Development Overview of a Distributed Strain Sensing Technology Using Optical Fiber Sensors for Aircraft Structures

Nozomi SAITO[1], Takashi YARI[1], Kiyoshi ENOMOTO[2]

[1] Research & Innovation center, Mitsubishi Heavy Industries, LTD., JAPAN
Corresponding author: nozomi_saito@mhi.co.jp
[2] SOKEIZAI center, JAPAN

Key words: Optical fiber sensor, Aircraft, Brillouin scattering,

Abstract
This paper reports the development results of a distributed strain sensing technology using optical fiber sensors. In order to implement the optical fiber sensing system on practical uses, the authors have been enhancing the technology readiness level of the system by verifying and validating durability, detection capability and measurement accuracy, for instance, durability against assumed chemical, thermal and mechanical environments. Additionally, our system was applied to a full-scale structural test and a flight demonstration test. In these tests, the feasibility of the system such as operability, measurement accuracy and durability for the real structures was demonstrated.

1 INTRODUCTION

Structural health monitoring (SHM) technologies for aircrafts potentially contribute to reducing maintenance costs and improving flight safety. Furthermore real time structural data during flights from SHM technologies will be utilized to design improvement for the next-generation aircrafts which are more light weight and have better fuel efficiency than that of the conventional design. Therefore airlines, maintainers and original equipment manufacturers have high expectations for the SHM implementations in services [1]. For practical use of the SHM, many kinds of sensors are developed such as piezoelectric (PZT) [2], comparative vacuum monitoring (CVM) [3] and optical fiber sensors (OFSs) [4].

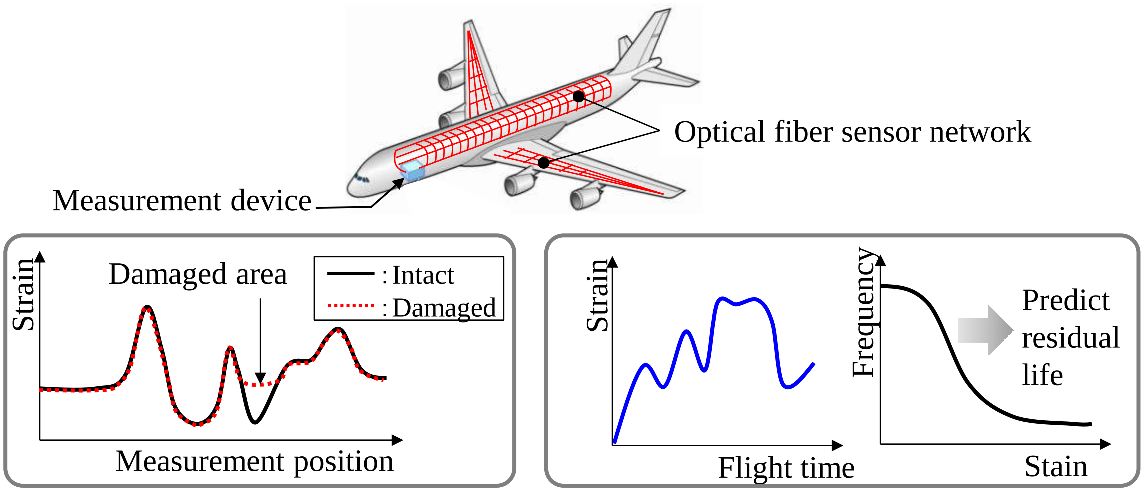
OFS has lighter weight and more immune to electromagnetic interference rather than PZT sensors. Furthermore OFS has capability to be embedded into composites because the diameter of OFS is much smaller than the others. From these reasons, OFS is expected to be applied to aircraft SHM. The authors have been developing the Brillouin optical correlation domain analysis (BOCDA) system [5] because it has more superior characteristics rather than the other OFS technologies for wide-area monitoring as shown in table 1. In this development, an airborne system was fabricated, therefore, the characteristics of the airborne system are also listed in table 1. In table 1, Brillouin gain spectrum (BGS) and dynamic gain spectrum (DGS) are the parameters which mainly affect strain and temperature measurement values, respectively. Additionally, BOCDA has two unique characteristics comparing with other distributed sensing technologies. Firstly, it measures strain and temperature simultaneously using polarization-maintaining fibers (PMFs). Secondly, you can measure strain at arbitrary points along an OFS. Measurement principle of BOCDA is described in the following section.

Application targets of the system are damage detection by distributed sensing and residual life prediction by dynamic sensing at arbitrary points during flights. Figure 1 shows the application scenarios of the system.

For implementing the application scenarios, the authors have been conducting the verification and validation process in corporation with Airbus in the Japan-Airbus SHM technology for aircraft composite (JASATC) project. The JASTAC is composed by Airbus, SOKEIZAI center, Japanese heavy industries (Mitsubishi Heavy Industries, LTD., Kawasaki Heavy Industries, LTD. and Fuji Heavy Industries, LTD) and Japan Aerospace Exploration Agency (JAXA). The purpose of the project is to enhance the technology readiness level of the OFS-SHM technologies of MHI, KHI and FHI towards practical uses by following the Airbus V&V process [6]. Many verification tests for durability, detection capability and measurement accuracy have been conducted in accordance with the building block approach as shown in Figure 2 [7-11]. For example, table 2 lists the durability tests which are required for the OFS system under the various kinds of environments expected on the typical aircraft operations. The OFS system in this paper means OFS attached to structures by using epoxy-based adhesives and coated using sealant and silicon-based top coatings. The OFS system was evaluated to have sufficient durability for the environments.

Table 1: Characteristics of BOCDA

Characteristics (unit)	Highest values in the Lab.	Values of the airborne system
Measurement range (m)	1,000	500
Spatial resolution of BGS (mm)	1.6	30
Spatial resolution of DGS (mm)	100	300
Sampling rate (Hz)	5,000	80



(a)Damage detection by distributed sensing (b)Fatigue life prediction by dynamic sensing

Figure 1: Application scenarios of BOCDA

Table 2: Durability tests for the OFS system

No.	Environment
1	Temperature
2	Altitude / Pressure
3	Decompression
4	Temperature variation
5	Waterproofness
6	Humidity
7	Fire resistance
8	Flammability
9	Water resistance
10	Kerosene
11	Hydraulic fluid
12	Lubricating
13	Solvent
14	Toilet fluid
15	De/Anti-icing fluid
16	Insecticide
17	Disinfectant
18	Coolant dielectric
19	Extinguishant
20	Salt spray
21	Xenon light
22	QUV light
23	Static loading
24	Fatigue loading

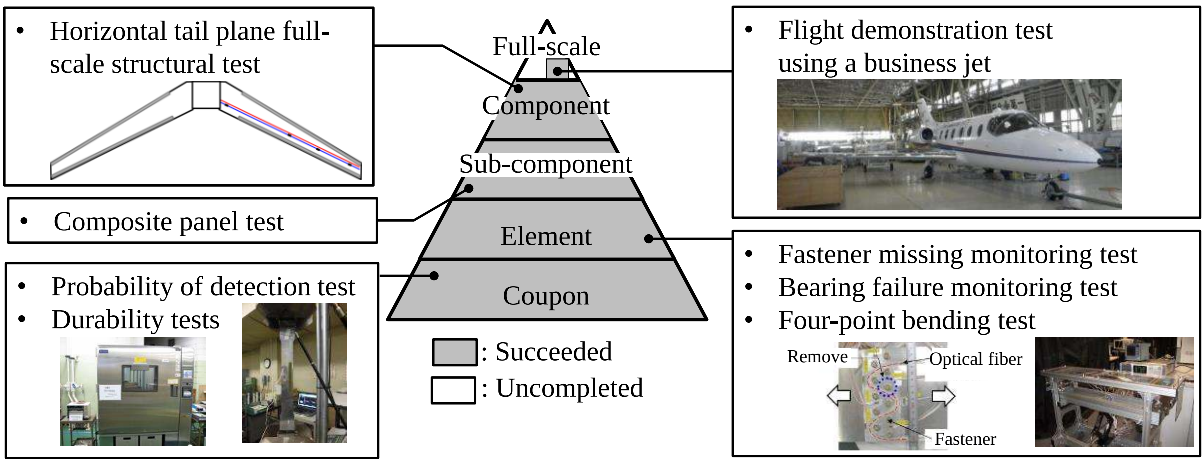


Figure 2: Building block approach

2 BOCDA MEASUREMENT PRINCIPLE

BOCDA is based on a stimulated Brillouin scattering (SBS) and birefringence phenomena in an OFS. Because the two parameters are physically independent, this method ensures a complete discrimination of strain and temperature. SBS occurs when two light waves, the pump light and the probe light, counter-propagate inside an OFS, and the probe light frequency is lower than the pump light frequency by ν_B called as the Brillouin frequency shift (BFS). Its spectrum is called the BGS. When an axial strain is loaded to an OFS, the BFS changes, that is, the strain changes of an OFS. BOCDA measurement principle is shown in Figure 3. The temperature changes are obtained from f_{yx} called as the central frequency deviation of the DGS generated in the SBS process where f_{yx} is proportional to the birefringence [12]. Strain and temperature changes ($\Delta\varepsilon$ and ΔT) are calculated on equation (1):

$$\begin{pmatrix}\Delta\varepsilon \\ \Delta T\end{pmatrix} = \frac{1}{C_\nu^\varepsilon \cdot C_f^T - C_\nu^T \cdot C_f^\varepsilon}\begin{pmatrix} C_f^T & -C_\nu^T \\ -C_f^\varepsilon & C_\nu^\varepsilon\end{pmatrix}\begin{pmatrix}\Delta\nu_B \\ \Delta f_{yx}\end{pmatrix} \qquad (1)$$

C_ν^ε and C_ν^T are coefficients of ν_B, which affect to strain and temperature, respectively. C_f^ε and C_f^T are coefficients of f_{yx}, which affect to strain and temperature, respectively. These coefficients, which were evaluated in tensile strain and temperature loaded test, are presented on equation (2):

$$\begin{aligned} C_\nu^\varepsilon &= 4.98 \times 10^{-2} && \text{MHz}/\mu\varepsilon \\ C_\nu^T &= 1.02 && \text{MHz}/^\circ\text{C} \\ C_f^\varepsilon &= 1.03 && \text{MHz}/\mu\varepsilon \\ C_f^T &= -62.3 && \text{MHz}/^\circ\text{C} \end{aligned} \qquad (2)$$

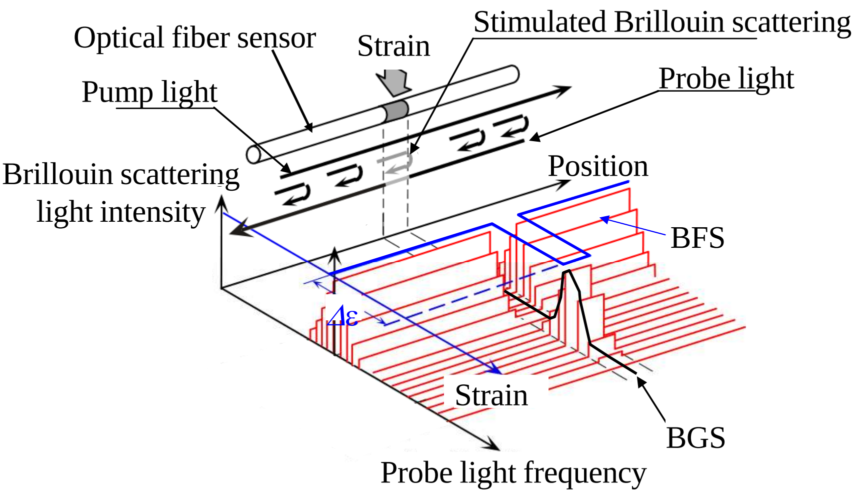


Figure 3: BOCDA measurement principle

3 FULL-SCALE STRUCTURAL TEST

In order to verify the operability and measurement accuracy of the BOCDA-SHM system, it was applied to a structural fatigue test using a full-scale horizontal tail plane article in corporation with Airbus. Strain on the upper skin of the article along the span direction was measured by OFSs of BOCDA during fatigue loadings. Fiber Bragg grating (FBG) sensors were also used for comparison of the strain measurement data.

3.1 Test article

The test article is a full-scale horizontal tail plane whose wing length is about 8 m. The article was made of mainly carbon fiber reinforced plastics excepting the center fitting area. Figure 4 shows the overview of the test setup. An OFS of BOCDA was attached on the upper skin surface along the stringers of the article using an epoxy-based adhesive. In order to handle the OFS easily, sensing OFS was connected by the jacked OFSs with the BOCDA-SHM system. FBG sensors were also installed parallel to the BOCDA-OFS.

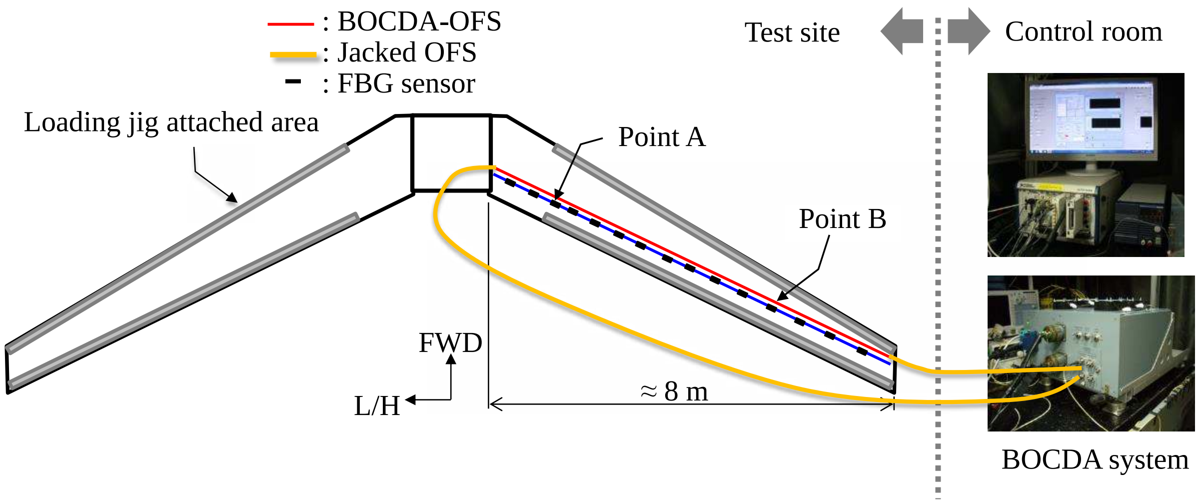


Figure 4: Overview of the full scale horizontal tail plane

3.2 Measurement

Dynamic and distributed strains during the fatigue loading were measured by the BOCDA system. Spatial resolution of the system in the test was 30 mm. In order to evaluate the measurement accuracy of BOCDA, the measured strain values were compared with that measured by FBG sensors. FBG sensor is the most famous optical fiber sensor and it has the highest measurement accuracy rather than the others. The dynamic strain measurement positons of BOCDA were determined by measuring the length between the center of the article and the FBG sensors using a tape measure.

3.3 Results and discussions

Figure 5 shows comparison between the dynamic strain changes by BOCDA and FBG sensors at two positions. Point A was located near the inboard of the article where higher stress was loaded and point B was located near the outboard of the article where lower stress was loaded. Dynamic strain change measured by BOCDA at point A is almost the same with that measured by the FBG sensor. On the other hand, at point B, there are small differences between dynamic strain change measured by BOCDA and that by the FBG sensor. It was thought there are two reasons. Firstly, the measurement positions of BOCDA might be different from the actual FBG positions because, as mentioned earlier, BOCDA measurement positions were calibrated using actual measurement results by a tape measure. Secondly, higher optical loss due to inappropriate optical fiber installation process and routing might causes lower measurement accuracy. Figure 6 shows the wave spectrum at point A and point B. Optical intensity at point B was lower than that at point A. Therefore, a calibration method of BOCDA measurement positions and a procedure which controls OFS installation quality have to be developed. Strain distribution measured by BOCDA as shown in figure 7 has the same tendency with strain values measured by FBG sensors.

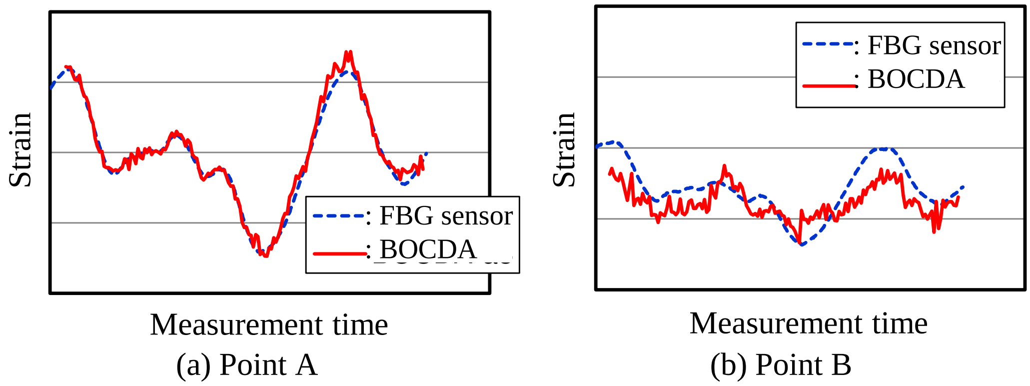


Figure 5: Dynamic strain changes at point A and point B

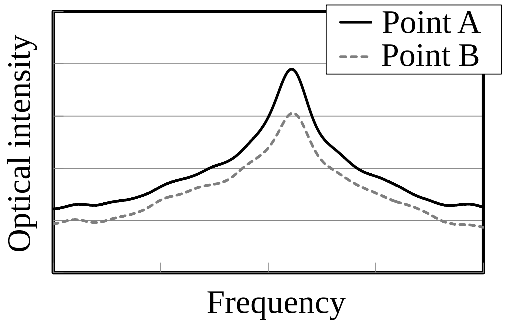


Figure 6: Wave spectrums at point A and point B

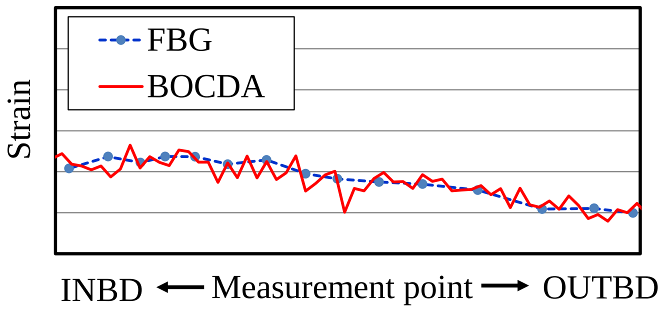


Figure 7: Strain distribution

4 FLIGHT DEMONSTRATION TEST

Flight demonstration test was conducted in order to verify operability and feasibility of the BOCDA-SHM system. A business jet, MU-300, was used as the test bed. An OFS was attached on the front spar of the vertical stabilizer and devices were on the cabin floor of the jet. Dynamic strain changes during a right-left turning flight were measured. Two types of test cases were conducted in the test, strain-temperature simultaneous measurement case and strain-only measurement case. As an example of the test results, this paper reports the test results in the strain-only measurement case.

4.1 Test bed

Test bed in the flight demonstration test was an eleven-seated business jet, MU-300, which was manufactured by Mitsubishi heavy industries, LTD. Its length and width are 14.7 m and 13.7 m, respectively. An OFS was attached on the front spar of the vertical stabilizer using epoxy based adhesive. Strain gauges were installed near the OFS for reference. A thermocouple was also attached in order to calibrate temperature effects to the OFS. Stain and temperature were measured. The OFS and lead wires of the strain gauges and the thermocouple were through the pressure bulkhead, and connected to the measuring devices on the cabin floor. Figure 8 shows the test bed in the flight demonstration test.

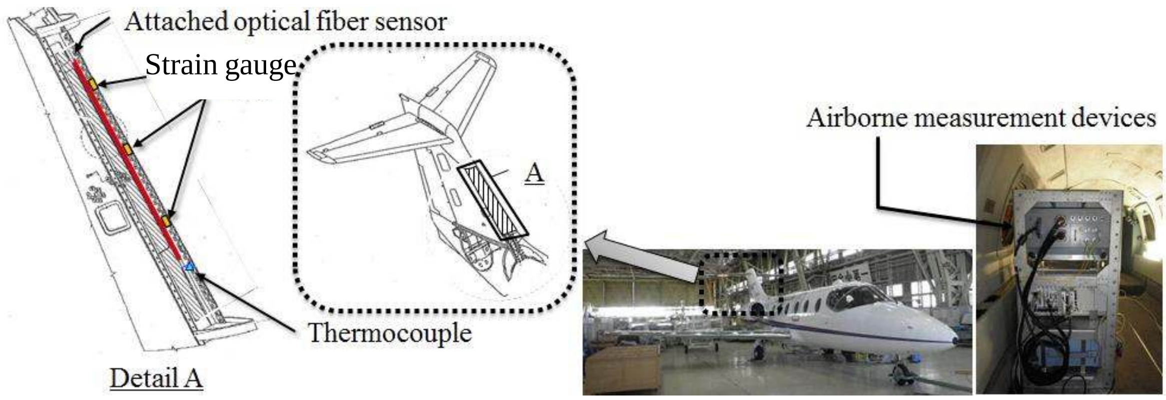


Figure 8: Test bed in flight demonstration test

4.2 Results and discussions

Figure 9 shows dynamic strain measurement results at the center of the front spar of the vertical stabilizer during a right-left turning flight. Strain changes were measured by BOCDA and by the strain gauge. Measurement results almost coincided with each other although there were small errors.

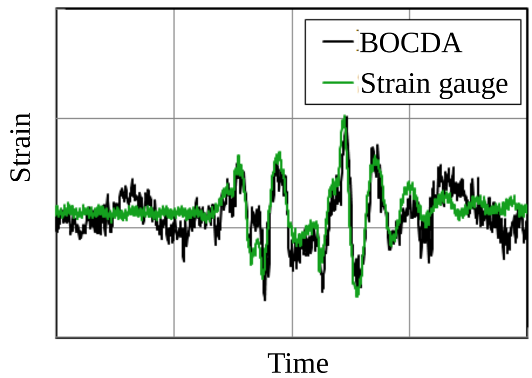


Figure 9: Dynamic strain measurement result

5 CONCLUSIONS

The airborne BOCDA-SHM system was applied to the structural fatigue test using the full-scale horizontal tail plane in order to verify the operability and measurement accuracy of the system as a part of the JASTAC project. Although strain measurement data by BOCDA at some measurement points were almost the same with the FBG sensors, a few challenges which will have to be solved for the practical uses were found out. Additionally, the flight test was conducted by using the business jet and the feasibility of the system for practical uses was demonstrated.

ACKNOWLEDGEMENT

This work was conducted as a part of the project, "Advanced Materials & Process Development for Next-Generation Aircraft Structures" under the contract from the New Energy and Industrial Technology Development Organization (NEDO), founded by the Ministry of Economy, Trade and Industry (METI) of Japan.

REFERENCES

[1] D. Roach, S. Neidigk, Does the Maturity of Structural Health Monitoring Technology Match User Readiness?, Proceedings of the 8th International Workshop on Structural Health Monitoring, 1:39-52, 2011.

[2] N. Salowitz, Z. Guo, S. Roy, R. Nardari, Y. H. Li, S. J. Kim, F. Kopsaftopoulos, F. K. Chang, A Vision on Strechable Bio-Inspired Networks for Intelligent Structures, Proceedings of the 9th International Workshop on Structural Health Monitoring, 1:35-44, 2013.

[3] M. Wishaw, D. P. Barton, Comparative Vacuum Monitoring: a New Method of In-Situ Real-Time Crack Detection and Monitoring, Proceedings of the Symposium – International Committee on Aeronautical Fatigue, 657-666, 2002.

[4] A. Othonos, K. Kalli, Fiber Bragg Gratings: Fundamentals and Applications in Telecommunications and Sensing, Norwood, Arthech House Publishers, 1999.

[5] K. Y. Song, Z. He, K. Hotate, Distributed Strain Measurement with Millimeter-order Spatial Resolution based on Brillouin Optical Correlation Domain Analysis, OSA Optics letters, 31, 17:2526-2528, 2006.

[6] C. Bockenheimer, H. Speckmann, Validation, Verification and Implementation of SHM at Airbus, Proceedings of the 9th International Workshop on Structural Health Monitoring, keynote presentation, 2013.

[7] T. Yari, N. Saito, K. Nagai, K. Hotate, K. Enomoto, Development of a BOCDA-SHM system to reduce airplane operational costs, Mitsubishi Heavy Industries Technical Review, 48, 4, 2011.

[8] T. Yari, N. Saito, K. Hotate, S. Matsuura, K. Enomoto, Cost reduction technology for airframe maintenance, Mitsubishi Heavy Industries Technical Review, 52, 1, 2015.

[9] N. Saito, T. Yari, K. Nagai, K. Enomoto, Damage detection method for CFRP bolted joints using embedded BOCDA optical fiber sensor, Proceedings of the 8th International Workshop on Structural Health Monitoring, 1:455-462, 2011.

[10] N. Saito, T. Yari, K. Hotate, M. Kishi, S. Matsuura, Y. Kumagai, K. Enomoto, Developmental status of SHM applications for aircraft structures using distributed optical fiber, Proceedings of the 9th International Workshop on Structural Health Monitoring, 2:2011-2018, 2013.
[11] N. Saito, T. Yari, K. Enomoto, Flight demonstration testing with distributed optical fiber sensor, Proceedings of the 7th European Workshop on Structural Health Monitoring, TuBT1.3, 2014.
[12] W. Zou, Z. He, K. Hotate, Demonstration of Brillouin distributed discrimination of strain and temperature using a polarization-maintaining optical fiber, IEEE Photonics Technology Letters, 22, 8, 2010.