

Fiber-optic Distributed Strain and Temperature Sensor using BOCDA Technology at High Speed and with High Spatial Resolution

- Taking on Aircraft Structural Health Monitoring -

Yoshihiro Kumagai *¹ **Satoshi Matsuura** *¹ **Takashi Yari** *² **Nozomi Saito** *²
Kazuo Hotate *³ **Masato Kishi** *³ **Mikio Yoshida** *⁴

Yokogawa Electric Corporation, Mitsubishi Heavy Industries Ltd., the University of Tokyo, and the Materials Process Technology Center (SOKEIZAI Center) are developing a new fiber-optic distributed strain and temperature sensor for aircraft structural health monitoring (SHM) using Brillouin optical correlation domain analysis (BOCDA) technology. The BOCDA is suitable for aircraft SHM because it can measure the distribution of strain and temperature simultaneously at high speed and with high spatial resolution. A prototype on-board system was developed and mounted on a business aircraft in order to evaluate it during actual aviation. Changes in strain and temperature on the aircraft during ascent have been successfully measured. This paper outlines the prototype and explains the results of the evaluation.

INTRODUCTION

In recent years, lightweight and high-strength composite materials have been used for many airframes, and their rate for the Boeing 787 aircraft is more than 50%. Although many composite materials are used in a primary structure, much manpower is required for its inspection due to the complexity of its fracturing process. Thus, structural health monitoring (SHM) technology for an aircraft structure is expected to reduce the burden.

We are developing a new aircraft SHM technology applying an optical fiber as the strain sensor. It uses Brillouin optical correlation domain analysis (BOCDA) to measure the distribution of strain and temperature simultaneously at high speed and with high spatial resolution. We have developed a prototype shown in Figure 1 which achieves a discriminative measurement of strain and temperature, which has been the

difficulty in sensors using Brillouin scattering. This report describes its performance evaluation results and the issues to be resolved.



Figure 1 External view of the BOCDA prototype

BOCDA MEASUREMENT TECHNOLOGY

Brillouin scattering and fiber-optic sensor

As light propagates through an optical fiber, slight scattering occurs in every location of the fiber. As shown in Figure 2, the light scattering is classified into three types: Rayleigh, Brillouin and Raman scattering.

Among these, Brillouin scattering can be used for distributed strain and temperature measurement in an optical fiber, which is the sensor itself. Thus, features such as compact size, light weight, explosion proofness, lightning resistance, immunity to EMI, long life, low corrosiveness, no power supply required, and a wide operating temperature range are attained.

*1 Research & Development Division, Innovation Headquarters
*2 Structural Mechanics Research Laboratory, Nagoya Research & Development Center, Technology & Innovation Headquarters, Mitsubishi Heavy Industries, Ltd.
*3 Department of Electrical Engineering and Information Systems, Graduate School of Engineering, The University of Tokyo
*4 Aircraft Materials Engineering Division, RIMCOF Research Center of Advanced Metals and Composites, The Materials Process Technology Center (SOKEIZAI Center) Currently, Civil Aircraft Engineering Service Co., Ltd.

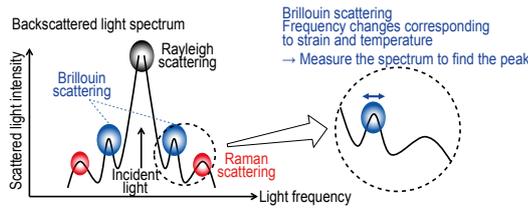


Figure 2 Light scattering within an optical fiber

Brillouin scattering is the phenomenon in which light is scattered by an acoustic wave in an optical fiber. Brillouin scattering is categorized into spontaneous Brillouin scattering caused by a natural acoustic wave in a fiber, and stimulated Brillouin scattering caused by interaction of light and an induced acoustic wave in a fiber which is generated when two lights propagating in opposite directions in a fiber meet certain conditions.

When 1.55 μm band light is launched into a single-mode optical fiber, the scattered light frequency is approximately 11 GHz apart from the incident light frequency. This frequency difference between them is called a Brillouin frequency shift (BFS). It is known that the BFS changes in a linear dependence corresponding to the strain in the fiber axial direction ⁽¹⁾, and research and development for applying this characteristic to SHM is progressing.

In order to determine a BFS, measurement of a Brillouin gain spectrum (BGS) is required. Typical methods for measuring the distribution of the BFS along the longitudinal direction of a fiber are a time-domain method and a correlation-domain method.

In the time-domain method, light pulses are launched into an optical fiber and the temporal change in Brillouin backscattering which is generated at every place along the fiber during the propagation of the light pulses is observed. The observation results determine where and how much scattered light is generated in the fiber, i.e. measured positions are identified. The measurement technology / instrument measuring spontaneous Brillouin scattering in the time domain is called the Brillouin optical time domain reflectometry / reflectometer (BOTDR). Corresponding Yokogawa’s products have been widely used for quality management of the manufacturing and installation of optical fibers, monitoring for landslides, and SHM for bridges and tunnels. ⁽²⁾

The correlation-domain method is a technology proposed by the Hotate group in the University of Tokyo, featuring the control of a measured position by light source modulation, high-speed, high spatial resolution, random access to any desired positions to be measured, and so on. ⁽³⁾

Because the aircraft SHM requires both high spatial resolution and high speed measurement, the BOCDA method measuring stimulated Brillouin scattering in the correlation-domain is most suitable.

Principles of the BOCDA method

As shown in Figure 3, the pump and probe light are launched into each end of the fiber-optic sensor, and they

propagate in opposite directions. The pump and probe light are frequency modulated with the same frequency. At the specific point in the fiber called the correlation peak, the frequency difference between the two lights becomes constant.

When the pump light frequency is higher than that of the probe light by the BFS, the probe light is amplified with the Brillouin gain, caused by stimulated Brillouin scattering. In contrast, at any locations other than the correlation peak point, the probe light is hardly affected by the gain, because the frequency difference between the pump and probe light fluctuates significantly. As a result, the BFS of the detected probe light is nearly equal to that at the correlation peak point. Thus, the strain or temperature at the correlation peak point can be obtained from this BFS.

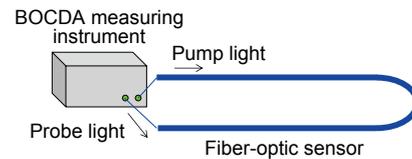


Figure 3 Principles of the BOCDA method

Technology for discriminative measurement of strain and temperature ⁽⁴⁾

Because the BFS is affected by both the strain and temperature of the fiber as described above, it is necessary to identify whether the cause of the change in BFS is due to strain or temperature, in order to apply the BOCDA to an aircraft exposed to significant changes in ambient temperature.

Discriminating strain and temperature can be accomplished by additionally measuring a second parameter which is affected by both strain and temperature and independent of the BFS. Strain and temperature can be calculated by using the BFS and the second parameter. The birefringence of a polarization maintaining fiber (PMF) can be adopted as the second parameter.

First, the pump and probe light are launched into a PMF aligning their directions of polarization with the x-axis (slow axis) of the PMF section to generate a Brillouin dynamic grating (BDG) at the correlation peak point. Then, read-out light is entered into the PMF aligning its direction of polarization with the y-axis (fast axis) of the PMF section while sweeping its frequency to obtain the frequency f_{yx} at which the dynamic grating spectrum (DGS) from the BDG reflection is maximum. Because the f_{yx} is derived from the birefringence, strain and temperature can be calculated from the BFS and f_{yx} .

Specifically, the variation in strain and temperature, $\Delta\varepsilon$ and ΔT , are given by the equation below; where C_v^ε and C_v^T are the coefficients of strain and temperature dependency on the BFS respectively, C_f^ε and C_f^T are the coefficients of strain and temperature dependency on the f_{yx} respectively, and $\Delta\nu_B$ and Δf_{yx} are the variation of the BFS and the f_{yx} respectively.

$$\begin{pmatrix} \Delta\varepsilon \\ \Delta T \end{pmatrix} = \frac{1}{C_v^\varepsilon \cdot C_f^T - C_v^T \cdot C_f^\varepsilon} \begin{pmatrix} C_f^T & -C_v^T \\ -C_f^\varepsilon & C_v^\varepsilon \end{pmatrix} \begin{pmatrix} \Delta\nu_B \\ \Delta f_{yx} \end{pmatrix}$$

EVALUATION RESULTS OF THE PROTOTYPE

Overview of the prototype and the performance evaluation of the discriminative measurement of strain and temperature ⁽⁵⁾

We have developed a prototype using the principles described in the previous section, and evaluated performance of the discriminative measurement of strain and temperature. Table 1 shows the specifications of the prototype. To use it on aircraft, it conforms to the ARINC 600 Series standards for avionics equipment. The prototype consists of an optical system unit, a power supply unit and a measuring unit. Figure 4 shows its configuration and evaluation system.

Table 1 Specification of prototype

Dimensions	Optical system unit: 400 mm (W) × 450 mm (D) × 200 mm (H) Power supply unit: 60 mm (W) × 450 mm (D) × 200 mm (H)
Maximum measurable distance	500 m
Spatial resolution	30 mm (BGS), 300 mm (DGS)
Strain and temperature resolution (σ)	Strain: 60 $\mu\epsilon$, Temperature: 1 °C
Measurement rate	4 Hz (simultaneous measurement of strain and temperature) 160 Hz (BFS only)

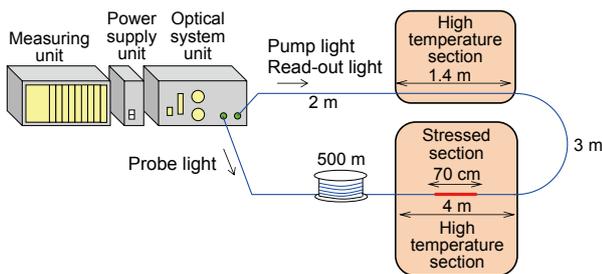
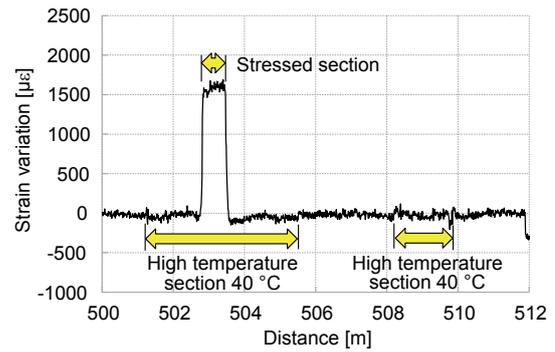


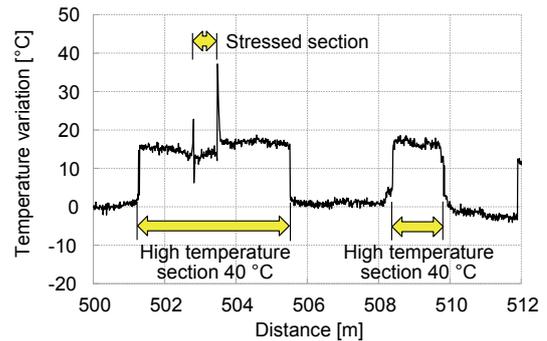
Figure 4 Configuration of the prototype and its evaluation system

The optical fiber prepared for the evaluation is comprised of a 500 m room temperature section, a 4 m high temperature section at 40 °C (which includes a 70 cm portion with a strain stress applied), a 3 m room temperature section, a 1.4 m high temperature section at 40 °C and a 2 m room temperature section, in that order. The probe light is entered into the 500 m room temperature section, and the pump and read-out light are entered into the 2 m room temperature section.

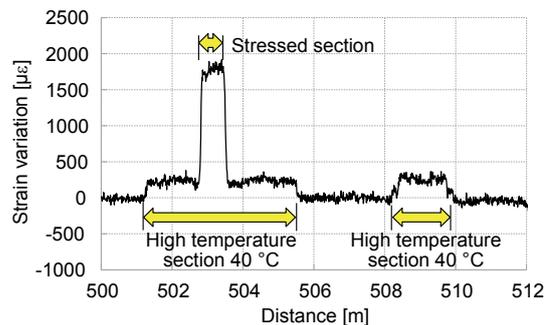
The measurement results are shown in Figure 5 (a), (b). For comparison, the results of the measurement using the conventional method employing BFS only, which does not discriminate strain and temperature, are shown in Figure 5 (c). These figures show that the conventional method cannot distinguish the variation in strain and temperature; in contrast the new method can discriminate strain and temperature. In the results of the temperature measurement after discrimination, temperature disturbances are seen at both ends of the stressed section. This is because the BDG is spread over the correlation peak point ⁽⁶⁾. We will continue to address this issue.



(a) Strain variation after separation of strain and temperature



(b) Temperature variation after separation of strain and temperature



(c) Strain variation by conventional method

Figure 5 Evaluation of discriminative measurement of the strain and temperature of the prototype

Evaluation using a business aircraft ^{(7), (8)}

The prototype was mounted on a business aircraft to evaluate its performance, and identify the issues. The aircraft was a MU-300 business jet manufactured by Mitsubishi Heavy Industries Ltd. As shown in Figure 6, approximately 1 m of a fiber-optic sensor was attached on the front spar of the vertical tail, and strain gauges and a thermocouple were also placed adjacent to the sensor for reference.

The strain and temperature were measured from the start of the taxiing and during ascent. Figure 7 shows the measurement results.

The aircraft traveled on the ground for approximately 100 seconds from the start of the measurement. Significant fluctuation was seen in the measurement results and it was found that the vibration while taxiing affected the

measurements. We will continue to address this issue.

From taking off to the time approximately 600 seconds after the start of the measurement, it was shown that ambient air temperature went down as the aircraft ascended. During this period, there were no significant changes in the strain measurement results, and so strain and temperature separate measurements were considered to be working properly. After that, the deviation of the measurement results by the BOCDA method from those by the strain gauge and thermocouple was increasing. We consider that this was due to the change in the birefringence characteristics in the fiber-optic sensor. As the ambient air temperature drops, the aluminum alloy (material of the aircraft) shows thermal contraction and causes strain of the fiber-optic sensor from tensile to compressive. It can be resolved by giving a tensile strain to the fiber-optic sensor in advance when attaching it.

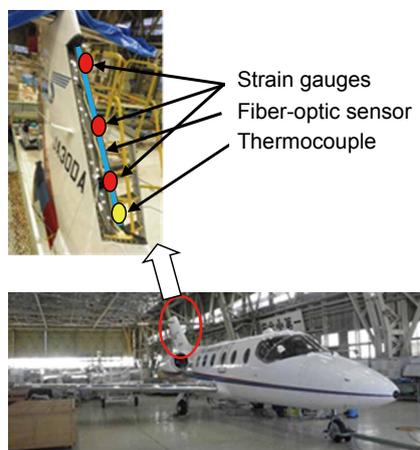


Figure 6 MU-300 business jet used for the evaluation and its mounted sensor portion

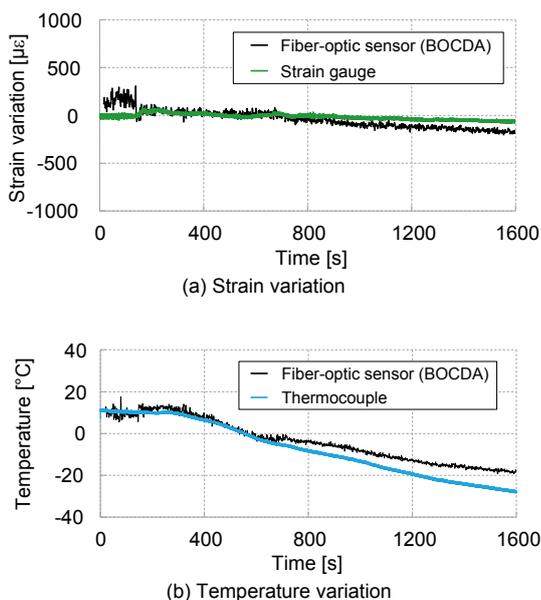


Figure 7 Strain and temperature measurement results during aircraft ascent

CONCLUSION

In this paper, the research and development status of a fiber-optic distributed strain and temperature sensing technology for aircraft structural health monitoring has been described.

We have developed the prototype of a measuring instrument using a BOCDA method capable of measuring strain and temperature simultaneously at high speed and with high spatial resolution, and then evaluated it, using an actual aircraft and identifying the issues to be resolved.

We will work to improve the characteristics and resolve the issues for practical usage, and plan to apply this technology to other areas.

This research is part of the project “Advanced Materials & Process Development for Next-Generation Aircraft Structures,” under contract with The Material Process Technology Center (SOKEIZAI Center), founded by the Ministry of Economy, Trade and Industry (METI) of Japan. Finally, we would like to express our appreciation for the contributions of all related parties to this research.

REFERENCES

- (1) Tsuneo Horiguchi, Toshio Kurashima, et al., “Tensile Strain Dependence of Brillouin Frequency Shift in Silica Optical Fibers,” *IEEE Photonics Technology Letters*, Vol. 1, No. 5, 1989, pp. 107-108
- (2) Haruyoshi Uchiyama, Yoshiyuki Sakairi, et al., “An Optical Fiber Strain Distribution Measurement Instrument Using the New Detection Method,” *ANDO Technical Bulletin*, 2002, pp. 52-60
- (3) Kazuo Hotate, Takemi Hasegawa, “Measurement of Brillouin Gain Spectrum Distribution along an Optical Fiber Using a Correlation-Based Technique: Proposal, Experiment and Simulation (Special Issue on Optical Fiber Sensors),” *IEICE Transactions on Electronics*, Vol. E83-C, No. 3, 2000, pp. 405-412
- (4) Weiwen Zou, Zuyuan He, and Kazuo Hotate, “Complete discrimination of strain and temperature using Brillouin frequency shift and birefringence in a polarization-maintaining fiber,” *Optics Express*, Vol. 17, No. 3, 2009, pp. 1248-1255
- (5) The Material Process Technology Center (SOKEIZAI Center), “Development of Advanced Materials & Process Development for Next Generation Aircraft Structures (Development of aircraft structural health monitoring system technology for composites),” 2012 in Japanese
- (6) Rodrigo K. Yamashita, Zuyuan He, and Kazuo Hotate, “Simulation for Estimating Spatial Resolution in Distributed Measurement of Brillouin Dynamic Grating by Correlation Domain Technique,” *Conference on Lasers and Electro-Optics 2012 (CLEO2012)*, 2012, JW2A111
- (7) N. Saito, T. Yari, K. Hotate, M. Kishi, S. Matsuura and Y. Kumagai, “Development of Aircraft Structural Health Monitoring System technology Using the Brillouin Optical Correlation Domain Analysis Method,” *Symposium on Advanced Materials and Process Development for Next Generation Aircraft Structures*, 2013 in Japanese
- (8) N. Saito, T. Yari, K. Hotate, M. Kishi, S. Matsuura and Y. Kumagai, “Developmental Status of SHM Applications for Aircraft Structures Using Distributed Optical Fiber Sensor,” *9th International Workshop on Structural Health Monitoring*, 2013, pp. 2011-2018

* Product and company names in this article are trademarks or registered trademarks of their respective holders.