

Evaluation of Flight Data from an Airworthy Structural Health Monitoring System Integrally Embedded in an Unmanned Air Vehicle

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ABSTRACT

Data processing obtained from an airborne, real time, load tracking and structural health monitoring system is presented. The system is based on optical Fiber Bragg sensors embedded in the two tail booms of an unmanned aerial vehicle. The embedded Bragg sensors were continuously interrogated at 2.5 KHz, making it possible to identify and trace the dynamic response of the airborne structure during flight.

Flight data were analyzed both in the frequency and time domains so that abnormal structural behavior could be identified and tracked, and its impact on structural integrity evaluated.

Tracking the structural behavior over time can be used for Condition Based Maintenance (CBM), with the hope to eventually reduce maintenance cost and aircraft down-time.

INTRODUCTION

The high maneuverability and harsh operational conditions of modern Unmanned Aerial Vehicles (UAVs), requires constant monitoring of their structural airworthiness. This is highly important for composite-made UAVs, where accessibility for inspections is limited and conventional inspection methods are time consuming and require highly trained technicians. The recently introduced Health and Usage Monitoring System (HUMS) concept, aims towards effective real-time

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assessment of the structural integrity of flying vehicles, should provide practical means of maintaining structural airworthiness at minimal cost. Fiber optic sensors, in particular Fiber Bragg Grating sensors (FBG), appear to be excellent candidates to be used in HUMS applications due to their high sensitivity to mechanical strain, excellent signal to noise ratio, large dynamic range, small size, immunity to electrical interference, low weight, long life and excellent durability under extreme environmental conditions. Moreover, multiplexing techniques have been devised, where quite a few sensors, longitudinally spaced on the same Fiber, can be individually addressed to spatially cover strain and temperature fields. For composite structures, these sensors can be easily embedded during manufacturing, eliminating the need for sensor protection [1].

This work presents data analysis of an advanced smart load monitoring, airworthy system, for the composite tail booms of a UAV, based on an array of FBG sensors, embedded in the tail booms during manufacturing. The FBG sensor net, comprising four Fibers per boom, each with four sensors per Fiber, was tailored to monitor critical locations along the boom, based on a detailed finite element analysis. The system was tested and calibrated on ground in order to verify its ability to track both static and dynamic boom loading. Structural characteristics like strain distribution under static loading, impact response, and normal modes were successfully traced by the system. As a final proof of the concept, the system was integrated in the UAV and was successfully flown. Below we provide a detailed description of the implementation, followed by diagnostics and prognostics studies inferred from the collected data.

THE IMPLEMENTED HUMS CONCEPT

The Nishant UAV (Figure 1), designed and manufactured in India by ADE was selected as the test-bed for the evaluation of this HUMS concept. Each of the two tail booms of the Nishant is a composite structure made of two thin wall "C" section channels, riveted together to form a close rectangular beam. The back the booms hold the empennage, comprising a horizontal tail (with elevator) and two vertical tails. The thickness of the composite boom walls is optimized for both strength and stiffness [2].



Figure 1. The Nishant UAV on the launcher.

The boom is basically a cantilever beam with a relatively large mass at the back end. The main boom loading conditions are vertical and horizontal bending. In order to track the expected loading conditions, two Fibers were embedded at the centers of the boom ("center Fibers", CH2, CH3 in Figure 2) and another two Fibers were embedded near the corners ("side Fibers", CH1, CH4 in Figure 2). Four FBG sensors were imprinted on each Fiber. Thus, each critical section of the boom is monitored by four FBGs: two on top and two on the bottom (Figure 2). For such sensing net arrangement, the two centre Fibers are only sensitive to vertical bending while the side Fibers are sensitive to the vertical bending in a similar manner as the central ones, but will also react to horizontal bending. Since no tension loading is applied on the boom, the vertical bending will introduce theoretically identical but opposite strains in the top and bottom Fibers. The two side Fibers are on the same side with respect to the center line. Hence, the horizontal bending will induces similar strains on both side Fibers, in addition to the vertical bending contribution. In the reported test flight only the center Fibers of both booms were tracked, enabling tracking of the vertical bending of the two booms.



Figure 2. Boom general layout and routing of the embedded optical fibers inside the boom. 16 FBGs were located at points of interest.

A solid state, high sampling rate (2.5 kHz) FBG interrogation unit is used, capable of tracking multiple Fibers, having multiple FBGs on each. The optical Fibers are polyimide-coated to assure good bonding to the composite structure during embedment. The interrogation and data logging systems were placed in the UAV payload bay. Optical Fibers were routed in the UAV from each boom to the interrogation unit in the payload bay.

The Nishant UAV, equipped with the airworthy HUMS system, was flown at Kolar air field near Bangalore, India. It was demonstrated that the flight worthy interrogation system, integrated into the Nishant UAV, withstood all flight conditions including a catapulted launch, flight maneuvers and parachute landing. Measured readings (in terms of the optical strain: $\Delta\lambda_B/\lambda_B$, where $\Delta\lambda_B$ is the FBG strain-induced wavelength shift from its initial value of λ_B) of a pair FBG1 gratings (Figure 2), one on top center and the other on bottom center, are shown in Figure 3 for the duration of the entire flight.



Figure 3. Typical FBG readings during flight.

STRUCTURE DIAGNOSTICS AND PROGNOSTICS

The basic concept for tracking the structural integrity of the booms is based on cross correlation between normalized sensors [3, 4]. Since the boom itself is light with respect to the weight of the horizontal and vertical tails, the first vibrational bending mode is dominant. This is especially true for the case of ground touch-down impact during UAV landing. FBG readings during ground tail impact test of the instrumented boom are presented in Figure 4.



Figure 4. FBG readings during ground impact at the tail attachment.

In this test a 60Kg weight, attached to the boom at its end, was suddenly released. It is clearly seen that all sensor reacted in a similar manner, though the amplitude is not the same. It is concluded that in this test only the first vibration mode was excited since no phase shift between the sensors is observed.

Unlike metal structures, where cracks can grow under relatively moderate loading while high loading may retard their growth, composite materials are especially vulnerable to high loading. The most critical loading condition during the Nishant UAV test flight is its landing, especially the ground touch-down, as can be seen in Figure 3. The main focus of the current work was to track and identify events during landing that are associated with high loading and evaluate if damages occurred during such incidents.



Figure 5. FBG readings during landing.

An interesting test case is shown in Fig. 5. Taken during the actual touch-down, it describes readings from all eight center FBGs of one of the booms. All sensors are clearly in phase, indicating first bending mode vibration behavior at a frequency of f=7.4Hz. Note the small glitch near time 125.242 min, which may indicate a small elastic buckling. How can such a rare incidence be identified in the more than 7GByte of collected data?

In view of the similarity among the different sensors, a load and damage tracking algorithm was constructed, based on the detection of deviations from the expected modal behavior. The need to handle large data, obtained by many sensors also calls for means to reduce the order of the problem. In the current case, where only the deviations from the first mode of vertical bending are of interest, the following approach was taken. The first step was to decimate the data by down sampling to 250Hz, followed by normalizing all sensors amplitudes to have the same reading a moderate loading level (at 125.243 Min.). To compensate for the 180° phase shift between the top and bottom sensors, the readings from the latter were inverted. The normalized sensors data is shown in Figure 6. The final step is to plot all sensors readings (normalized and down sampled at 250Hz) as a function of one sensor to get the cross correlation function. Thus, Figure 7 plots the instantaneous normalized readings from seven FBGs as a function of simultaneous readings from the eighth one. Had only pure linear first mode vibration behavior existed, all normalized sensors data would have fallen on the same unit slope straight line. This is generally true for the data of Figure 7 with one important clear exception near -800 microstrains. This deviation is a direct consequence of the above-mentioned glitch in Figure 3, this time automatically detected through an efficient reduction of the order of the problem to a single two dimensional chart, which presents data from all sensors during as prescribed time period. Finally, since *all* deviating points were found to belong to a single incidence, it is safely concluded the boom fully recovers and remains intact!



Figure 6. Normalized FBG readings during landing.



Figure 7. Cross correlation of FBG readings.

SUMMARY AND CONCLUSIONS

A Fiber-optic-based concept for tracking the structural integrity of UAV composite booms was demonstrated using UAV sensors data obtained during flight. The ability to have many sensors on each boom, at virtually no weight penalty, made it possible to track natural frequencies and normal modes. By study the cross correlations among the normalized readings from multiple sensors, both boom overload and boom damage can be classified without the need for any additional flight parameters information. Tracking vibration modes by comparing normalized sensors data also reduces the order of the problem. Using this approach, local buckling was identified at the high touch-down impact. It was also shown that this local buckling did not cause permanent structural damage.

In conclusion, high count fiber optic sensors arrays together with proper data processing techniques of the type introduced here, promise to reduce periodic grounding of airborne platforms and pave the way to condition-based maintenance.

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