Chapter 5 – ON-BOARD STRUCTURAL TRANSFER FUNCTIONS

One of the most significant benefits of FOSS technologies and FBG-OFDR is the amenability for these measurements to be used in conjunction with closed-form analytical equations. These so called data-driven models, can use a multitude of highly multiplexed FBG measurements to accurately determine a variety of engineering parameters in real time. Parameters such as wing shape, structural properties, externally applied aerodynamic forces, mode-shapes, and fatigue life have proven very difficult to determine, especially in real-time flight environment. Because these transfer functions are analytically- and not numerically based, they provide exact solutions to partial differential equations and are therefore very accurate. This accuracy is further ensured because the models are continuously updated in real time with the structure's physical response during flight. Furthermore, this approach is more amenable to real-time on-board processing because these equations can be fed with actual in-flight data efficiently as compared to numerical methods, such as finite-element models. Numerical finite-element approaches, which usually consist of thousands of degrees of freedom and the mathematical inversion of large stiffness matrices, have proven too cumbersome for real-time implementation. This section presents three of these data-driven on-board structural transfer functions: wing shape, external loads, and fatigue life.

5.1 WING SHAPE

Wing shape transfer functions based on NASA Dryden patented technology [20] have been developed, implemented, and flight validated. Two of these displacement methods are presented in the following section.

5.1.1 NASA Dryden Real-Time Data-Driven Displacement Methods

Development of data-driven displacement methods for determining the deformed shape of structures was motivated in 2003 by the Helios flying wing, which had a 247-ft wing span with wingtip deflections reaching 40 ft (Figure 5-1). The Helios flying wing (AeroVironment Inc., Monrovia, California) failed in midair in June 2003 due to possible un-damped pitch oscillations of highly deformed wing. The Helios mishap created the need to develop a new technology to determine in-flight deformed shapes of unmanned aircraft wings and then visually display the results to ground-based pilots to ensure flight safety.

NASA Photo ED01-0209-2

Figure 5-1: Helios UAV (AeroVironment Inc.).

Using a data-driven modeling approach, the structure deformed shape could be determined by feeding the surface strains into real-time structural transfer functions for transforming the surface strains into out-of-plane deflections and cross-sectional rotations for mapping out the overall deformed shapes of the structure. [6, 21-23]

FBG-OFDR fiber optic strain sensors are the most attractive candidate to accurately and comprehensively determine structural shape and are the most practical approach to input into the structural transfer functions. The highly multiplexed sensor output is input at strain-sensing stations at desired sensing intervals. The conventional strain gage system is impractical for flight vehicles because of excessive lead wire weight. Another powerful characteristic of FBG-OFDR is that the strain-sensing station number can be increased easily as needed using a single command without the need to actually install additional strain sensors one by one as in the case of conventional strain gage system.

5.1.1.1 Theory

Displacement equations combined with the on-board fiber optic strain-sensing system form a new powerful tool for in-flight deformed shape monitoring of flexible wings and tails, such as those often employed on unmanned flight vehicles by the ground-based pilot for maintaining safe flights. In addition, the real-time wing shape monitor could then be input to the aircraft control system for aero-elastic wing shape control.

5.1.1.2 Formulation

The formulation of the displacement transfer functions stemmed from the integrations of the beam curvature equation (second order differential equation). An aircraft wing, considered as a cantilevered beam-like structure was first discretized into multiple small domains so that beam depth and surface strain distributions could be represented with piece-wise linear functions. This discretization approach enabled stepwise integrations of the beam curvature equation in closed forms to yield slope and deflection equations for each

domain in recursive formats. The final deflection equations in summation forms (called displacement transfer functions), which contain no structural properties (such as bending stiffness), were then expressed in terms of domain length, beam depth factor, and surface bending strains at the domain junctures. In fact, the effect of the structural properties is contained in the surface strains.

5.1.1.3 Implementation

For flying wings, such as the Helios-class UAVs, the two-line strain-sensing system (Figure 5-2) is a powerful method for simultaneously monitoring the bending and cross-sectional rotations. [23] The two-line strain-sensing system eliminates the need for installing the shear strain sensors to measure the surface distortions through which the wing structure cross-sectional rotations could be determined.

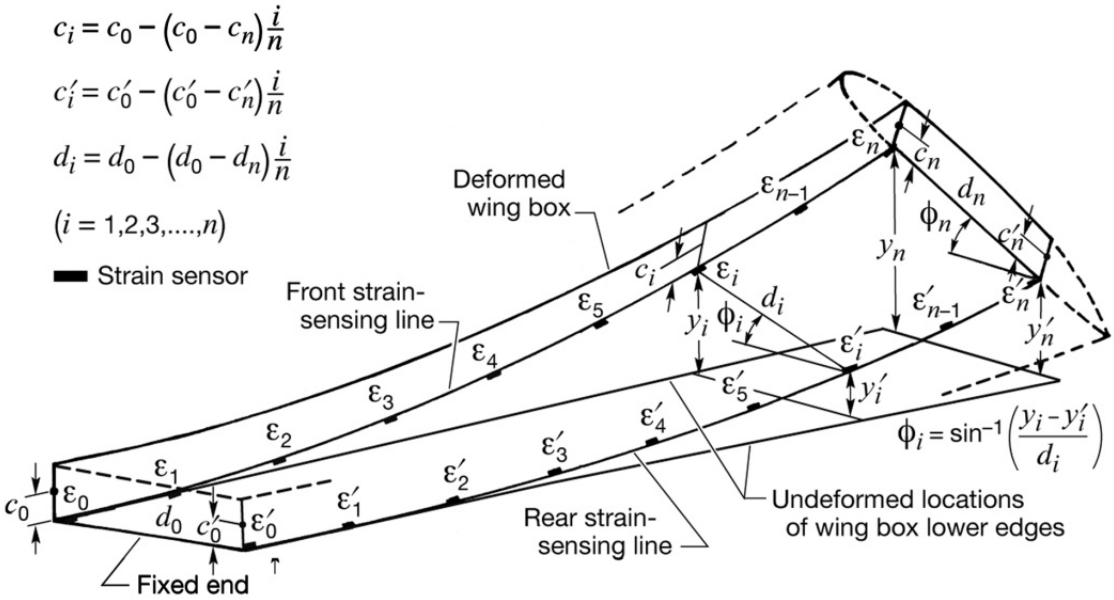

Figure 5-2: Tapered Wing Box Instrumented with Two-Line Strain-Sensing System.

By averaging the front and rear deflections calculated from the displacement transfer functions using the measured surface strains, torsion effect may be eliminated to yield the true bending deflections of the wing structure. Also, the calculated front and rear deflections can be used to calculate wing structure cross-sectional rotations due to torsion effect. Thus, the overall structure-deformed shapes can be mapped out for visual displays before the ground pilots, thereby accomplishing the objective of in-flight wing structure deformed shape sensing.

Recently, the NASA Dryden real-time displacement method was applied on a 175-ft span full-scale wing. [24] FBG-OFDR-acquired strain measurements were input to the displacement transfer functions. Wing tip displacements determined using the Dryden method were within +/- 2.7 in (out of 155-in max deflection) for nearly all the load steps, indicating that the fiber optic-based displacement method can be relied upon to accurately determine wing displacement on realistic structures using real-world measurements.

5.1.2 NASA LaRC/Dryden Displacement Theory

Although a very powerful tool, one of the drawbacks of the methods described above is the requirement to transfer structural strains from a substrate structure, such as the aircraft wing, to the FBG sensing element in order to calculate structural shape. Recent research has resulted in an alternative approach that can determine

wing shape without the requirement to first transfer surface strains from the structure into the surface-mounted FBG sensor. One of these developments is the fabrication of FBG sensors written inside a multi-core fiber. Typical FBG sensors are written into a regular communication-based single mode fiber, which has one narrow core (~8-μm) that resides in the middle of the optical waveguide surrounded by a cladding region. In a multi-core fiber, there are three individual cores; each core is 120 degrees apart (Figure 5-3a). Each core supports a particular single mode, therefore acting as if three single mode fibers are bundled together. By creating an algorithm that relates the cylindrical symmetry of the strain distribution, it is theoretically possible to recreate the shape of the sensors. However, there were limitations that existed to the technology. Multi-core fiber is considered to be a specialty fiber and therefore expensive. The multi-core fiber is also difficult to manufacture. Fusing a multiple cores into a conventional single mode fiber is challenging. Another aspect is that the prior-developed shape-sensing algorithm cannot recreate shape in real time.

(a) 3 Core Fiber **(b) 3SMFs Aligned in 120˚**

Figure 5-3: Three-Core Fiber and Three Single-Mode Fibers Arranged 120° Apart.

In recent years, NASA Langley has developed and patented a software algorithm that can distinguish shape with respect to strain based on the three-core fiber concept. [25] However, a limitation of the methods was that in order to demonstrate shape sensing, strain information of the smart-fiber first needed to be pre-determined and calculated to obtain the desired shape. To overcome this limitation for real-time operation, NASA Dryden collaborated and integrated NASA Langley's software into the high-speed, real-time fiber grating interrogation system. A demonstration apparatus, which consists of a hexagon rod with 3 faces, 120 degrees apart instrumented with three individual FBG sensors, is fabricated and demonstrated with Langley's algorithm. Results show shape sensing is possible and accurate for the bending of structures in all directions. Knowing the strain value of each fiber, the three-dimensional position of the fiber can be accurately rendered in real time.

The advantage of the three-core shape sensing is that it provides additional installation flexibility. Three fibers can be bonded together as shown in Figure 5-3b, or they can be attached 120 degrees apart on a very flexible structure, like a hose or cable. There is no requirement for the fiber to be mounted on a structural component in order to calculate structural displacement. In addition, the derivative of the deforming structure does not have to be unique (i.e. there can be hinges, wing folds, et cetera). The fiber shape can be determined from the fiber deformation alone, without requiring a carrier structure to transfer strain to the FBG sensors.

The three single-mode fiber approach has opened up new applications for aerospace vehicle monitoring and control. Other sectors of society have benefited as well, such as the medical community. NASA Dryden collaborated with a medical company to physically bundle three single-mode-fibers with FBGs, where FBG sensors are spaced 1/2 in apart, into one single-fiber structure with a total diameter >300 μm. By utilizing the same algorithm, the shape of this smart-sensor can be accurately recreated from the strain information. There are many potential applications to this shape sensing technology, from large-scale

aerospace applications such as wing-shape monitoring all the way to medical applications such as integration within robotically controlled cardio-catheters.

5.2 STRUCTURAL PROPERTIES AND EXTERNAL LOADS

In addition to wing and component shape, efficient real-time structural monitoring transfer functions have been developed to provide extensive information about the physical response of structures under load. [26] Similar to the previous examples, these transfer functions are driven by actual strain data to accurately measure local strains at multiple locations on the surface of a structure. Through a single point load calibration test, these structural strains are then used to calculate key physical properties of the structure at each measurement location. Such properties include the structures flexural rigidity (the product of the structures modulus of elasticity, E, and its moment of inertia, I), and the section modulus (the moment of inertia, I, divided by the structures half-depth, c, or I/c). The resulting structural properties at each location can be used to determine the structures bending moment, shear, and structural loads in real time while the structure is in service.

The amount of structural information can be maximized through the use of highly multiplexed FBG technology using OFDR. Since local strains are used as input to the transfer functions, this system serves multiple purposes of measuring strains and displacements, as well as determining structural bending moment, shear, and loads for assessing real-time structural health.

The method first requires that an aircraft wing, preferably instrumented with a high number of multiplexed FBG sensors, be subjected to a simple point-load calibration test for bending and torsion. Using the classical bending equation for a uniform beam, the structural properties of the wing structure can then be determined at a multitude of locations along the wing span. For the simple flexure case, the section properties can be determined by inputting the measured strains into equation (1).

$$(ES)_i = \frac{P(l - i\Delta l)}{\varepsilon_i} \tag{1}$$

These experimentally determined section properties from the as-built structure can be used for two purposes. The properties can be input in finite-element analysis because these properties are far more accurate than the properties normally assumed in finite-element models. These properties, together with measured in-flight strains can also be used to determine bending, shear, and external loads in real time during the flight. The external loads can then be used as feedback to adaptive control systems. Figure 5-4 shows an analytical demonstration of the method on a simple tapered wing, subjected to a distributed load along its span. The forces calculated from computationally-generated strains obtained from the method are shown in Figure 5-5.

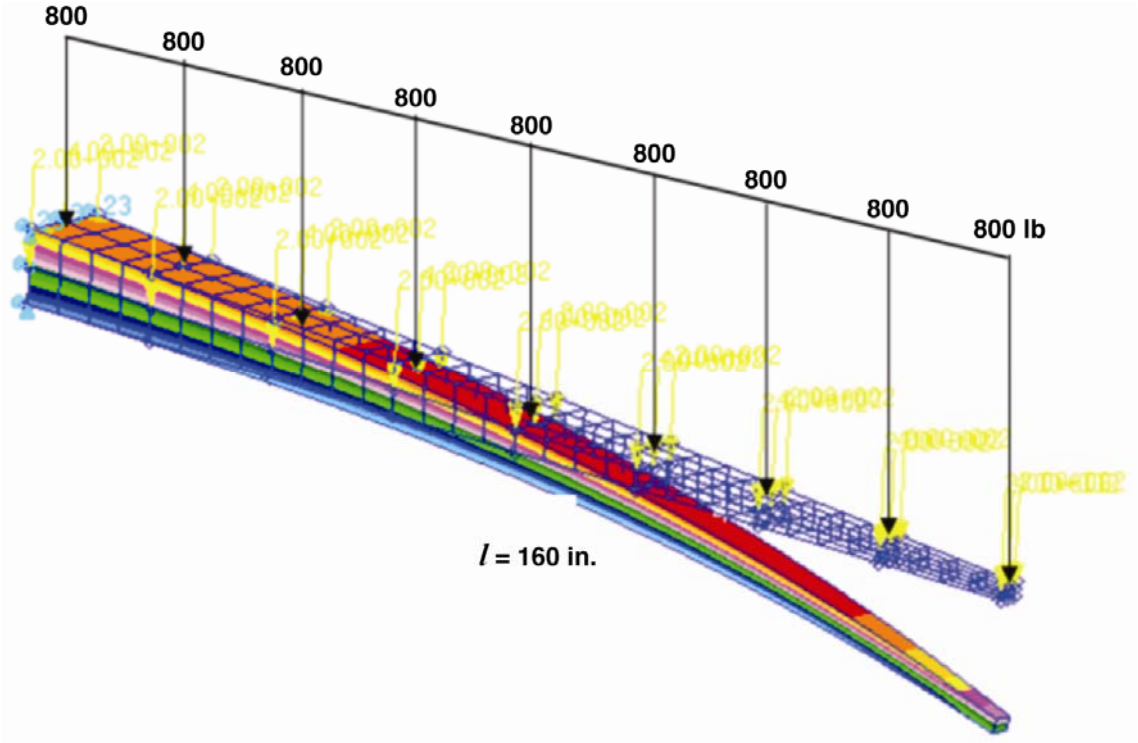

Figure 5-4: Finite-Element Model.

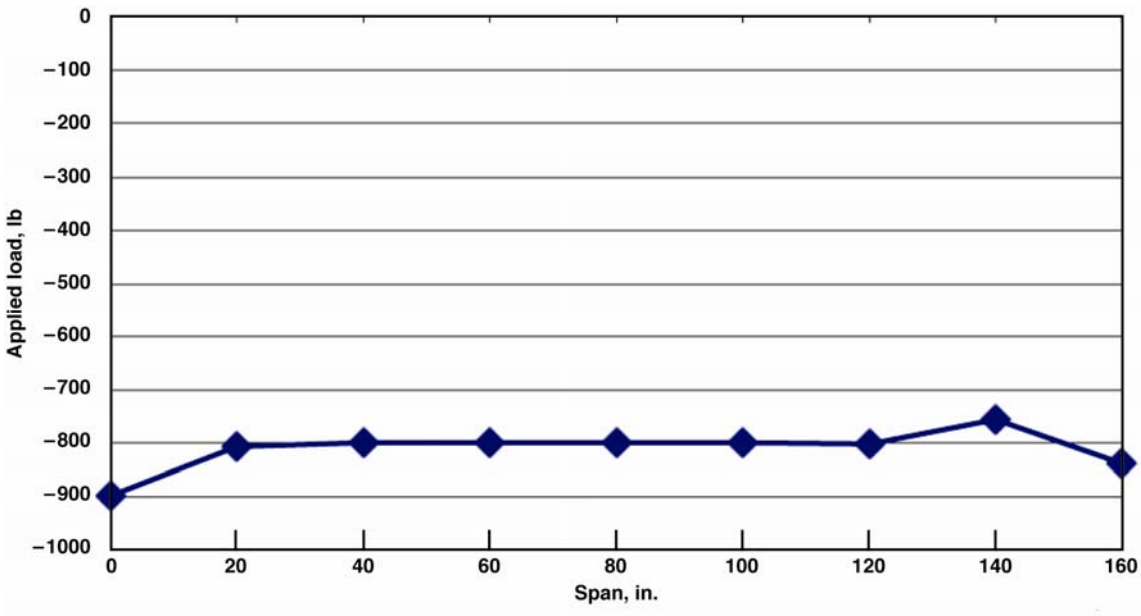

Figure 5-5: Analytically Determined Loads.

5.3 FATIGUE LIFE

For flight vehicles, most of the failure critical, high stress concentration points are located in hard-to-reach narrow regions where installments of conventional strain gages are practically impossible. FBG-OFDR

system technology is ideal for this application because FBG sensors possess high spatial resolution and can be conformed to fit the complex geometries in which critical stress points exist. The random stress cycles monitored by the fiber optic sensors can then be fed into the Walker crack growth equation to calculate the amount of crack growth induced by each flight. Based on the calculated crack growth, an operational life equation can calculate the remaining operational life (number of flights left) for each critical stress component. [27,28] A typical crack growth curve for B-52 pylon front hook (failure critical component) is shown in Figure 5-6.

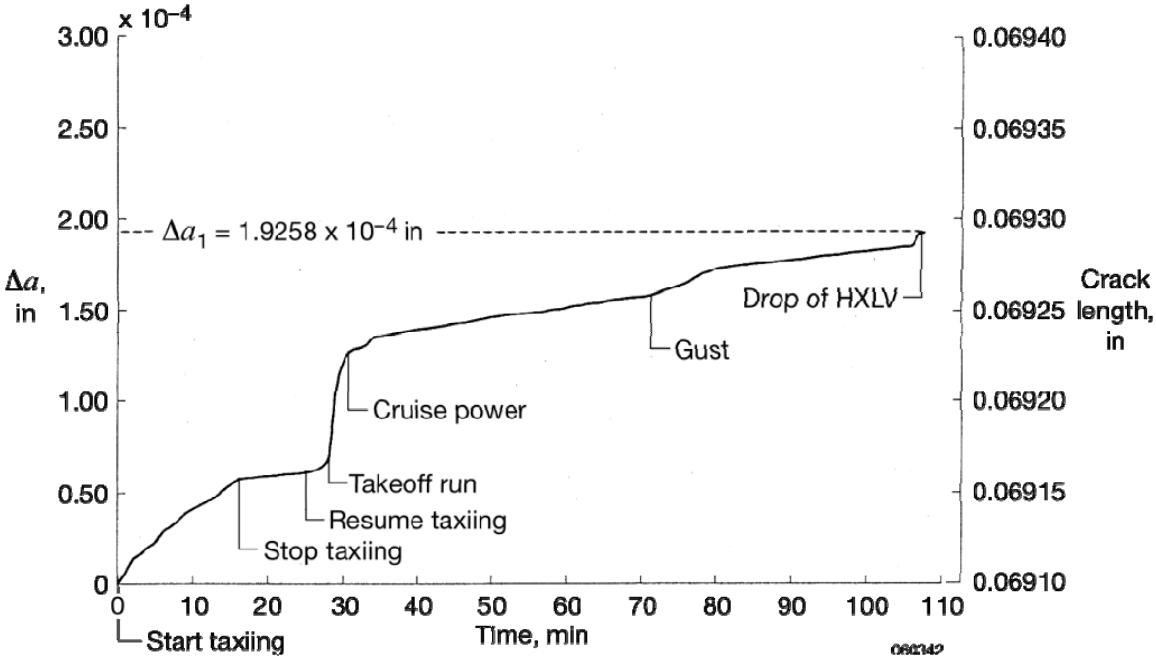

Figure 5-6: Typical Crack Growth Curve for B-52 Pylon Front Hook.