International Conference on Space Optics—ICSO 2008

Toulouse, France

14–17 October 2008

Edited by Josiane Costeraste, Errico Armandillo, and Nikos Karafolas

A versatile fibre optic sensor interrogation system for the Ariane Launcher based on an electro-optically tuneable laser diode

M. P. Plattner

F. Hirth

M. S. Müller

L. Hoffmann

et al.

International Conference on Space Optics — ICSO 2008, edited by Josiane Costeraste, Errico Armandillo, Nikos Karafolas, Proc. of SPIE Vol. 10566, 105661D · © 2008 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2308218

A VERSATILE FIBRE OPTIC SENSOR INTERROGATION SYSTEM FOR THE ARIANE LAUNCHER BASED ON AN ELECTRO-OPTICALLY TUNEABLE LASER DIODE

M. P. Plattner, F. Hirth, M. S. Müller, L. Hoffmann, T. C. Buck, A. W. Koch

Technische Universität München, Institute for Measurement Systems and Sensor Technology
Theresienstr. 90, 80333 München, Germany, Email: m.plattner@tum.de

ABSTRACT

Availability of reliable flight sensor data and knowledge of the structural behaviour are essential for safe operation of the Ariane launcher. The Ariane launcher is currently monitored by hundreds of electric sensors during test and qualification. Fibre optic sensors are regarded as a potential technique to overcome limitations of recent monitoring systems for the Ariane launcher [1]. These limitations include cumbersome application of sensors and harness as well as a very limited degree of distributed sensing capability. But, in order to exploit the various advantages of fibre optic sensors (high degree of multiplexing, distributed sensing capability, lower mass impact, etc.) dedicated measurement systems have to be developed and investigated. State-of-the-art fibre optic measurement systems often use free beam setups making them bulky and sensitive to vibration impact. Therefore a new measurement system is developed as part of the ESA-study [2].

1. INTRODUCTION

Instruments based on tuneable lasers are established devices for demodulation of fibre optic sensors [3]. However, when it comes to the number of sensors, versatility in application, cost, vibration hardness or installation space, shortcomings in the current generation of these measurement systems are obvious.

We propose a new tuneable laser measurement system based on an electro-optically tuneable laser diode that is capable of demodulating various kinds of fibre optic sensors. In this work we focus on interrogation of fibre Bragg grating sensors and explain the system setup in hard- and software. New measurement algorithms are implemented in order to reduce measurement time.

2. MEASUREMENT SETUP

Our measurement setup that demodulates the individual sensors of a sensor network basically consists of three parts: The tuneable laser diode, a controller and a data acquisition unit (figure 1).

The laser diode is a monolithic device. Its output wavelength is tuneable in the wavelength range from 1527 nm to 1568 nm by adjusting an input current triplet.

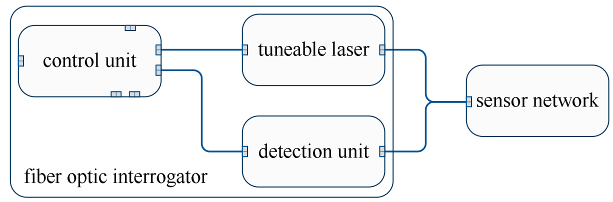

Figure 1. Setup of fiber optic interrogation unit. The output of the tuneable laser diode is adjusted by the control unit. The sensor answers are measured by a detection unit and evaluated by the control unit.

The controller unit adjusts the output wavelength of the laser diode by the use of three digital to analogue converters which produce the set of control currents. The control currents can be adjusted in the range of 0.5 mA to 30 mA. The control inputs of the laser diode show a characteristic curve as depicted in figure 2. Therefore the output voltage of a DAC has to be adjusted in the range of 0.79 V to 1.01 V.

The detection unit basically consists of photo detectors and amplifiers. Reflected intensities of sensors in the sensor network are measured and sent to the controller unit for evaluation. The measured intensities have to be assigned to the corresponding output wavelength without any ambiguity.

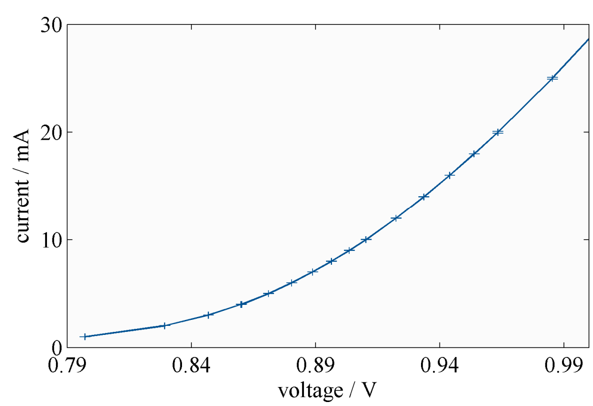

Figure 2. One of three input control currents of the tuneable laser diode. Adjusting the output wavelength is done by controlling three input currents.

2.1. Tuneable laser diode

Adjusting the minimal stepsize of the DACs to 5 mV, a theoretical number of 64,000 different wavelengths is available. Since not every current triplet leads to a stable

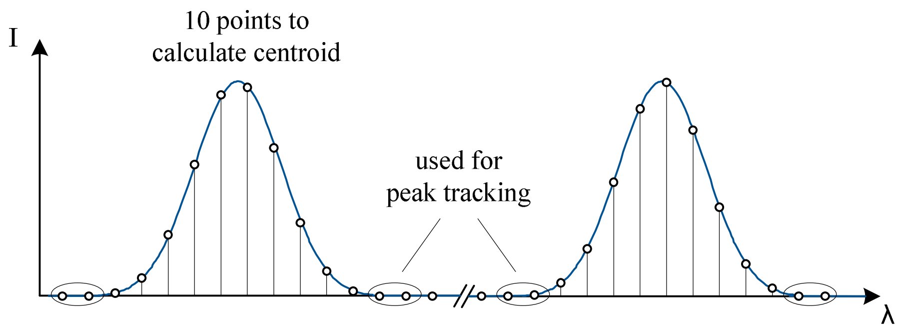

Figure 3.Two sensor answers sampled for centroid determination scheme. Ten wavelengths with a mean distance of ≈20 pm are used to sample one sensor. The peak wavelength is calculated by centroid algorithm. The zero-intensity points at the ends of the sensor answer are observed for the peak tracking algorithm. The skipped part of the wavelength axis contains ≈10^3 sampling points that are all zero and therefore unneeded for the measurement.

output wavelength, the laser source needs to be characterized prior it can be implemented in the measurement setup. Therefore an additional wavelength meter must be used instead of the intensity based detection unit. A characterization cycle is performed, that alters all control currents subsequently and maps the obtained output wavelength to the adjusted current triplet. If current triplets do not yield stable output wavelengths, these are skipped.
A total number of approximately 10^4 stable wavelengths are available after laser characterization. The mean spectral distance between two consecutive output wavelengths of the laser diode is ≈4 pm. Considering a nominal fiber bragg grating that has a spectral width of ≈200 pm, 50 sampling wavelengths can be used to calculate the current sensor position. If for example one sensor was sampled by 10 wavelengths, the used subset of wavelengths would be chosen such that two successive sampling points have a spectral gap of ≈20 pm.

2.2. Controller unit

The Controller unit is used for adjusting the current triplet of the laser diode and for recording the intensity values of the detection unit. Therefore it utilizes a FPGA connected to three DACs for generating the required set of control voltages. Furthermore ADCs are addressed by the FPGA to convert the analog output signals of the detection unit. One ADC is used for one fiber channel. At the current configuration four ADCs are included which allow three sensor fibers to be connected to the interrogator. The fourth ADC is used for monitoring the intensity of the actual output wavelength. The output intensity varies with the current wavelength. Thus by monitoring the output intensity, the detected intensities are normalized. The laser output and the detector input signals must be synchronized. This is achieved by time of flight (ToF) measurement as described in chapter 3 of this article.

2.3. Detection unit

A photo diode is used for converting the optical input signals to intensity dependent voltages. The output voltages of the detector are amplified by an operational amplifier and fed to the ADC of the controller unit. During the characterization cycle of the laser diode, the described intensity detection unit is replaced by a wavelength meter to find stable wavelengths.

3. MEASUREMENT SCHEMES

The aim of the interrogator system is to measure the peak wavelength of a fiber sensor signal. Two different schemes for detecting the peak of a fiber sensor are described in this paper: Centroid determination and edge scanning.

3.1. Centroid determination

Sampling through the full width of the peak with ten sampling points results in ten intensities that characterize the sensor's answer (figure 3). The peak wavelength will thereafter be calculated by centroid algorithms. A shift of the peak wavelength causes changes in the intensities of the reflected wavelengths.

3.2. Edge scanning

By scanning one or both edges of the sensor as depicted in figure 4, an intensity proportional to the position of the sensor is received. A wavelength shift leads to linear (within 20 to 80 % of the sensors maximum reflectivity) relation between the peak wavelength and the reflected intensity amplitude. By scanning both edges of a sensor peak, the spectral width of it is determined. Therefore also birefringence may be detected if the peak splits up to two polarization components.

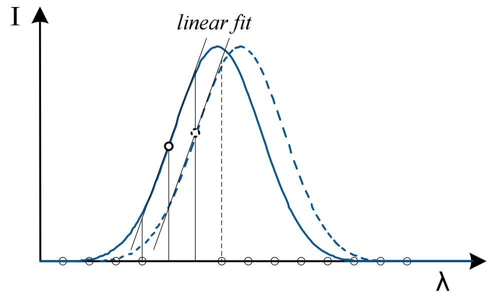

Figure 4. Edge scanning scheme. The left edge of the sensor is sampled by one wavelength (solid line). If the peak shifts to higher wavelengths (dashed line) and leaves the linear approximation area, the next higher wavelength point will be used for measurement.

4. SOFTWARE ARCHITECTURE

Continuously tuneable laser sources usually sweep through their entire wavelength range during one measurement cycle [3]. Since our laser diode is capable of switching to every stable wavelength within its 40 nm range, a continuous sweep is not practical. To avoid needless sampling of points that show zero-intensity a peak tracking algorithm can be implemented.

4.1. Peak tracking

Under normal operation conditions one sensor is evaluated by sweeping through its spectrum and sampling it on different wavelength points. By the use of these intensity values, the centroid is calculated. A sensor shifts in wavelength due to environmental influences. The wavelength area that it is able to cover during its nominal operation needs to be reserved. It has to be ensured that two consecutive sensor answers are not able to overlap. If for example one temperature sensor is defined to measure a temperature range of 100 K this results in a wavelength shift of approximately 1.5 nm which needs to be reserved for this sensor. Having a mean sample distance of ≈5 pm, 375 sampling points can be used to evaluate the sensor's answer. Since the width of the sensor peak is only ≈200 pm, 325 sample points yield zero intensity. By not sampling the unnecessary points, measurement time can be reduced to less than 15 % compared to a sweep through the whole wavelength spectrum of one sensor. To achieve this reduction in measurement time a special peak tracking needs to be performed in order not to lose the sensor position.

This algorithm uses two additional samples, one sample at each end of the peak. Both additional samples have zero intensity. In the event that the peak starts shifting due to e.g. a rise in temperature, the right zero-intensity point switches from zero to none zero intensity. Additionally the number of zero intensity points at the left end of the peak rises. The next point at higher wavelengths needs to be evaluated; the most left point is skipped.

It has to be insured that the sample rate is high enough in order to cope with the expected speed in wavelength shift.

4.2. Time of Flight (ToF) measurement

The output pulses of the laser need to be synchronized with the input intensity measurement. As shown in figure 5, several fiber sensors can be implemented in one single measurement channel. The maximum number is limited by the application. Every sensor has its reserved wavelength area. If for instance one sensor has a reserved area of 5 nm, the maximum number of sensors within one fiber is limited to eight. Since the quantities and positions of the sensors inside one channel vary for each measurement application, the

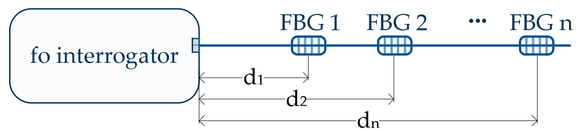

Figure 5. One sensor channel connected to the interrogator. Up to n sensors can be implemented into one single sensor fiber depending on the reserved spectral area per sensor.

"Time of Flight" (ToF) for each sensor has to be evaluated prior to the operation of the system. The ToF_i of sensor i is dependent on the distance d_i between the interrogator unit and the sensor:

$$ToF_i = \frac{2d_i \cdot n}{c} \qquad (1)$$

wherein c is the vacuum speed of light and n stands for the refractive index of the fiber.

At the beginning of a new measurement the ToF of every sensor in the sensor network needs to be measured and saved in the controller unit. If sensor i shall be evaluated, the controller adjusts the laser to produce wavelengths within the spectral width of sensor number i. After one sampling pulse has been sent to sensor i, the controller must wait a time period equal to ToF_i before valid intensities can be transferred from the detection unit.

Although the refractive index $n=n(\lambda)$ inside the sensor fiber is a function of the laser's wavelength λ (chromatic dispersion), it alters only by 0.034 % (according to the Sellmeier equation [4]) within the full 40 nm bandwidth of the laser diode. The ToF of a sensor with the distance of 100 m to the interrogator therefore only changes by less than 0.3 ns.

4.3. Sample rate calculation

It must be distinguished between two different sample rates. The laser diode is able to produce sample rates at 10 GHz. But this sample rate of one single wavelength is limited by the ADC which has a maximum sample rate of SR_{ADC}=25 MS/s at the current hardware configuration. This means that the minimum time for one sampling point is 40 ns. Since a sensor is sampled by several different wavelengths for the centroid scheme (usually ten), the maximum sample rate per sensor (SRPS) is by the factor of sampling points (SP) lower. The SRPS is also dependent on the number of sensors *n* that shall be evaluated. In general the SRPS is given by

$$SRPS = \frac{SR_{ADC}}{n \cdot SP}\,. \qquad (2)$$

Averaging which yields improved SNR further reduces the SRPS.

5. CONCLUSION

We have discussed our activities concerning the development of a fiber optic interrogator for sensing applications. The work is part of the *European Space Agency* study “Structural Monitoring of Ariane Launcher using Fiber Optics” [2]. The interrogation system consists of a monolithic tuneable laser diode, controller and detection unit. Evaluating the peak wavelength of Bragg gratings with two different measurement schemes was described. New algorithms implemented in the controlling unit reduce the measurement time compared to continuously sweeping systems. The possibility of peak tracking and time of flight measurement was explained.
The implemented system is set up in an industrial PC to a quite compact size as a first step towards a system for space use. Environmental tests assuring space requirements are to be executed.

6. ACKNOWLEDGEMENT

We would like to thank Arnd Reutlinger from Kayser-Threde GmbH for his support during the project.

REFERENCES

[1] McKenzie I., Karafolas N., *Fiber Optic Sensing in Space Structures: The Experience of the European Space Agency*, Proceedings of SPIE 5855, p. 263, 2005.

[2] European Space Agency, *Fiber Optic Sensors for Structural Monitoring of the Ariane Launcher*, Statement of Work, contract number 1-5353/07/NL/CP, 2007.

[3] Measures R. M., Ohn M. M., Huang S. Y., Bigue J., Fan N. Y., “Tunable laser demodulation of various fiber Bragg grating sensing modalities,” Smart Materials and Structures 7 (2), p.237, 1998.

[3] Betz D. C., Thursby G., Culshaw B., Staszewski W. J., *Identification of structural damage using multifunctional Bragg grating sensors: I. Theory and implementation*, Smart Materials and Structures 15, p. 1305, 2006.

[4] Malitson I. H., *Interspecimen comparison of the refractive index of fused silica*, Journal of the Optical Society of America 55, p. 1205, 1965.