HAL
open science

High Speed, In-Flight Structural Health Monitoring System for Medium Altitude Long Endurance Unmanned Air Vehicle

Iddo Kressel, J. Balter, Naama Mashiach, Ido Sovran, O. Shapira, N.Y. Shemesh, Benny Glamm, A. Dvorjetski, T. Yehoshua, Moshe Tur

To cite this version:

Iddo Kressel, J. Balter, Naama Mashiach, Ido Sovran, O. Shapira, et al.. High Speed, In-Flight Structural Health Monitoring System for Medium Altitude Long Endurance Unmanned Air Vehicle. EWSHM - 7th European Workshop on Structural Health Monitoring, IFFSTTAR, Inria, Université de Nantes, Jul 2014, Nantes, France. hal-01020352

HAL Id: hal-01020352

https://inria.hal.science/hal-01020352v1

Submitted on 8 Jul 2014

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

HIGH SPEED, IN-FLIGHT STRUCTURAL HEALTH MONITORING SYSTEM FOR MEDIUM ALTITUDE LONG ENDURANCE UNMANNED AIR VEHICLE

I. Kressel[1], J. Balter[1], N. Mashiach[2], I. Sovran[3], O. Shapira[4], N.Y. Shemesh[4]
B. Glam[4], A. Dvorjetski[2], T. Yehoshua[3], M. Tur[3]

[1]*IAI Engineering Division, Ben Gurion International Airport Israel*
[2]*IAF UAVs Branch, Tel-AvivIsrael*
[3]*School of Electrical Engineering, Tel-Aviv University, Tel-Aviv Israel*
[4]*IAF Aircraft Structure Branch, Tel-Aviv Israel*

ikressel@iai.co.il

ABSTRACT

This work presents the design, qualification and flight service evaluation of an embedded Fiber Bragg Gratings (FBG) based, Health and Usage Monitoring System (HUMS) for the Israeli Air Force Medium Altitude Long Endurance (MALE) Unmanned Aerial Vehicle (UAV).A total of 54 FBG sensors were embedded on the wing and tail booms, enabling accurate tracking of both the vibrations signature and the actual loading conditions of these components. Reliable flight data, obtained during flight tests and normal UAV operational missions were recorded and analyzed both in the frequency and time domains so that normal structural behavior could be identified and tracked. Based on the data obtained, it is now possible to track the actual loads spectra of both the booms and wing during each flight, with emphasis on the landing impact vibration signatures. The sensing system has already gained over 1000 flight hours, including more than 300 logging hours.It is the purpose of this system to early detect and identify dangerous changes in the normal structural behavior of an individual UAV, prompting the required corrective action, thereby, paving the way to condition-based maintenance.

KEYWORDS:*UAV Health and Usage Monitoring System,FBG, Airworthy SHM system.*

INTRODUCTION

The increasing value of modern Unmanned Aerial Vehicles (UAVs), together with their high usage under variety of missions, at extreme environmental conditions, demands continuous monitoring of their structural airworthiness over their life span. Reliability, safety and the economic implications of maintaining aging UAV fleet, subject to cyclic loading, corrosion, wear and material degradation are the prime concerns of both the operator and the UAV manufacturer due to their logistics implications. In recent years, the concept of Health and Usage Monitoring System (HUMS) was proposed in order to assure safe and economic operation of UAVs. This concept is based on tracking the individual UAV by evaluating its real flight history and the impact of the latter on the structure, combined with real time identification of events that may eventually lead to undesired failure. HUMS has a unique benefit for UAVs since conventional maintenance, based on periodic inspections, requiring direct access to all of the UAVs critical structural components, is hindered by limited accessibility and the need for highly trained, i.e., costly technicians, not always available at remote sites. It should also be noted that UAVs are missing the human pilot, who practically acts as a full time highly sophisticated sensor, having the ability to identify unusual behaviors, caused by wear, fatigue, bird or hail impact, lightning strike etc. [1]. One of the purposes of HUMS is to fill this gap.
By applying the HUMS concept, maintenance action should be performed only when the need arises, reducing the UAV ownership cost. This concept also coincides with the recently introduced airworthiness requirements for UAVs, like the STANAG 4671 [1, 2] where, for example, the

Copyright © Inria (2014)

substantiation of structural bonded jointsmay be based on: "repeatable and reliable non-destructive inspection".
The concept of Structural Health Monitoring (SHM) which is included in HUMS, has been discussed for many years. Summary of early Health Monitoring literature 1996–2001 [4] indicates that a multidisciplinary effort should be directed to solve issues in sensors reliability, data processing for damage diagnostics and prognostics [5,6,7].
Among the available sensing technologies, the use of fiber-optic sensors to implement an online system appears quite attractive [8]. Due to their small diameter optical fibers can be easily embedded within composite materials, having currently ubiquitous presence in modern UAVs. Optical fibers are flexible, passive, quite tolerant to environmental conditions and insensitive to electromagnetic disturbances. Quite a few sensors can be multiplexed on a single fiber strand, and the overall technology, including the interrogators is already quite mature, and well-known to be highly reliable [4].
Structure Health Monitoring systems based on Surface bonding of fiber-optic sensors proved itself in lab scale and prototype demonstrations [9,10]. One of the first successful attempts to demonstrate an in-flight, real-time, fully embedded, airworthy SHM system was on the Indian Nishant UAV [11]. This Fiber Bragg Grating (FBG) based system successfully monitored the two tail booms during flight and traced the boom loading during the entire test flight.

This paper presents a complete airworthy HUMS system that was integrated in the Israeli Air Force Medium Altitude Long Endurance (MALE) Unmanned Aerial Vehicle. The purpose of this project is to evaluate such system benefits under tight military operational environment.This airworthy system is based on an array of FBG sensors, embedded in the two composite-made, tail booms, as well as in the central wing. The FBG sensor net was tailored to monitor critical locations in the wing and along the tail booms. The system was first tested and calibrated on ground in order to verify its ability to track both static and dynamic boom loadings. Structural characteristics like strain distribution under static loading and impact response were successfully monitored by the system. The high signal to noise ratio of the optical sensors enables tracking of booms vibration signature during all the UAV manoeuvers, including cruise, turns, steep ascents and descents and heavy landing. As a final and definitive proof of the concept, the system, including the FBG multi-channel interrogator and data storage device, was integrated in the UAV. The system entered service and reliable flight data were recorded by the sensors during a dedicated flight test, covering the full UAV flight envelope, and continued to be recorded during the normal operation of the aircraft. The on-board collected data are processed off-line on the ground and analyzed both in the frequency and time domains so that critical components such as the individual UAV wing and booms load spectra and vibration signatures can be identified, characterized and tracked. The sensors data were also integrated with the flight parameters on a single GUI, for visual and quantitative correlation of the sensors readings and flight manoeuvers. Based on the data obtained, it is now possible to track this UAV actual load spectrum and use its characteristics to make reliable predictions on the UAV structural integrity.
This paper discusses the system implementation on the UAV booms, including the sensor layout, system architecture and data processing.

THE IMPLEMENTED HUMS CONCEPT

AMALE UAV (Figure 1), designed and manufactured in Israel by Israel Aerospace Industries was selected by the Israeli Air Force as the test-bed for the evaluation of this fiber-optic based HUMS concept in operational real-field environment. Each of the two tail booms is a composite beam

Figure 1: One of IAI's UAVs after takeoff. In the current project two fibers were embedded on each boom and wing, see Fig. 2 for details

structure attached to the wing in the front and at the back holds the empennage, comprising a horizontal tail (with elevator) and two vertical tailsand rudders.
Each boom is basically a cantilever beam with a relatively large mass at the back end. The main boom loading condition is vertical bending. In order to track these loading conditions, two fibers were embedded at the center of the boom ("Top" and "Bottom" in Figure 2). Eight FBG sensors were imprinted on each fiber. Thus, eight section of the boom are monitored by two FBGs; one on top and another on the bottom (Figure 2). For such a sensing net arrangement, the two fibers are only sensitive to vertical bending. Since the cross-section of the boom is not symmetrical with respect to the horizontal plane, vertical bending will introduce non-identical but opposite strains in corresponding top and bottom FBGs.

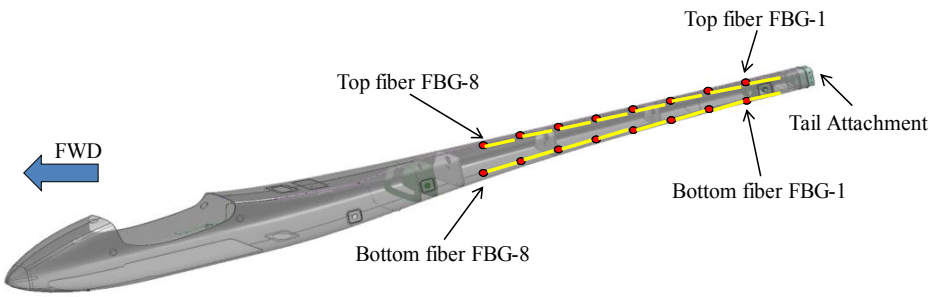

Figure 2: Boom general layout and the routing of the embedded optical fibers in the boom.
16 FBGs were located at points of interest (RHS boom shown. LHS is similar.)

The optical fibers were polyimide-coated to ensure good bonding to the composite structure during embedment. To successfully solve the ingress/egress issue, a special pre-cured composite protective patch, made of glassfabric was used for each pair of fibers at the egress point providing good shielding for the bare fiber as it leaves the structure and enters the protective (3 mm) sleeve strengthened by Kevlar fibers. The patch was located at the front of the boom, where it is attached to the wing. For accurate sensor placement, a pre-fabricated glass-fiber composite sensing mat, containing the polyimide-coated optical fiber, was fabricated. This sensing mat was then bonded to the UAV structure, minimizing the risk of optical fiber damage and FBG sensor reflection attenuation. The shielded fibers were internally routed inside the UAV from each boom and wing to the interrogation and logging unit located in the payload bay. FC/APC connectors were used to enable wing and booms disassembly. Similarly the wing fibers monitor the outer wing attachment and track the wing bending moment at the center.

A solid-state, high sampling rate (2.5kHz) FBG interrogation unit was used, capable of simultaneously tracking 4 fibers, having multiple FBGs on each. The interrogation included a data-logging system was placed in the UAV payload bay, and was powered by the UAV electrical system. While the data logger had significant processing power, all data analysis reported here was done offline. The interrogator containing data-logger unit has been successfully subjected to environmental testing fully compatible with the environmental requirements of the MALE UAV.The sensors data were also integrated with the flight parameters on a single GUI, Figure 3, for visual and quantitative correlation of the sensors readings and flight manoeuvers. Based on the data obtained, it is now possible to track this UAV actual load spectrum and its impact on UAV structural integrity.

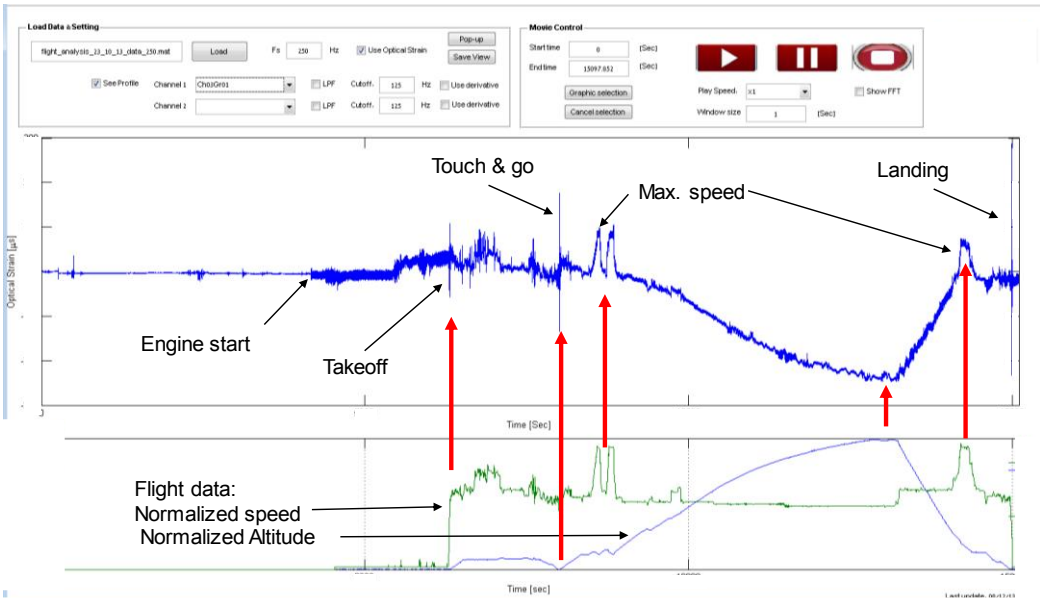

Figure 3: Flight data GUI; Typical Boom FBG readings during flight. Note the 'touch & go', maneuver and landing

SYSTEM VALIDATION AND CALIBRATION

Static calibration tests were performed in order to correlate the embedded FBG readings with the boom loading under vertical bending load. Tail loadings were applied at the boom end near the tail, up to 30Kg. FBG readings were taken at 10Kg increments. Typical calibration results are presented in Figure 4, demonstrating the linearity of the FBG readings with respect to the applied load as expected.

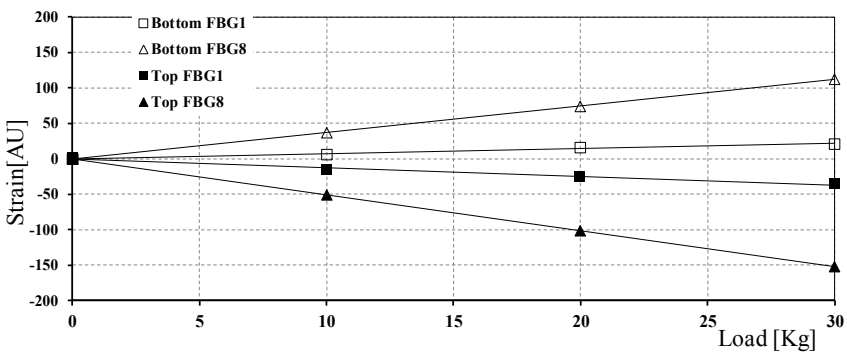

Figure 4: Typical Boom FBG calibration. At identical boom stations, top and bottom FBGs will have different strain magnitude

As explained earlier, the boom main loading condition is vertical bending. The bending moment distribution along the boom is complex and varies during UAV manoeuvers according to the loads induced by the wing and tail. It is extremely important to make sure the UAV do not exceed its designed limits during flight and automatic or manual controlled landing. Once the strain-to-bending conversion factors are evaluated by the above mentioned ground procedure, proper determination of the bending moment can be obtained from the measured strain at each FBG station. It should be noted that this strain to bending moment calibration, obtained by static test is also valid for dynamic loading. Since the UAV flies at high altitudes, where the temperature is significantly lower than on ground, temperature compensation for the FBG data is required. In order to evaluate the sensitivity of the embedded sensors to temperature, a heating (or cooling) test was conducted. FBG records were taken, on ground, both at a hot day and a cold night, resulting in a 20°C difference. The derived overall sensors sensitivity at each FBG station, assuming the temperature is the same at each FBG pair location, was thus found to be:

$$\begin{bmatrix} \varepsilon_{top} \\ \varepsilon_{bottom} \end{bmatrix} = \begin{bmatrix} K_{1T} & K_{1M} \\ K_{2T} & K_{2M} \end{bmatrix} \begin{bmatrix} T \\ M \end{bmatrix}, \tag{1}$$

where ε is the optical strain ($\Delta\lambda/\lambda$), T is the temperature change and M is the bending moment at a boom station, where strain is measured by pair of FBGs. The K matrix can be inverted making it possible to get both the temperature and bending moment for each pair of FBGs. Once the bending moment is known, using the ground calibration again, top and bottom mechanical strains can be calculated.

FLIGHT DATA EVALUATION

The first flight with the system fully operational was on October 2013. Typical FBG readings of boom mounted FBG (Top and bottom FBG-8, see Figure 2) is seen in Figure 5. The effect of engine start, takeoff, touch and go landing, acceleration to maximum speed and landing are clearly depicted by the FBG sensors. The effect of temperature is also seen as the UAV climbs to high altitude.

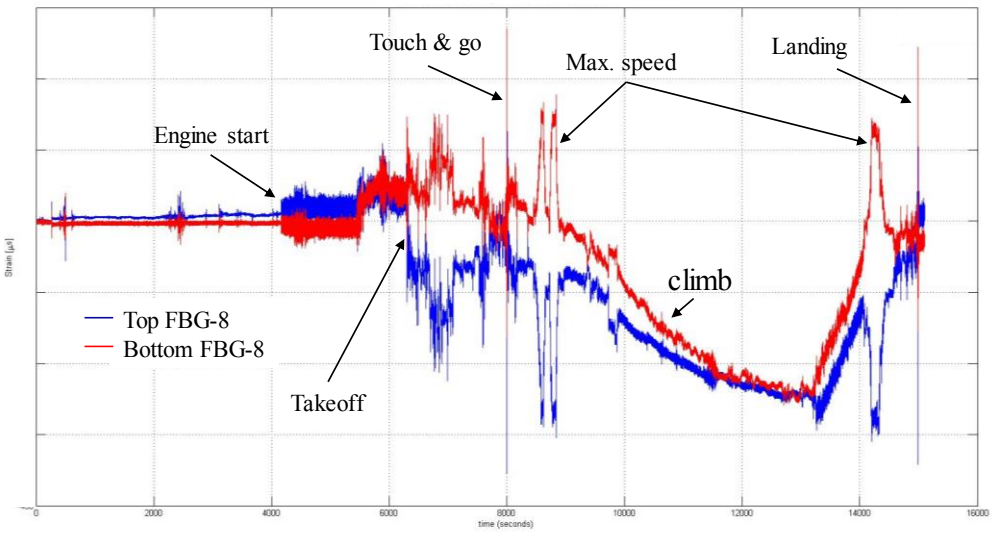

Figure 5: Typical FBG readings of boom mounted FBG (Top and bottom sensors)

By using Equation 1, the mechanical bending moment can be calculated and the individual mechanical strain at each sensor pair can be derived, as can be seen in Figure 6.
The high sampling rate of the interrogator enables tracking the dynamic behavior of the wing and booms. Since landing impact is the most critical boom loading it is of great interest to closely monitor the bending loads developed in the boom during the landing impact.
Typical boom bending moments derived from a specific landing are presented in Figure 7. The almost constant distribution of the bending moment along the boom indicates a complex loading condition, associated to its dynamic behavior.

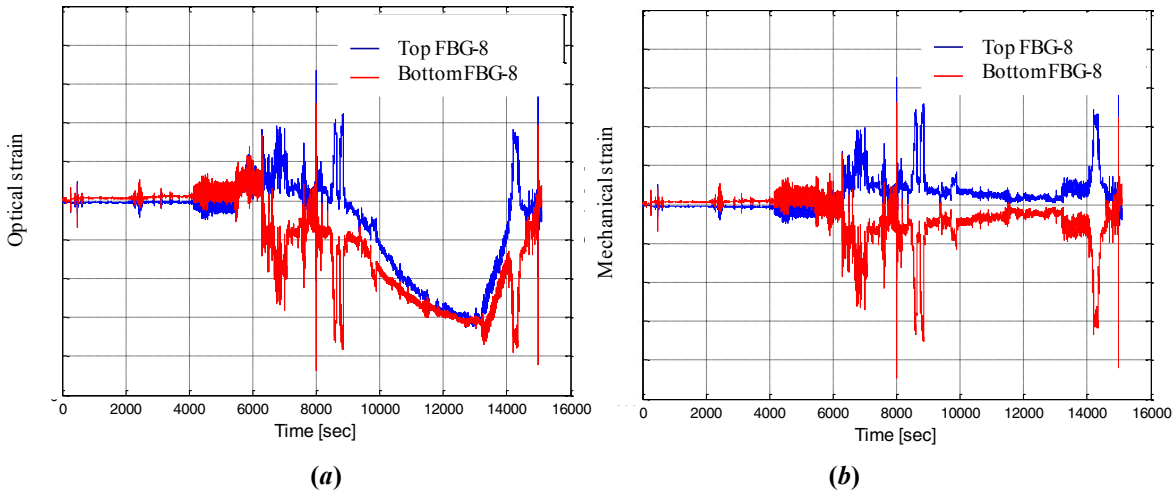

Figure 6: Boom FBG calibration. (a) Original FBG optical strain data. (b) Mechanical strain

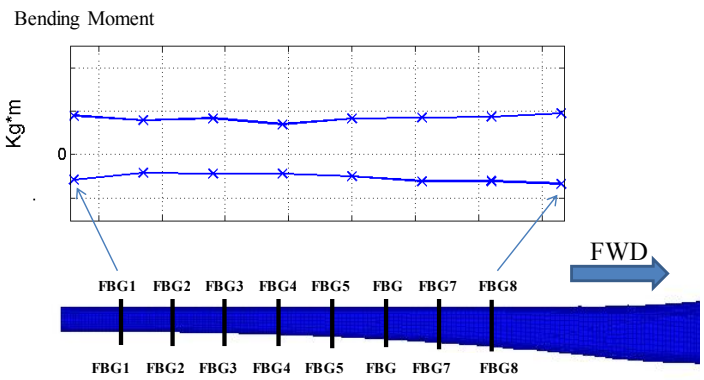

Figure 7: Boom bending moment envelope during landing

CONCLUSION

This fiber-optic-based sensing concept has already accumulated hundreds of flight hours without any failure in "real world" service environment. The system is easy to operate by the squadron personnel and flight data unloading for ground evaluation after flight is fast. All major flight events were clearly detected by the FBG sensor net. The system is easy to operate and the visual GUI enables a quick and basic evaluation of flight data. It also provides a deeper analysis when required. 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.

REFERENCES

[1] M. Neubauer, G. Gunteher and K. Fullhas, Structural Design Aspects and Criteria for MilitaryUAV.RTO-MP-AVT 145 UAV Design Processesand Criteria 2007.

[2] "STANAG 4671 (Edition 1) – Unmanned Aerial Vehicles Systems Airworthiness Requirements(USAR)," North Atlantic Treaty Organization Standardization Agreements, 2009

[3] C.R. Farrar and H.Sohn, Structural Health Monitoring Using Statistical Pattern Recognition Techniques, Journal of Dynamic Systems, Measurement, and Control, Volume 123, Issue 4, 706, 2001

[4] A Review of StructuralHealth Monitoring Literature: 1996–2001, Los Alamos National Laboratory Report, LA-13976-MS, 2004

[5] Staszewski W, Boller C and Tomlinson G. eds. Health monitoring for aerospacestructures, Wiley, Chichester, UK, 2004.

[6] K. Worden, C. R. Farrar, G. Manson, G. Park, The fundamental axioms of structural health monitoring, Proc. R. Soc. A 2007 463, 1639-1664, 2007

[7] C.R. Farrar and K. Worden, An introduction to structural health monitoring, Phil. Trans. R. Soc. A 15 vol. 365 no. 1851 303-315, 2007

[8] Todd, Michael D., et al. "Bragg grating-based fibre optic sensors in structural health monitoring." Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 365.1851 (2007): 317-343.

[9] C.Y. Park, J.H. Kim, S.M. Jun, A structural health monitoring project for a composite unmanned aerial vehicle wing: overview and evaluation test, Structural Control and Health Monitoring, Vol 19 Issue 7, 2012

[10] Derkevorkian A; AlvarengaJ.a; Sami F. Masri ; Helen; W. Lance Richards. "Computational studies of a strain-based deformation shape prediction algorithm for control and monitoring applications."." SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring. International Society for Optics and Photonics, 2012.

[11] M. Tur, I. Kressel, Y.Botsev, A. Handelman, P. Gud's, S. Ronen, S. Cohen, ACR Pillai, M. Hari Prasad, GM Kamath, N. Gupta, A. Khatkhate, S. Gali. "Flight Data from an Airworthy Structural Health Monitoring System for an Unmanned Air Vehicle Using Integrally Embedded Fiber Optic Sensors." 8th International Workshop on Structural Health Monitoring. USA: DEStech Publications, Inc. Vol. 1. 2011.