Chapter 7 – THE FUTURE OF FOSS AND FBG-OFDR TECHNOLOGIES

The previous sections have highlighted research conducted at NASA Dryden to overcome some of the technical barriers to large-scale implementation of FOSS technologies into aerospace vehicle design. The need to overcome the cultural barriers to FOSS acceptance, as articulated in the Introduction, is more critical now than ever before. Trends in the aerospace community towards ultra-lightweight, elastically tailorable long-span structures that can competently fly at higher altitudes for longer durations are forcing aircraft design into new realms without the underpinning of fundamental understanding of physical phenomena. To achieve new mission requirements, Uninhabited Aerial Vehicle (UAV) designs are converging on solutions with hundreds of feet of wing span, requiring the use of non-traditional engineering materials, such as balsa wood and mylar. Thin gage materials cease to perform in a manner consistent with handbook values that were determined with bulk materials. Decoupled, single discipline, linear design, and analysis models are insufficient to address the complexity associated with the new challenges in aerospace vehicle designs. These trends are also growing for transport and commercial aircraft designs with the perennial goals of reducing weight, reducing fuel burn rates, increasing range, and payload capacity.

The benefits of FOSS technology and its potential to address these formidable challenges, make its acceptance by the aerospace community that much more important. The prospect of dramatically improving the measurement count-to-total sensor weight, or data-to-weight ratio has the potential to benefit the vehicle management and operations from early design to final retirement. One recent in-house study estimates that FBG sensors based on OFDR can provide 100 to 1000 times the number of conventional strain/temperature measurements at 1/100 to 1/1000 of the total sensor weight, depending on the application. Conventional technologies and business-as-usual cultural practices and methodologies must be overcome to realize the full potential that the FOSS technologies offer.

To illustrate the potential game-changing benefits of FOSS technology, this section first presents the notion of a vision vehicle. This vision vehicle could represent the state of the art for aircraft designs flying in the next generation. Such a vehicle is first introduced and then the benefits of FOSS at each stage in the vehicle life cycle are described.

7.1 THE FOSS VISION VEHICLE

A FOSS vision vehicle would be instrumented with large arrays of sensor networks analogous to biological systems. These networks would be bonded primarily to the outer external surfaces of the vehicle using efficient, large-scale attachment methods. Other sensors would be incorporated during fabrication on interior structures and embedded within the composite laminate on key components. Comprehensive knowledge of the flight vehicle airframe would be underpinned by a structured build up approach where FOSS sensors would provide unparalleled feedback in all parts of ground test structures, from coupon to qualification unit. Models at each stage of the structural test would be refined and updated by correlating with FOSS measurements. In flight, hundreds of thousands of FBG sensors would provide a litany of measurands; a sub-set of which would be used for feedback control and updating on-board simulations. Sensor mesh densities on the vehicle airframe would be commensurate with the degrees of freedom present with detailed finite-element models. These networks would be judiciously arrayed such that high spatially resolved sensor meshes would exist in areas of non-uniform gradients and lower densities in larger acreage portions with lower gradients. Sensor networks would be defined such that component strains/stresses in multiple directions would be available to determine principal, normal, shear, and von Mises stresses/strains. Mode shapes and buckling modes (eigenvectors) from elastic instabilities could be assessed, and if significant, could be displayed to key personnel by an on-board Structural Health Monitoring System in real time. If catastrophic failure was imminent, such information could be fed to appropriate on-board sub-system

computers to mitigate failure without human intervention. Regions on the aircraft where damage was suspected would be identified and automatically targeted for post-flight non-destructive evaluation and condition-based maintenance.

This section shows how FBG-OFDR sensing technology supports the initial stages of structural design; facilitates new advances in fabrication and manufacturing; reduces time, cost, and complexity of ground test and evaluation; provides real-time structural monitoring capability during nominal and off-nominal flight operations; improves maintenance turn-around times; and provides comprehensive vehicle life predictions for end of life decisions.

7.2 DESIGN AND DEVELOPMENT

A vehicle with FOSS technologies flying in the future could look radically different and have pronounced economic and military benefit than vehicles flying today. Many aspects of vehicle design and development can benefit from FOSS technologies. One key benefit is providing a better fundamental understanding of the complex behavior of future designs. Having high-spatial and temporal physical response feedback throughout the development cycle (from ground test articles to flight structures) would ensure that such a vehicle would have been designed with a better understanding of the fundamental physics that govern such vehicles and the environments in which they fly. This profound understanding would produce comprehensively validated multi-disciplinary physics-based models that will ensure the lightest and most efficient designs possible. Benefits to these optimized tools would be enormous: they will save weight, reduce fuel costs, minimize operating and maintenance costs, and improve overall vehicle performance. Installing thousands of sensors on structural components in faster times and with less personnel would ensure that vehicle development path from sub-component testing to first flight would have been faster and less expensive. Efficient and accurate multi-disciplinary design tools would optimize design margins approaching 1.0 such that excessive weight could be pulled from the vehicle structure. Structural design uncertainty, which drives higher design margins, would be reduced by comprehensive structural feedback at every step of the test program. This feedback would also identify areas where additional strength was required due to under-designed regions, thus ensuring greater safety. These design and analysis tools would have been validated throughout all phases of the structure development process, from the ground (coupons, sub-components, qualification units, flight structures) through the flight envelope expansion process.

Another key benefit of FOSS designs is that in-service performance data can now be fedback to designers who rarely have access to such data to validate their design assumptions. According to a Wall Street Journal report, following the aftermath of a crash of an Alaskan Airlines MD-83 (McDonnell Douglas, now The Boeing Company, Chicago, Illinois) off the coast of Southern California in January 2000, an independent report addressing airline safety found in part that the validity of initial design assumptions was seldom verified by comparison with databases of in service performance. [29] By providing finite-element-like results with these experimental measurements, designers now can evaluate the efficacy of their structural designs and improve their models. Compared to current structural designers, who rarely have more than a handful of strain gage channels to assess structural performance of the entire vehicle, designers of the FOSS vision vehicle have hundreds of thousands of hair-like sensors to validate their design assumptions.

Design tools for the FOSS vision vehicle would be based on a better understanding of the complex airframe response to external environment forces. Current vehicle development efforts focus on building a specific platform for a specific application rather than developing a thorough understanding of the fundamentals associated with vehicle performance. Previous design tools based on linear structural analysis, linear-elastic materials, linear control theory, linear and steady aerodynamic assumptions, and decoupled disciplinary analyses are not acceptable to satisfy current and future aircraft design requirements. The lack of fundamental knowledge of issues directly related to lighter weight designs inhibits fast and efficient development, and safe operation of new UAVs. Such was the case with the in-flight breakup of the Helios UAV (Figure 7-1). The mishap investigation board concluded that for these complex airframes, more accurate, multi-disciplinary,

time domain design and analysis tools were essential for examining the effects of disturbances on the behavior of highly flexible vehicles (Thomas Noll, et al, "Investigation of the Helios Prototype Aircraft Mishap Volume 1 Mishap Report", NASA internal document, January 2004).

NASA Photo ED01-0209-2

NASA Photo ED03-0180-03

Figure 7-1: Helios UAV at Take-Off (Left) and In-Flight Break-Up (Right).

The goal of reducing aircraft weight means that aircraft structures will inherently be more flexible, which translates into greater risk of structural instabilities and adverse coupling between aerodynamic forces and structural response. The fluid-structure interaction problem means that flight control laws must be more robust and able to safely control the vehicle throughout its life. With these vast networks of hair-like sensors, model validation can be accomplished comprehensively. In addition, traditionally crude design assumption regarding gusts, unsteady aero, etc., can be better understood (i.e. yielding weight reductions) and can be placed in regions previously not possible (within bolted joints, embedded within composite structure). Embedded FBGs will increase the physical understanding of curing the process and material system performance during the life of the structure.

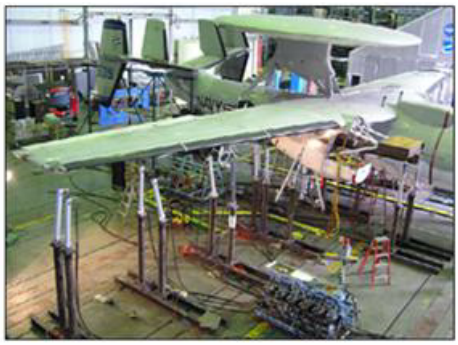
7.3 FABRICATION AND SENSOR INSTALLATION

Structural sensors for the FOSS vision vehicle would be efficiently bonded to the vehicle surfaces in large pre-packaged sheets (i.e. SMART Layer, as described in Section 4.3), either during, or immediately following fabrication. These ultra-thin, plastic layers would contain integrated arrays of FBG sensor networks as part of the overall integrated vehicle design. FBG sensor networks could also be embedded with the composite airframe during the fabrication process. The sensor sheets could result in the installation of thousands of sensors in a fraction of the time required for conventional and FBG sensors today. These integrated packaged layers may also further minimize the already nearly negligible geometric disturbances that the small fibers might cause.

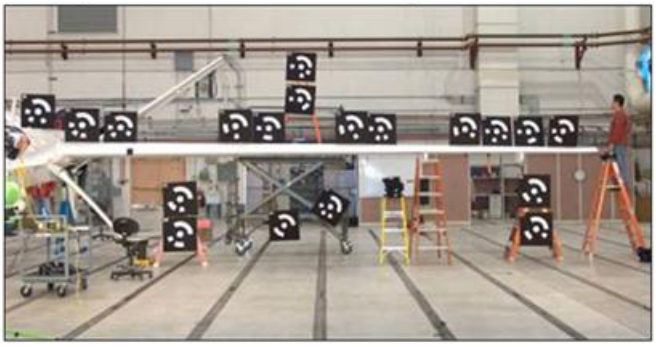
7.4 GROUND TESTING

Despite the increasing complexity of future aircraft designs, the FOSS vision vehicle should be able to achieve first flight in a fraction of the time it takes for current vehicle designs. Schedule reductions should result from more efficient test techniques afforded by vast numbers of surface-mounted sensors operating in conjunction with real-time structural models. New ground test techniques using fiber optic sensors have the potential to reduce the test complexity and increase a greater understanding of physical response of the airframe throughout ground testing.

Figure 7-1 shows the complexity of current ground test techniques compared to the simplicity of ground tests conducted with fiber optic sensor arrays. Figure 7-2 shows a typical strain gage loads calibration being conducted on the Northrop Grumman (Falls Church, Virginia) E2C Hawkeye. These tests required 16 channels of load actuation to apply an array of mechanical loads in order to determine stiffness coefficients for strain-gage-based loads equations. These equations are required to monitor the flight loads produced on the airframe during a conventional flight research program. To monitor the flight loads, dozens of strain gage channels had to be installed on the interior load bearing structures in the wing. Wing skins had to be removed and strain gages and thermocouples had to be installed. Typical installation times for foil strain gages are approximately 4 hours per gage.



NASA Photo EC04-0360-1192



NASA Photo ED08-0016-12

Figure 7-2: Traditional Strain Gage Loads Calibration Testing in NASA Dryden's Flight Loads Lab, and Simplified Tests for Determining Structural Properties of as Built Structures and Real Time in Flight Loads.

The FOSS vision is to perform ground tests in fractions of the time, saving time at all phases of the test program. During the instrumentation phase, a few fiber channels, each containing thousands of sensors can be hooked up, checked out, and identified in much shorter time than with conventional strain and temperature sensors. Conventional strain sensors require one channel per sensor. As shown previously, the number of instrumentation channels is significantly reduced with a few small fibers.

The other advantage of FBG instrumented structures is that these sensors are small enough that they can be installed at high-lift locations on the aircraft. Conventional strain gage technology is too massive and perturbative to be placed in these high lift regions. Because of their small size, FBG sensors can also remain on the structure throughout the vehicle life cycle, unlike other ground-test-specific instrumentation that has to be removed prior to flight. Therefore, extra time is required before and after testing to both install and remove instrumentation required for ground testing.

7.5 FLIGHT OPERATIONS

7.5.1 Nominal Flight

Perhaps the greatest benefit of the FOSS technology is realized when the FOSS vision vehicle performs its mission in the actual flight environment. The efficient ultra-light airframe design, enabled by FOSS technologies is now able to save hundreds of millions of dollars of fuel per year for the entire inventory of FOSS vehicles in commercial and military fleets. The shape of the wings and tails of the vehicle are well known and can be used in combination with the conventional control surfaces to more optimally tune the wings in-flight to improve aerodynamic performance. Advances in actuator technology enable the aeroelastic control of the aerodynamic surfaces to increase lift, reduce drag, and redistribute aerodynamic loads to regions having greater load bearing capacity. A few percent increase in aerodynamic efficiency

allows the FOSS vision vehicle to travel further and carry more cargo and passengers than previous generations of aircraft designs. The ability to determine many real-time parameters opens up the prospect for future vehicles to perform real-time simulations. Data driven simulations can be used to predict near-term vehicle response to changes in flight environment, such as weather conditions. Real-time on-board data driven simulations can also be used to update control laws for a variety of scenarios, such as loss of control surface that might occur due to battle damage or lightening strikes.

The FOSS vision vehicle is equipped with a real-time health monitoring system that can provide thousands of engineering parameters to monitor and manage vehicle health. FBG sensors can be placed on high-pressure and extreme temperature tanks, hoses, and cables to monitor system health. These sensors can be placed on and embedded within Composite Over-Wrapped Pressure Vessels (COPVs) to monitor the health of these vessels and avoid stress rupture. The monitoring of COPVs is a current topic of a considerable amount of research within NASA. Overloading of key structural components can be monitored and four-dimensional mapping (three spatial-coordinates and time) will provide accurate assessment of system and structural health. With the highly resolved mapping capability, the FOSS structures can pinpoint areas for post-flight inspection. Condition-based, rather than time-based maintenance can now be better achieved.

7.5.2 Off-Nominal Flight

Another significant benefit to FOSS technologies is the ability for the FOSS vision vehicle to make real-time adjustments to mission plans based on sensory feedback. On-board simulations can be performed and models can be validated for sudden changes in aircraft performance due to control surface malfunction or damage. Sudden changes in atmospheric conditions, such as increased turbulence and wind shear can be addressed with FOSS-facilitated gust-alleviation techniques. With sensor networks on FOSS structures, other unexpected and dramatic changes in external environment such as buffeting can be handled effectively. In order to prevent elastic instabilities such as buckling and flutter, FOSS structures along with advanced materials and actuators can effectively control mode shapes and buckled regions. By maintaining orthogonal mode shapes to prevent off-diagonal interactions in the mode shapes, flutter can be suppressed for FOSS vision vehicles of the future.

For other off-nominal flight conditions, FOSS technology also has the potential to avoid truly catastrophic results of loss of life, loss of mission, and loss of assets. When aircraft systems suffer in-air emergencies, having validated information is always indispensible in determining the most appropriate remediation strategy. For missions in which assets are deployed for long periods of time, such as HALE missions and space exploration, off-nominal emergencies can be difficult to overcome. Validated data from sensors covering the vehicle with a few dozen fibers could prove to the difference between mission success and failure.

7.6 END OF LIFE DECISION MAKING

Finally, at the later stages of aircraft service, the question remains as to how much longer an aircraft can remain in service and safely fulfill its mission. As military and civilian budgets become smaller, military and civilian aircraft are more commonly expected to be used well beyond their service lives. Sampath, for example, notes that in 1993, 51 percent of U.S. Air Force inventory was 15 years and older, while 44 percent were over 20 years old. [30] The problem is further exacerbated by shrinking budgets that require many of these aircraft to continue fleet service for years beyond their design life. The more these vehicles fly beyond their design life, the higher maintenance costs become. The scheduled inspection and repair of each EF-11A (General Dynamics, now the Lockheed Martin Corporation, Bethesda, Maryland) aircraft in the depot had risen from 2200 hours in 1985, to 8000 hours in 1996. [30] The problem of aging aircraft, similar to that of an aging family car, is that issues of maintenance and operational expense become a serious budgetary concern. FOSS structures have been envisioned by many as the mechanism to

help alleviate such problems. The ability to provide real-time continuous structural health management of fleet aircraft and aerospace vehicles is envisioned to dramatically reduce operational and maintenance costs, and thus allow these vehicles and structures to extend their service lives.

A clear example of the consequence of using aircraft beyond their safe life occurs when the U.S. Air Force decommissions fleet aircraft. Agencies such as the U.S. Forest Service are able to retro fit these aircraft to support their mission. With these conventional airframes, there is a serious lack of detailed knowledge to accurately predict the remaining fatigue life in these structures. Figure 7-3 shows the in-flight catastrophe of such an aircraft. This Forest Service aircraft experienced a catastrophic wing structure failure on this C-130 (Lockheed Martin Corporation, Bethesda, Maryland) while performing a mission in 2002. The U.S. Air Force placed the aircraft in service in 1957. Future FOSS airframes can be certified for future use because they have the ability to use data driven models to facilitate end-of-service life decisions, such as those discussed in earlier.

Figure 7-3: B52 Aircraft Boneyard (Left), and Video Capture of an In-Flight Structural Failure of a C-130A (Right).