

# Advances in High temperature Fiber Optic Sensors for Turbine Engine Applications

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## ABSTRACT

Fiber optic based sensor arrays can provide multipoint temperature measurements and are lightweight, EMI-immune, electrically passive, and high temperature resistant. We report on recent results for a fiber optic temperature probe operating reliably and repeatedly in a turbine engine environment at 1080°F (over 580°C).

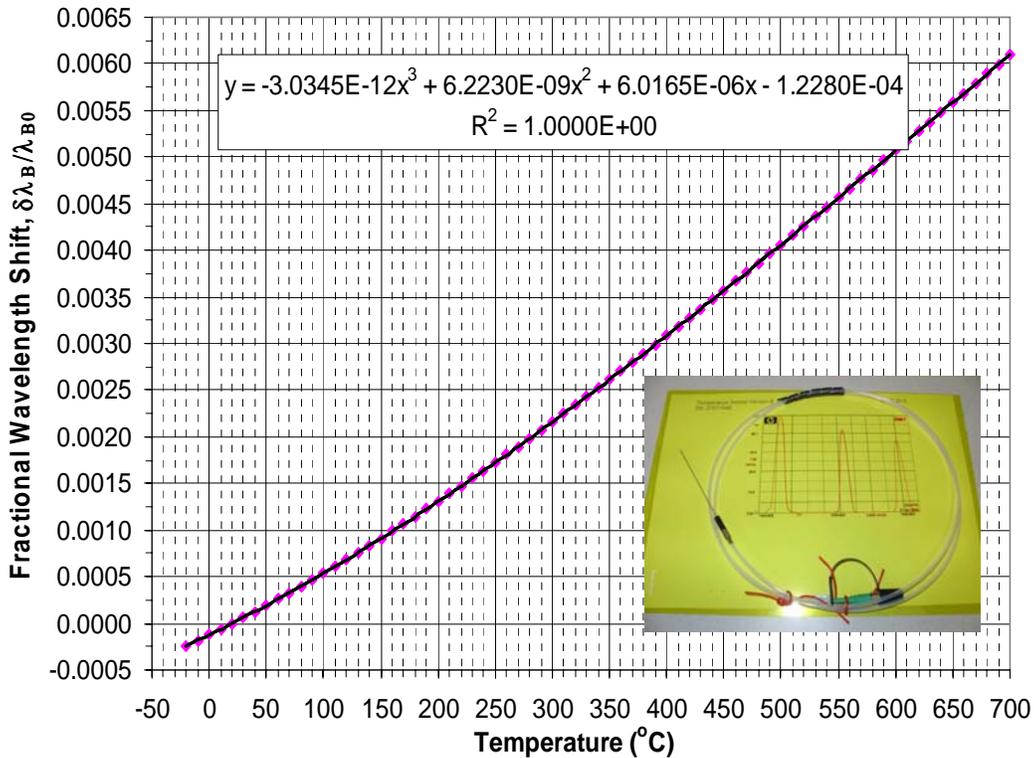
## 1 INTRODUCTION

In a paper [Mos11] presented at the 2011 International Instrumentation Symposium, we demonstrated multipoint temperature measurement using optical fiber sensors on a jet engine casing to 250°C. This work was part of a project involving development of a distributed sensor network for turbine engine applications based on a fiber optic backbone [Xia08] as a foundation for distributed engine control [Beh07, Cul08]. Fiber optic based sensor arrays can provide multipoint temperature measurements and are lightweight, EMI-immune, electrically passive, and high temperature resistant [Mos12]. In this paper, we demonstrate a significant advance using a robust multipoint temperature sensing probe to repeatedly measure temperatures with flawless operation at temperatures approaching 1100°C (600°C). The high temperature multi-FBG probe was able to respond to 10 Hz spikes while thermocouples were not. The probe also produced signals that were less noisy than thermocouple signals, particularly at high engine throttle settings, which affect thermocouple sensors more than they do the optical probe. Furthermore, it was also able to measure temperature profiles within the exhaust stack.

In the following sections, we first, in Sec. 2, describe the sensor probe supporting multiple sensors and calibration of this probe. Then, in Sec. 3, we described mounting of the probe in a jet engine exhaust stack and, in Sec. 4, temperature cycling measurements illustrating the above mentioned optical sensor array properties.

## 2 SENSOR PROBE AND CALIBRATION

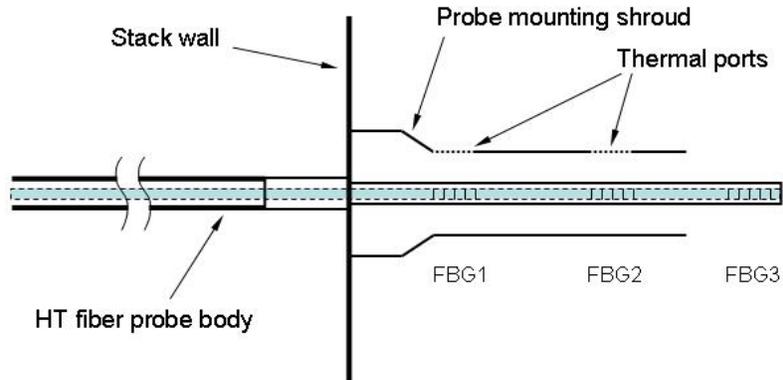
A fiber temperature sensing probe was developed including three high temperature fiber Bragg gratings (FBGs) on a single optical fiber with each FBG separated by 20 mm (center-to-center). While the resonant (Bragg) wavelength reflected by FBGs typically varies on the order of 10 pm per degree C, the temperature dependence is in general slightly nonlinear and depends on the FBG writing process. Thus, characterization of the response is particularly important in obtaining accurate FBG-based temperature sensors. The FBGs were calibrated against a type K thermocouple to obtain the temperature dependence of the fractional wavelength shift, i.e., the Bragg wavelength change  $\delta\lambda_B$  divided by the initial Bragg wavelength  $\lambda_{B0}$ , as shown in Figure 1.



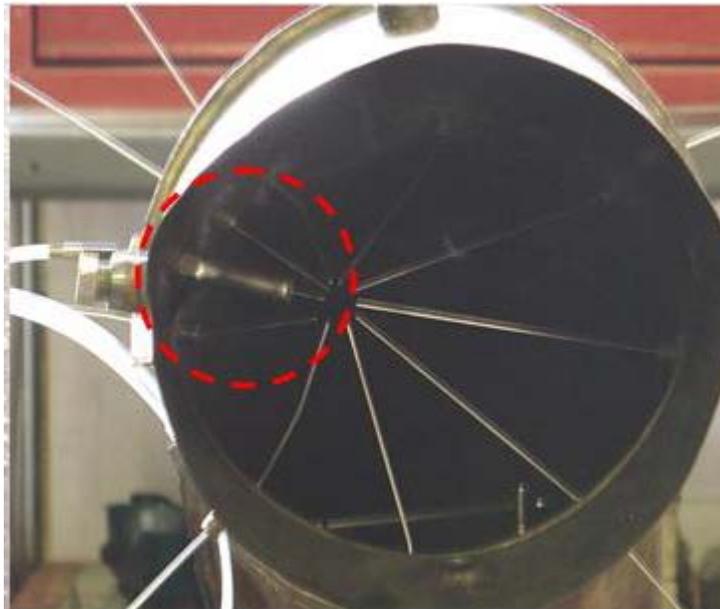
**Figure 1: Nonlinear temperature dependence of the 3 FBGs used for probe shown in the inset - a polynomial fit for the dependence is given where y corresponds to the fractional wavelength shift relative to the wavelength at 20°C and x is the temperature in °C and the  $R^2$  value for the fit is 1.**

## 3 EXHAUST STACK HIGH TEMPERATURE FBG SENSOR ARRAY MOUNTING

Our objective was to evaluate reliability and repeatability of the high temperature probe in the exhaust stack. Results for the high temperature (HT) FBG sensor probes in previous engine test showed incongruent responses, which apparently was due to the probe mounting shroud shielding two of the sensors in the array from sensing exhaust flow directly. To resolve this, careful probe measurements were made and the shroud was correspondingly modified to port exhaust gases such that all three FBG sensors can experience the exhaust flow, as shown in Figure 2.



**Figure 2: High temperature FBG probe mount modifications executed to improve response.**  
 The completed probe mounting in the exhaust stack is shown in Figure 3.



**Figure 3: Mounting of probe - thermal ports (hidden from view) on the shroud face the exhaust gas flow.**

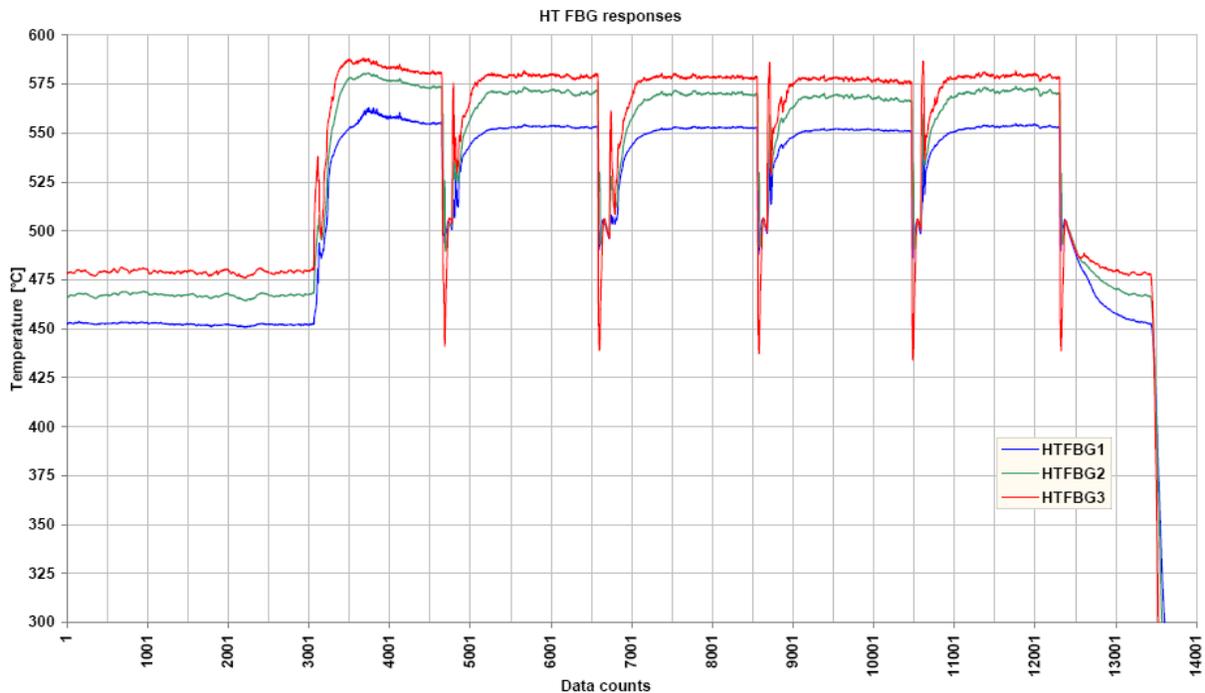
#### **4 JET ENGINE TEMPERATURE CYCLING & EXHAUST STACK MEASUREMENTS**

Successive temperature measurements were made for a series of five tests plans. As an illustrative example, Table 1 shows the fifth test plan. This plan was devised to simulate an urgent touch-and-go flight pattern. As can be seen from Figure 4, a fast throttle snap down towards Engine Power (EP) = 55~60% is possible with this PT6 engine, as well as the ability to maintain fairly consistent EP = 100% operation levels after each snap. Figure 4 definitively shows the superior transient response capability of high temperature FBG arrays for jet engine performance monitoring.

With all test plans completed and documented, they clearly showed that the exhaust gas is indeed hotter towards the center of the flow pattern. Furthermore the exhaust stack data patterns correlate with those of the engine casing RTD.

**Table 1: Test plan**

|     | Test Plan: Idle snap + maximum power dwell – 4 (snap) cycles | Total Elapsed Time (Mins, Secs) |
|-----|--|---------------------------------|
| 1.  | Idle for 5 minutes   | 05'00"                          |
| 2.  | Fast ramp to max and hold for 3 minutes                      | 08'00"                          |
| 3.  | Fast ramp down to idle, count 5, fast ramp up to max         | 08'30"                          |
| 4.  | Fast ramp to max and hold to 3 minutes from ramp             | 11'30"                          |
| 5.  | Fast ramp down to idle, count 5, fast ramp up to max         | 12'00"                          |
| 6.  | Fast ramp to max and hold to 3 minutes from ramp             | 15'00"                          |
| 7.  | Fast ramp down to idle, count 5, fast ramp up to max         | 15'30"                          |
| 8.  | Fast ramp to max and hold to 3 minutes from ramp             | 18'30"                          |
| 9.  | Fast ramp down to idle, count 5, fast ramp up to max         | 19'00"                          |
| 10. | Fast ramp to max and hold to 3 minutes from ramp             | 22'00"                          |
| 11. | Fast ramp down to idle and hold for 3 minutes from ramp      | 25'00"                          |



**Figure 4: High temperature FBG response for the the test plan in Table 1.**

## 5 CONCLUSIONS

The following conclusions can be drawn from the extensive testing carried out since our last year’s paper:

- Sensor accuracies achievable with optical sensors are comparable or better than legacy systems used in jet engine FADECs (Full Authority Digital Engine Control). Tests support a high degree of repeatability for the optical sensors. Certainly optical sensor data proved reliable and repeatable to a high degree. They also had much faster response times than legacy thermocouples and are generally believed to have much lower noise levels during high engine throttles. The external materials and mounting methods used for the optical probe were the same as for an equivalent legacy probe.
- Cost reductions in instrumentation system complexity and installation labor are still expected due to the simplicity and elegance of the optical networking solution.

- Weight reduction and fan efficiency improvements of engine system are expected due to the use of very low weight, low power fiber optic cables replacing complex and power hungry wire harnesses.
- Significant improvements in sensor scalability and data quality are expected due to the multiplexibility of the optical ring networks and the immunity of the optical circuits to EM noise, resulting in lower noise performance for high engine throttles.
- Improved engine test schedules and accelerated time to market are expected due to the suitability of the optical solution for introduction into test beds and engine development cycles and the commonality of the interfaces it requires.
- Measuring fan inlet and exit temperatures is used in the calculation of fan efficiency. Fractions of degrees can impact fan efficiency. The advances achieved in this program will allow high temperature optical sensors to be placed closer to hot points of interest for direct as opposed to deduced measurements. Given the sensitivity of turbo fan efficiencies to minute temperature variations across the fan and circumferentially around the fan, the optical system will lend itself well for a new level of control and efficiency.

## 6 ACKNOWLEDGEMENTS

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## 7 REFERENCES

- [Beh07] Behbahani, A. R., Culley, D., Smith, B. J., Darouse, C., Millar, R. C., Wood, B., Krodel, J., Carpenter, S., Mailander, W., Mahoney, T. D., Quinn, R., Bluish, C. P., Hegwood, B., Battestin, G., Roney, W., Rhoden, W., and Storey, W., "Status, Vision, and Challenges of an Intelligent Distributed Engine Control Architecture", Society of Automotive Engineers Paper 2007-01-3859, Sept. 2007
- [Bla10] R.J. Black, B. Moslehi, "Advanced end-to-end fiber optic sensing systems for demanding environments," (Invited Paper), SPIE Optics & Photonics 2010, Conference OP413 *Nanophotonics and Macrophotonics for Space Environments I*, Proc. SPIE **7817**, Paper 7817-20, 2010 - [http://spiedigitallibrary.org/proceedings/resource/2/psisdg/7817/1/78170L\\_1](http://spiedigitallibrary.org/proceedings/resource/2/psisdg/7817/1/78170L_1)
- [Cul08] D. Culley and A.R. Behbahani, "Communication needs assessment for distributed turbine engine control," in Proc. 44th AIAA Joint Propulsion Conference & Exhibit, Hartford, CT (2008).
- [Mos11] B. Moslehi, V. Sotoudeh, F. Faridian, J.M. Costa, R.J. Black (IFOS); A.Behbahani (AFRL);W. O'Brien, D.S. Ha (Virginia Tech); M. Austin (Pratt & Whitney), "Intelligent and Robust Sensors using Fiber optic Network Distributed Engine Control," Proc. 57th International Instrumentation Symposium, St. Louis, Missouri, June 20-24, 2011 – International Society of Automation (ISA) Vol. 488 – ISBN: 978-1-936007-86-8 - [http://www.isa.org/Template.cfm?Section=Technical\\_Paper\\_Collections&template=/Ecommerce/ProductDisplay.cfm&ProductID=11570](http://www.isa.org/Template.cfm?Section=Technical_Paper_Collections&template=/Ecommerce/ProductDisplay.cfm&ProductID=11570)
- [Mos12] B. Moslehi, R.J. Black, J.M. Costa, V. Sotoudeh, F. Faridian, "Highly scalable operational sensor system for harsh environment applications," SAMPE 2012, Baltimore, May 24, 2012.
- [Xia08] M. Xia, B. Moslehi, B. Mukherjee, A. Behbahani, and R. Millar, "CORIN/DORIN: A WDM-enabled platform for aero-engine control systems," in Proc. Avionics, Fiber optics and Photonics Technology Conference - AFOP'08 (IEEE, 2008), pp. 77–78.