of sensor locations

7. CONCLUSIONS

In conclusion to Aircraft monitoring project many advantages have been realized that will create additional interest in optical monitoring. With optical sensing reaching lower pricing and the level of importance of what is monitored makes a big difference for the future of optical systems.

Earlier it has been mentioned that the why's and reasoning are answered covering these areas of high interest, FAA regulations, Aircraft safety, Insurance for aircraft, continued history recording for inspections, long sensor life, immune to EMI, and lightweight sensor packages will drive this need.

By having the optical monitoring system in place while the aircraft is establishing FAA certification the optical interrogators and sensors will become certified. Having this certification will expand its use in this and other aeronautical industries once FAA requirements are met.

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