

An aircraft structural health monitoring using Brillouin scattering sensing system

TAKASHI YARI¹, MASATO ISHIOKA², KANEHIRO NAGAI¹,
TATEO SAKURAI³

ABSTRACT:

Structural health monitoring (SHM) means a system with the ability to detect damage and /or prediction structural life in order to improve reliability and reduce life-cycle cost. In the SHM, optical fiber sensor system is an attractive one for aircrafts SHM, because of its light weight, durability, and enable to be embedded into composite structures. We chose the Brillouin measurement method to detect strain distribution and strain history of structures, in order to monitor structural health.

In this paper, we developed a prototype Brillouin optical correlation domain analysis (BOCDA) and carried out three application tests to verify the capability for (SHM). The prototype BOCDA system is able to measure the distribute strain of full-length optical fiber sensor with 50mm of spatial resolution and 2.7Hz sampling for arbitrary point strain. Moreover, we conducted three application tests to evaluate the effectiveness of SHM using the BOCDA system, such as the panel buckling test, the dynamic strain measurement test, and the demonstration flight test. We verify the effectiveness of the BOCDA system for the aircraft SHM, and clarify the necessary development subject for the actual application.

INTRODUCTION

Recently, an application of the aircraft structural health monitoring (SHM) system is hoped by airline from the demand of low cost aircraft operation. Many researches have been conducted for application of SHM techniques. The SHM technology using an optical fiber sensor is very attractive method for aircraft SHM system because of its lightweight, durability, and to be embedded into composite structures. The Brillouin scattering method, that can measure distributed strain on the full-length optical fiber sensor, is one of the effective methods for large area monitoring. The Brillouin optical time domain reflectometer (BOTDR) is popular method of the distributed optical fiber

¹ Mitsubishi Heavy Industries, LTD. Nagoya Aerospace Systems
10, Oye-cho, Minato-ku, Nagoya 455-8515, Japan

² Mitsubishi Heavy Industries, LTD. Nagasaki R&D Center
5-717-1, Fukahori-machi, Nagasaki 851-0392, Japan

³ R&D and Institute of Metal and Composite for Future Industries
25-2, Toranomon 3-Chome, Minato-ku, Tokyo 105-0001, Japan

sensing system. Some researches are conducted to enhance the BOTDR system for applying to aerospace SHM [1], [2]. In spite of these efforts, the technical issues remain about application for aircraft SHM, such as low spatial resolution and long measuring time. Meanwhile, Brillouin correlation domain analysis method (BOCDA) is developed by Hotate et al [3]. The BOCDA system has high potential to apply for aerospace SHM. Because BOCDA system has the high spatial resolution and the high speed sensing, the application of BOCDA system can be contributed to aircraft SHM

In this work, we developed a prototype BOCDA system demonstrate effectiveness of the BOCDA system for aircraft SHM. The prototype BOCDA system operates 50mm of spatial resolution and 2.7Hz of sampling speed. Moreover, we conducted three application tests to evaluate the effectiveness of SHM using BOCDA system. These tests are the panel buckling test, the dynamic strain measurement test, and the demonstration flight test. These tests were conducted to verify the effectiveness of high spatial resolution and high-speed sampling.

DEVELOPMENT OF PROTOTYPE BRILLOUIN MEASURING SYSTEM

Principle of Brillouin Scattering Light

Stimulated Brillouin scattering is the phenomenon of interaction between the pump light wave and the probe light wave in optical fiber sensors. The pump light wave, the optical power exceeding the Brillouin threshold, generates acoustic wave in the optical fiber. The probe light wave obtain Brillouin gain with the Doppler shifts by acoustic waves. When an axial strain is loaded in the optical fiber sensors, the fluctuation of density changes the acoustic wavelength. The changing acoustic wavelength makes Brillouin frequency change. Consequently, the strain states of the optical fiber sensor are obtained from Brillouin frequency shift. Brillouin frequency shift by strain and temperature are known as 495MHz/% and 1MHz/°C in silica based optical fiber sensor. The Brillouin frequency shift ν_B is given by EQUATION (1) [4].

$$\nu_B = 2nV/\lambda \quad (1)$$

where n is the refractive index of an optical fiber, V is acoustic wave speed in an optical fiber, and λ is pump light wavelength.

The optics system is described in FIGURE 1. In this BOCDA system, the laser light source is divided with a coupler into a pump light and a probe light. The laser light source frequency is sinusoidal modulated. The pump light wave is amplified with erbium doped fiber amplifier (EDFA) up to 0.1~2W of peak intensity. The probe light wave is 10~11GHz frequency downshifted with phase modulator. The pump light wave and the probe light wave are launch into the optical fiber sensor at opposite ends. The phases of the pump and the probe light waves change periodically along the fiber, depending on their optical path difference. At the correlation peak position, the pump and the probe light waves are synchronously frequency modulated and maintain the frequency difference. We can ensure that a correlation peak occurs in the sensing fiber by choosing appropriate frequency modulation parameters. The effective Brillouin gain spectrum (BGS) was measured by sweeping the probe light frequency.

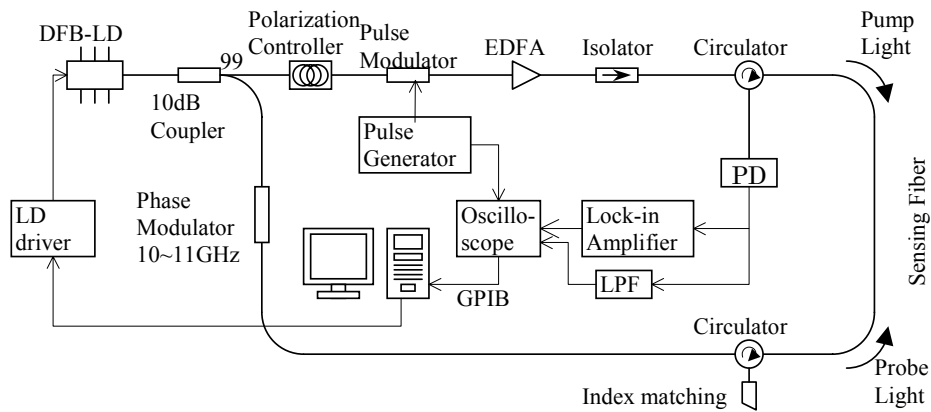


FIGURE 1 Brillouin optical fiber measurement system diagram

In this system, the spatial resolution is defined by frequency modulation width of laser light source. The spatial resolution δz of strain measurement is shown in EQUATION (2)

$$\delta z = \frac{1.52v_g}{2\pi\Delta f} \quad (2)$$

where, v_g is the velocity of light in optical fiber [m/s], and Δf is the frequency modulation width of laser light [Hz]. In the application tests described later, a frequency modulation width of laser light source was set to 1GHz equivalent to 5cm of spatial resolution.

Development of prototype transportable BOCDA system

We developed a prototype BOCDA equipment for the purpose of monitoring of aircraft structures. This prototype BOCDA system is shown in FIGURE 2. The size of measurement equipment is 600mm in width, 700mm in height, and 450mm in depth. And the weight of measurement equipment is 45kg without the rack. This measurement equipment is worked by 100VAC electrical power.

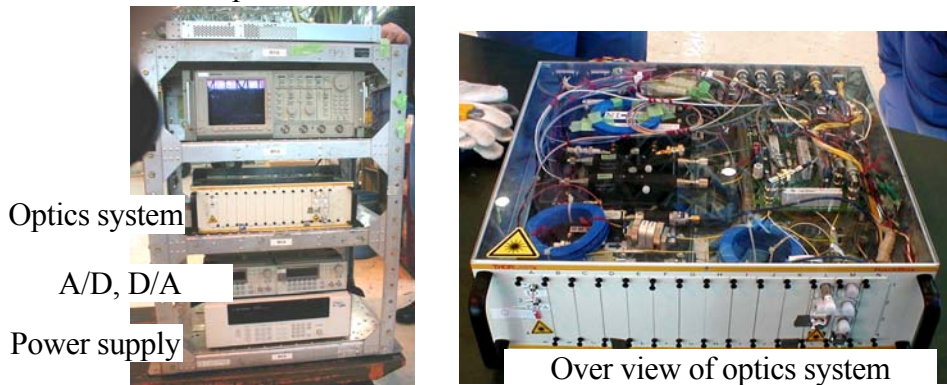


FIGURE 2. Prototype measurement equipment using BOCDA method

APPLICATION TEST

Panel Buckling Monitoring Test

In the civil aircraft, a hard landing may cause a fuselage skin panel buckling deformation around the static hole. Therefore it is necessary to inspect the structural deformations around static hole after the hard landing due to air speed measuring error by buckling deformation. However, the allowance of time until the next service is short for efficient aircraft rotation, which causes insufficient time of inspection. The aircraft structural deformations around the static holes should be monitored specifically. The strain distribution measuring techniques using the Brillouin scattering can be contributed to the reduction of inspection time in a routine and an occasional inspection. If this of monitoring becomes possible, the inspection time until next service will be shortened.

In this test, the test article simulated an aircraft fuselage skin panel in order to evaluate the skin panel buckling around the static holes after a hard landing. FIGURE 3 shows the overview of the test articles. One article had a stringer in the center of the panel and the other article had no stringer. Each of the test articles is 1000mm by 1000mm aluminum-alloy panel (2024-T3) and 3.0 mm thickness. The test articles were designed for the purpose of determining the possibility of permanent deformations monitoring caused by buckling. The optical fiber sensors were installed on the test article with epoxy adhesive (Hysol EA9394). Optical fiber sensors were fusion spliced as one measurement line, and measured with the BOCDA equipment. The conventional strain gages were installed linearly arranged with a 50 mm interval, and 8 mm apart from the optical fiber sensors in parallel to compare the distributed strain by the BOCDA system. The location of optical fiber sensors and strain gages is also shown in FIGURE 3. The in-plane shear loads were applied to the test articles using a hydraulic servo actuator. When the loads exceeded a certain level, the shear buckling was induced and caused out-of-plane deformations.

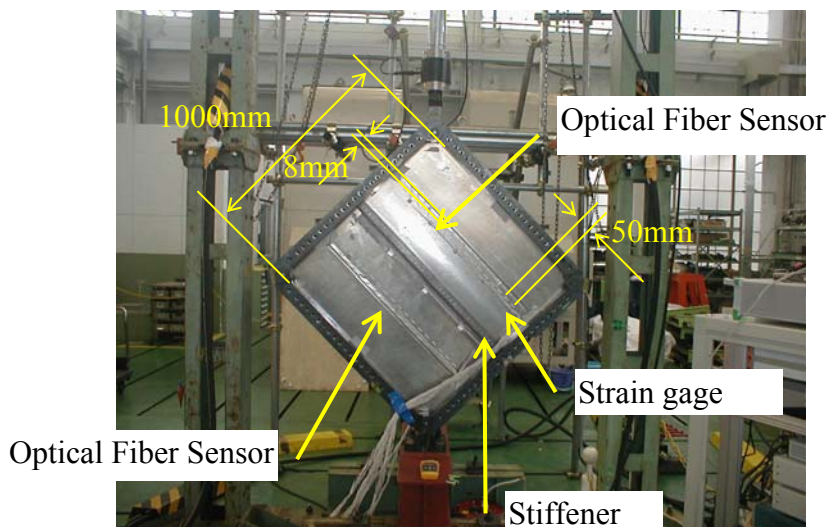


FIGURE 3. Panel buckling test setup

Comparison of a strain distribution measurement results with the optical fiber sensor and the strain gages are shown in FIGURE 4. This result has made it clear that the occurrence of the skin panel buckling deformation can be decided by monitoring the panel strains. The comparison of the measurement results between the optical fibers sensors and the strain gages shows that they are almost in good agreement, but some of the optical fiber

sensors measurements showed differences. The causes of precision error are considered to be decrease of the stimulated Brillouin scattering (SBS) gain because of the transmission loss and the less stability of the polarization state by optical fiber sensor installation. Next approach of this research is improvement of an optical fiber sensor installation method to avoid the transmission loss and the polarization state instability and develop robust equipment adaptable for these states.

It was confirmed through this application test that the buckling behaviors of the test articles assuming the aircraft fuselage skin panels could be measured even at the spatial resolution of 50mm. Thus we detected the panel shear buckling deformations around the static holes after the hard landing by the distributed strains monitoring system using Brillouin scattering. If the higher spatial resolution can be achieved, the permanent deformations could be more precisely detected.

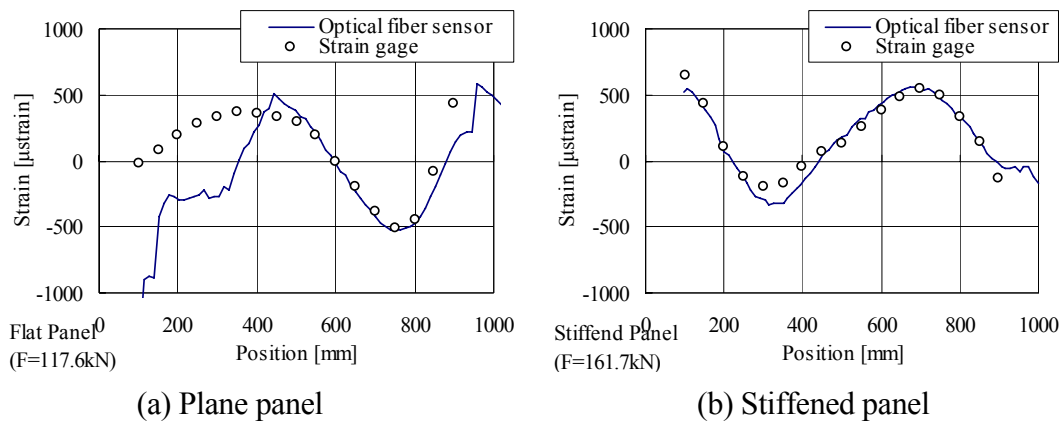


FIGURE 4. Comparison with the optical fiber sensor output and strain gage output

Dynamic Strain Measurement Test

In order to evaluate quantitatively the fatigue damage, the dynamic strain measurement technology using the BOCDA system is good solution for measuring the strain history generated in aircraft structure. If this becomes realize, aircraft structural checks are operated by condition monitoring in spite of periodical structural check. Therefore, we conducted dynamic strain measurement test to verify the effectiveness of the dynamic point measurement technology that is another feature of a BOCDA measurement system.

In this dynamic strain measurement test, the cantilever beam bending test was adopted. The test article was 500mm in length, 50mm in width, and 15mm in thick aluminum-alloy beam. The optical fiber sensor was attached on the test article with epoxy adhesive (Hysol EA9394), and the conventional strain gages were installed near optical fiber sensor for comparison. Test setup is shown in FIGURE 5. The BOCDA measurement was performed by 50mm of spatial resolution, and 2.7Hz of measurement sampling frequency. In this test, giving a displacement at the tip of beam generated a dynamic strain, and the strain amplitude was controlled 2000μstrain in the beam root section. A cycle speed was performed by 0.15Hz and 0.9Hz.

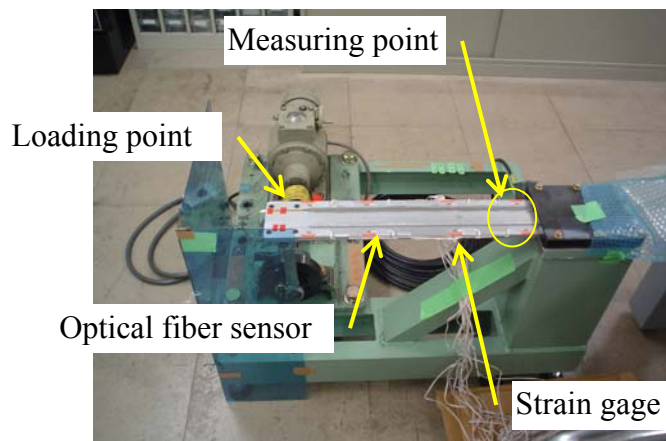
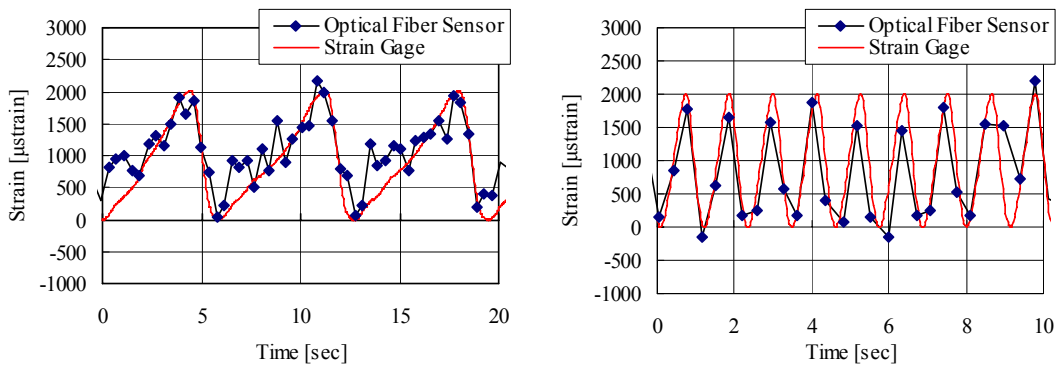


FIGURE 5. Overview of dynamic strain measurement test setup

The time histories of dynamic strain test are shown in FIGURE 6. This graph shows the profile of a dynamic strain. A linear fit of the optical fiber sensor and the strain gages has the regression coefficient of about 0.77 and the standard error of about 340 μ strain. The comparison of the measurement results between the optical fiber sensors and the strain gages shows that they are almost in good agreement. However, in a 0.9Hz case, it turns out that the peaks measured by the strain gages by BOCDA are not in agreement. This result shows it is necessary to improve a strain-sampling speed by changing the digital data bus between the oscilloscopes and the personal computer.



(a) Applied strain frequency is 0.15Hz

(b) Applied strain frequency is 0.9Hz

FIGURE 6. Measurement strain-time waveform at root of the beam article

Demonstration Flight Test

We conducted the demonstration flight test in order to verify the effectiveness of the structure monitoring by strain measuring under aircraft operation. In this demonstration flight test, we used MU-300 (Mitsubishi Heavy Industries, co.) aircraft as a test bed. The size of MU-300 is a width of 13.7m, and a length of 14.7m, a maximum cabin crew of 11. The overview of the test aircraft is shown in FIGURE 7.



FIGURE 7. Overview of aircraft for demonstration flight test

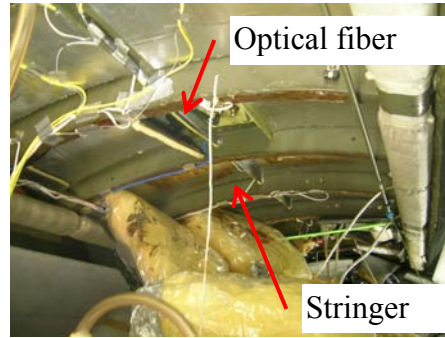


FIGURE 8. Aspect of optical fiber and strain gage installation

In this demonstration flight test, we measured the structural strain of upper panel stringer of mid fuselage. The measuring position could be accessed from the cabin. The optical fiber sensor was attached with epoxy adhesive (Hysol EA9394), and the strain gages for comparison were attached with cyanoacrylate adhesive. The sensor installation condition is shown in FIGURE 8. The prototype BOCDA system was bolted on the floor.

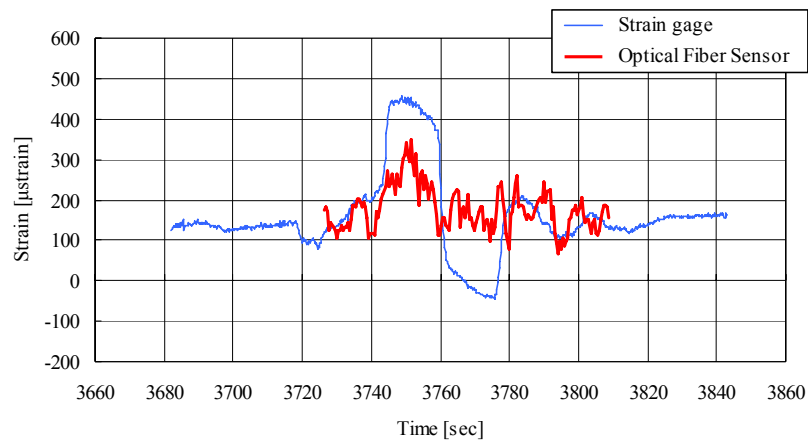


FIGURE 9. Strain histories of the BOCDA system and the strain gage in the demonstration flight test

The strain time history using BOCDA system under the demonstration flight test is shown in FIGURE 9. In this graph, the strain gage measurement data for comparison was also indicated. When the maximum strain occurs in this flight pattern, it turns out that the Brillouin frequency shifted upwards and responded to change of structure strain. However, the value of Brillouin frequency shifts did not correspond to the strain gage. The causes of this precision error are also considered to be decrease of the SBS gain because of the transmission loss and the low stability of polarization state by optical fiber sensor installation, as discussion above. So the improvement of an optical fiber sensor installation method to avoid the transmission loss and the polarization state instability and the development of robust equipment adaptable for these states should be required.

CONCLUSIONS

In order to apply the BOCDA method for aircraft structural health monitoring, we develop the prototype BODDA system with 50mm of spatial resolution and 2.7Hz arbitrary point strain sensing. And verified its possibilities through three application tests. However the prototype BOCDA system has some issues such as and strain measuring accuracy. Two approaches are under study for the purpose. First one is a development an optical fiber sensor installation method for avoiding the transmission loss and the polarization state instability, and second one is adopting polarization diversity scheme [5] to the prototype BOCDA system.

ACKNOWLEDGEMENTS

This study was conducted as a part of the “Civil Aviation Fundamental Technology Program-Advanced Materials & Process Development for Next-Generation Structures” project under contract with R&D Institute of Metals and Composites for Future Industries (RIMCOF) and funded by the Ministry of Economy, Trade and Industry (METI), Japan.

REFERENCES

1. T. Yari, K. Nagai, T. Shimizu, N. Takeda, “Overview of Damage Detection and Damage Suppression Demonstrator and Strain Distribution Measurement Using Distributed BOTDR sensors”, proceeding of SPIE vol. 5054, pp. 175-183. (2003)
2. T. Shimizu, T. Yari, K. Nagai, N. Takeda, “Strain Measurement Using a Brillouin Optical Time Domain Reflectometer for Development of Aircraft Structure Health Monitoring System”, Proceedings of SPIE 4335, pp.312-322. (2001)
3. K. Hotate, S. S. Ong, “Distributed Fiber Brillouin Strain Sensing by Correlation-based Continuous-wave technique: cm-order Spatial Resolution and Dynamic Strain measurement”, proceeding of SPIE vol.4920, pp. 299-310. (2002)
4. T. Horiguchi, T. Kurashima, and M. Tateda, “Tensile strain dependence of Brillouin frequency shift in silica optical fibers”, IEEE Photon. Tech. Lett. 1, 5, pp.107-108. (1989)
5. K. Hotate, K. Ave, “BOCDA fiber optic distributed strain sensing system with a polarization diversity scheme for enlargement of measurement range”, Proceedings of SPIE vol. 5855, pp. 591-594. (2005)