Monitoring Aircraft Structural Health Using Optical Fiber Sensors

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We have developed a system for monitoring aircraft structural health that uses optical fiber sensors. Our prototype device for Brillouin optical correlation domain analysis (BOCDA) uses an optical fiber as a sensor, and we verified that this device is sufficiently durable for installation on board aircraft. It functioned effectively as an aircraft structural health monitoring system in a flight demonstration test using a business jet. As the next development step, we plan to improve the reliability of this system for practical application as a product monitoring service.

1. Introduction

It is necessary to reduce the operating costs of commercial aircraft. Reducing the cost of inspecting the airframe and the maintenance downtime this requires would further this goal. A structural health monitoring (SHM) system that can evaluate the health of the airframe structure while the plane is in flight and on the ground would provide a practical application that would satisfy this requirement. Mitsubishi Heavy Industries, Ltd. (MHI) is developing just such an aircraft SHM technology that applies Brillion optical correlation analysis (BOCDA), which can measure the strain distributed along the total length of an optical fiber sensor and the dynamic strain at arbitrary points along the optical fiber sensor. Consequently, it will be possible to measure the strain distribution, monitor deformation, and diagnose damage from the load history in a continuous section of the airframe structure during operation.

This report introduces the development of an aircraft structural health monitoring technology that uses BOCDA.

2. Development of an onboard measuring device

2.1 Measuring technique

Optical fiber is a suitable sensor for SHM because of its light weight, electromagnetic non-inductiveness, and durability. Of the measuring methods using optical fiber as a sensor, BOCDA, which can measure the distributed strain along the total length of an optical fiber sensor or the dynamic strain at arbitrary points on the optical fiber sensor, is an excellent technique for detecting a wide range and variety of damage.[1] BOCDA utilizes stimulated Brillouin scattering generated by the interaction between the pump light and the probe light launched from opposite ends of an optical fiber. Since the frequency shift of the stimulated Brillouin scattering light is proportional to the strain generated in the optical fiber, the axial strain along the optical fiber can be assessed by measuring this frequency. This shift is approximately 50 kHz/$\mu\varepsilon$ for the optical fibers used for telecommunication.

Figure 1 shows the BOCDA measurement principle. When the frequencies of the pump and probe lights are modulated at the same period, the point where the correlation between these lights is always constant (the correlation peak point) appears in the optical fiber. As the correlation between the pump and probe lights is not

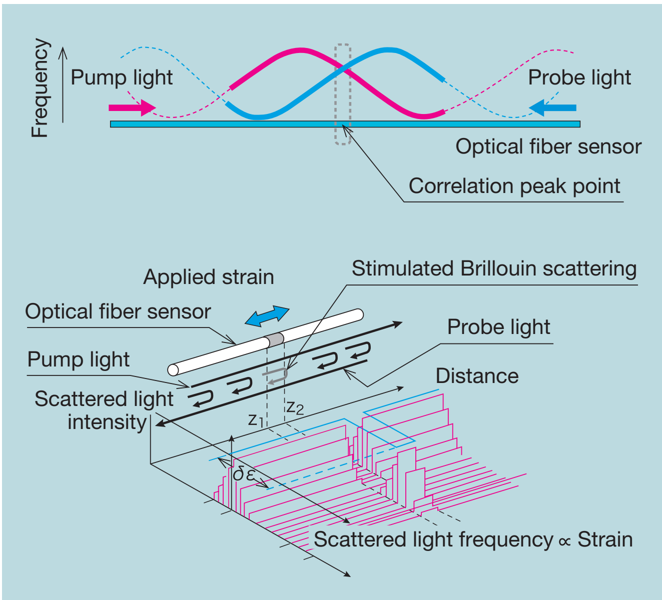

Fig. 1 BOCDA measurement principles

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constant except at the correlation peak point, the amount of stimulated Brillouin scattering light power is very low, and the scattered light generated at the correlation peak point can be measured selectively. In addition, this correlation peak point can be moved by changing the modulation periods of the pump and probe lights, and the distributed strain can be measured along the total length of the optical fiber sensor.

A prototype BOCDA measuring device was manufactured in cooperation with Yokogawa Electric Corporation. To improve its accuracy and increase the measurement range, polarization diversity[2] and temporal gating[3] schemes were adopted. The specifications of the measuring device included a spatial resolution of 30 mm (the minimum unit length for which strain can be measured), a measuring range of 500 m, a sampling time of 1/60 s, and a strain accuracy of ± 13 $\mu\varepsilon$. These substantially exceed the performance of conventional measuring devices utilizing Brillouin scattering light. With these specifications, the device can be applied to large equipment and structures other than airframes. The prototype of the BOCDA measuring device is 430 mm wide, 550 mm deep, and weighs 45 kg (**Fig. 2**).

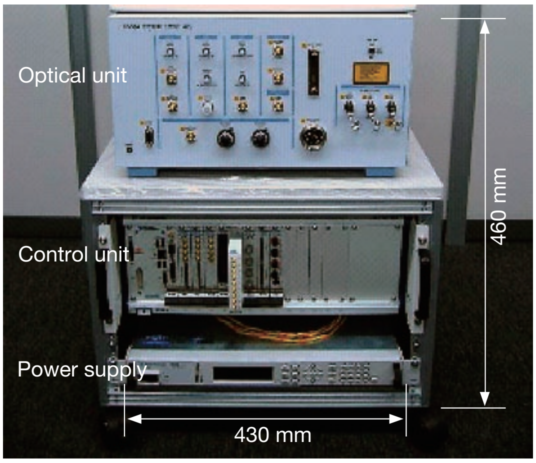

Fig. 2 The onboard BOCDA device

2.2 Performance of the onboard measuring device

For the aircraft SHM system under development, it is necessary to mount the BOCDA device on an aircraft in order to measure the strain generated in the airframe during flight. Any onboard measuring device must be durable and survive the temperatures, vibration, and shock encountered during the operation of the aircraft, while functioning accurately in such an environment. Therefore, we conducted three tests to verify the performance of our prototype BOCDA device (**Fig. 3**). 1. A temperature test to verify normal operation over a temperature range from 0–40°C. 2. A vibration test to verify normal operating at a frequency range of 10–2 kHz and an acceleration power spectral density of 3.2×10^{-6} to 3.4×10^{-4} G^2/Hz. And 3. a shock test to verify resistance of the device to shock at an amplitude of 6 G and a duration of 20 ms.

The results of the environmental tests are summarized

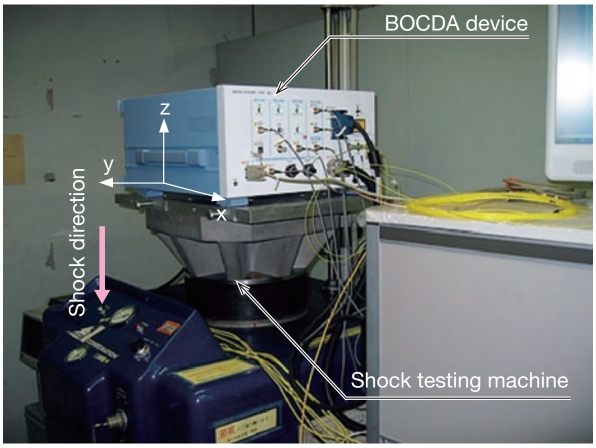

Fig. 3 The shock test of the BOCDA system

Table 1 Tests of environmental durability

Environmental test	Test condition	Test result
Temperature test	T = 0°C	Operates accurately
	T = 40°C	Operates accurately
Vibration test	x-axis vibration	Operates accurately
	y-axis vibration	Strain measurement accuracy was reduced to ± 25 $\mu\varepsilon$.
Shock test	6 G (z-axis)	Resisted the load

in **Table 1**. Although the stability of the BOCDA device was reduced slightly, it was sufficient for monitoring the structural health and estimate residual life of the airframe in a flight test environment.

3. Demonstration test

3.1 Test method

We conducted a test in an actual flight environment to verify the effectiveness of the SHM system by BOCDA. For the flight test, we used a Mitsubishi MU-300 business jet that was 13.7 m wide and 14.7 m long as the flight test bed (**Fig. 4**). We measured the structural strain in a skin panel stringer in the upper part of the fuselage. Generally, it is important to

Fig. 4 Flight demonstration test bed (MU-300)

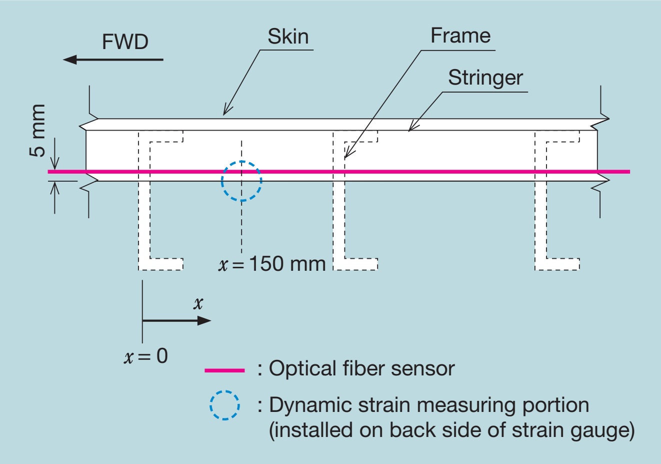

Fig. 5 Schematic view of the optical fiber installation

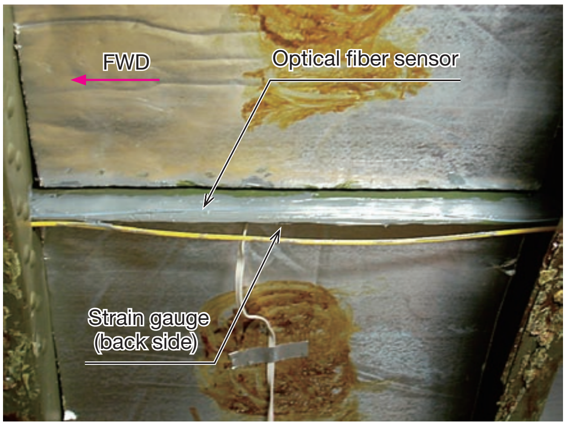

Fig. 6 The installed optical fiber

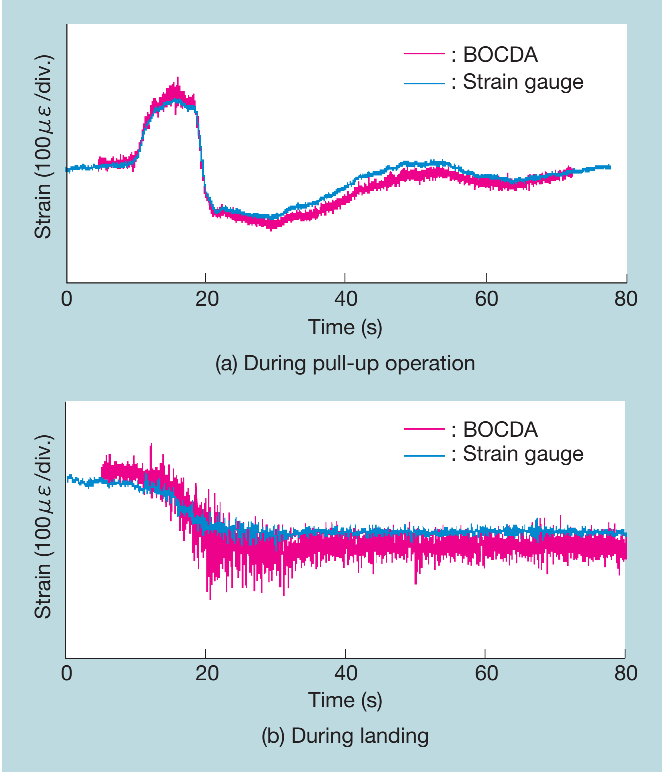

Fig. 7 The strain history in the fuselage panel measured using the BOCDA device
A comparison of the results using the BOCDA device and a strain gauge

assess the flight load or stress concentration sections such as at the mountings of the wings and tail, the joints between panels, and at holes. Our SHM technology should be used in these areas. However, to apply it to an existing airframe structure requires large-scale modification and approval from the Civil Aviation Bureau. Therefore, for the purpose of the tests, we monitored the stringer of a fuselage skin panel in a pressurized portion of the airframe. **Figure 5** is a schematic of the area where the structural strain was measured and the placement of the sensor. **Figure 6** is a photograph of the sensor bonded on the stringer. The optical fiber sensor was approximately 10 m long. For comparison, data were obtained by installing a strain gauge near the optical fiber sensor. The BOCDA system was bolted to the cabin floor (shown in the photograph at the top of this paper) and measured the dynamic and distributed strain of the test bed. The dynamic strain was measured during pull-up operation and during landing sequence. The distributed strain was measured during level flight.

3.2 Test results

Figure 7 shows the dynamic strain of the test bed measured during pull-up operation and during landing. Since the vertical acceleration fluctuates with airframe motion during pull-up and pull-down, a tensile or compressive load is generated in the panel in the upper surface of the fuselage due to bending. During landing, the point of support of the airplane weight moves from the wings to the landing gear, which causes the load condition of the airframe to fluctuate. As Fig. 7 shows, excellent agreement was observed between the BOCDA and strain gauge measurements during both flight and landing. Results indicated dispersion of the values measured using BOCDA during landing. This is thought to have arisen from vibrations transmitted to the BOCDA device when the landing gear was down and the flaps were moved to the landing position, which reduced the measurement accuracy. Nevertheless, we showed that the load (strain) history generated in the airframe could be measured and demonstrated the effectiveness of monitoring the aircraft structure.

Figure 8 shows the distributed strain measured during level flight. The out-of-plane deformation due to the cabin pressure at the level flight altitude of the aircraft could be detected as the distributed strain. The test results agreed approximately with the values calculated from the cabin pressure, demonstrating that the onboard BOCDA device can measure the distributed strain of the airframe in the flight environment. Consequently, it should be possible to detect damage from the fluctuation of the distributed strain measured using the BOCDA device at important sections of the airframe structure, such as pressure bulkheads.

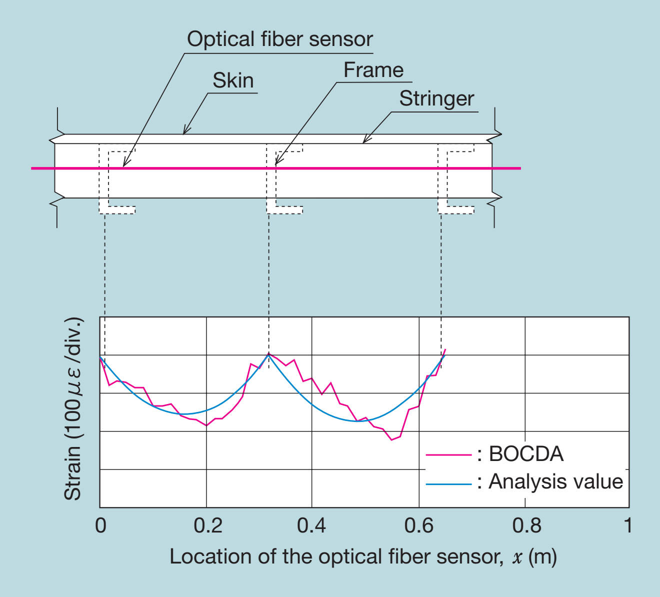

Fig. 8 BOCDA measurement of the fuselage panel distributed strain

4. Conclusion

In this study, we manufactured a prototype BOCDA measuring device that is capable of monitoring the health of an entire airframe and verified that it was sufficiently durable to be installed on a flight test bed by conducting a verification test for environmental durability. Then, we conducted a flight test and demonstrated that our device can measure the load (strain) history generated in the airframe structure from takeoff, during flight, and until landing. In addition, our system can detect damage from the distributed strain state change during flight.

As the next step, we plan to develop a durable, stable, reliable aircraft structural health-monitoring system based on this development and to establish technologies for damage evaluation and temperature compensation.

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References

1. Hotate K., Fiber Optic Nerve Systems for Structures and Materials That Can Feel Pain, IEEE Newsletter Feb. 2006, pp. 5-10 (2006)
2. Hotate K., et al., BOCDA Fiber Optic Distributed Strain Sensing System with a Polarization Diversity Scheme for Enlargement of Measurement Range, Proc. of SPIE vol.5855, pp. 591-594 (2005)
3. Kannou K., et al., Temporal Gating Scheme for Enlargement of Measurement Range of Brillouin Optical Correlation Domain Analysis for Optical Fiber Distributed Strain Measurement, Proc. in OFS-16 (2003)


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