ENHANCEMENT OF BOCDA SYSTEM FOR AIRPLANE STRUCTURAL HEALTH MONITORING

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Keywords: *Brillouin scattered light, Correlation domain analysis, distributed strain, Stability, Enlargement measuring range, bolted joint monitoring*

Abstract

Structural health monitoring (SHM) system using optical fiber sensor is powerful solution to reduced maintenance cost and structural weight. Especially, in order to monitor large area structural health monitoring, the Brillion optical correlation domain analysis (BOCDA) method is most compatible method because of its long-range measurement, high spatial resolution, and high-speed strain sampling.

In this paper, the authors report subcomponents test result, which is distribution strain measurement with 5mm spatial resolution BOCDA system. The test article is simulate airplane critical structural portion such as weight-lightened portion and bolted joint portion. The stress concentration and missing bolts can be detected with high spatial resolution BOCDA by strain distribution change.

1 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, was one of the effective methods for large area monitoring. The Brillouin optical time domain reflectometer (BOTDR) is popular method of the distributed optical fiber 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.

On the other hand, Brillouin correlation domain analysis (BOCDA) method is developed by Hotate et al [3], [4]. The BOCDA system can raise spatial resolution without broadened its Brillouin spectrum and can select measuring portion compared with BOTDR technology. For the reason, the BOCDA technology is suitable to Airplane SHM system.

The authors developed the prototype mobile BOCDA system, and clarified its application issue for structural health monitoring [5]. The spatial resolution of this first prototype BOCDA system is 50mm spatial resolution and 2.7Hz point sensing. In the previous research, the monitoring object is limited stiffened panel buckling behavior and flight load at low rare maneuvers as the first prototype BOCDA system has low accuracy. It is necessary, the additional development of the prototype BOCDA system.

On another front, the BOCDA method has high potential, in spatial resolution, sampling speed, and measuring accuracy. Therefore the BOCDA application portion can be expanded the, which are around of weight reduction hole portion and bolted joint portion (see Fig. 1 [6]). These portions are important portion on metal and composite airplane structures, and are application candidate of the BOCDA monitoring.

Fig. 1 Example of bolted joint portion

In this work, the authors conducted the element structure tests and monitored strain distribution change with high spatial resolution BOCDA system.

2 BOCDA measurements

2.1 Principle of BOCDA

A 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/ºC in silica based optical fiber sensor. The Brillouin frequency shift ν_B is given by equation (1) [7].

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

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 using stimulated Brillouin scattering in this work is described in Fig. 2. 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). On the other hand, the probe light wave is 10~11GHz frequency downshifted with Single Side Band (SSB) modulator. A pump light wave and a 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. In this work, a spatial resolution of the BOCDA system is about 4.5mm. The overview of the BOCDA system is shown in Fig.3.

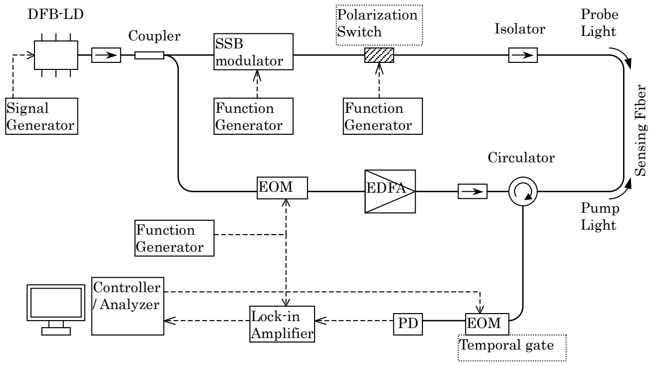


Fig. 2 Diagram of BOCDA system

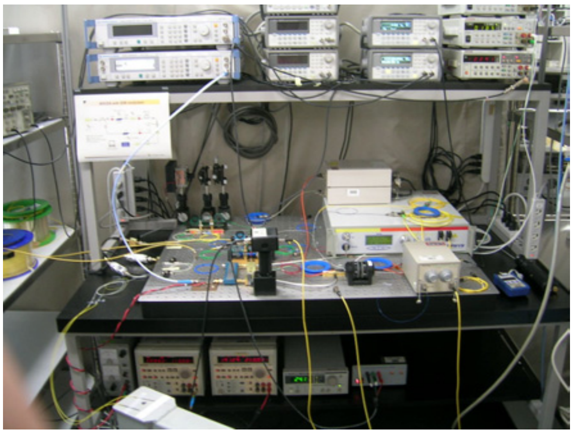


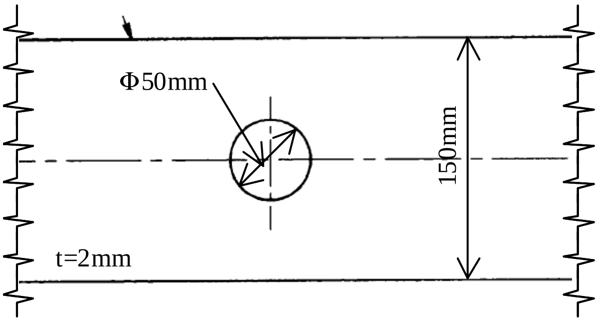
Fig. 3 Overview of BOCDA system

3. Subcomponents tests

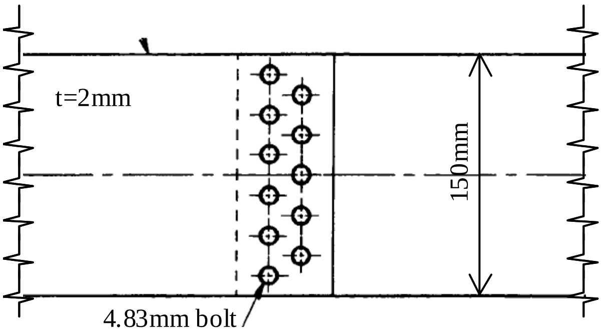
3.1 test article

In the element structure test, the test articles are simulated the around weight reduction hole or bolted joint panel which is a critical portion of structures. For the bolted joint test article, the test was conducted by removing some bolts in order to verify the probability of detection for missing bolts during airplane operation.

The weight reduction portion test article (Article A) is aluminum plate 2mm in thickness and 150mm in width with 50mm diameter hole in the center of the plate. The bolted joint portion test article (article B) is single lap bolted joint aluminum plate with 11 bolts of 4.83mm diameter. These two plates are 2mm in thickness and 150m in width. The test articles are shown in Fig. 4.



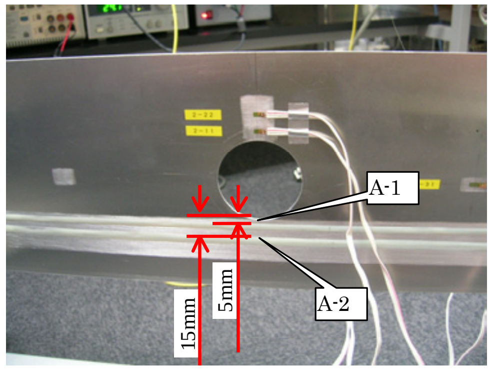
(a) Test article A (weight reduction portion)



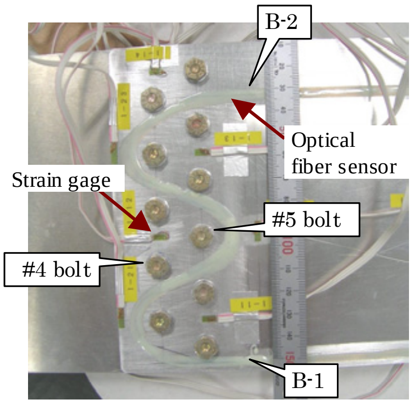
(b) Test article B (bolted joint portion)
Fig. 4 Illustration of test articles

3.2 Test setup

The optical fiber sensor was bonded with epoxy adhesives on the test articles around monitoring portion, so that strain distribution of these areas was measured. At the test article A, optical fiber sensor is located in 5mm and 15mm distance from the hole edge. At the test article B, optical fiber sensor is located between bolts. The optical fiber sensors were single mode coated with UV cured resin. An optical fiber sensor attachment situation is shown in Fig. 5. Strain gages are attached on the test article near by optical fiber sensors in order to compare with BOCDA results and monitor tension loading.



(a) Test article A (weight reduction hole portion)



(b) Test article B (bolted joint portion)
Fig. 5 optical fiber sensor location

The test article was attached in the test flame, and loaded tension load with screw jack. The overview of test setup is shown in Fig. 6. The tension load was 15.8kN, which is generated about 2000[με] on non-stress concentration portion.

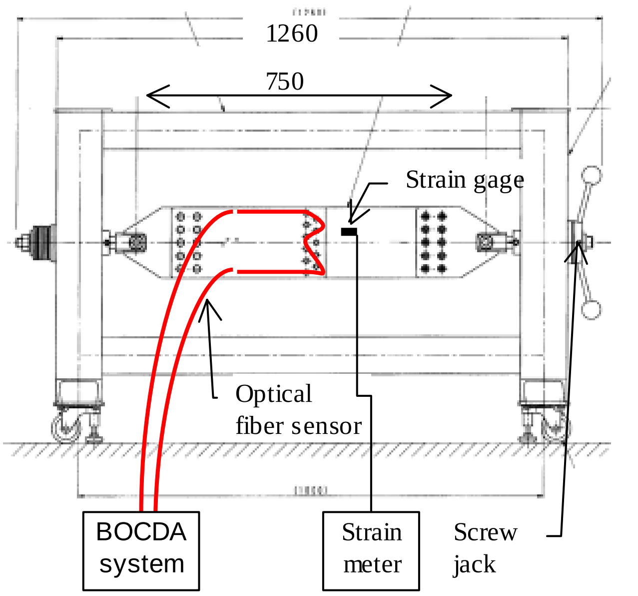


Fig. 6 over view of test setup

4 Test result

4.1 Test article A (Weight reduction hole)

The strain distribution results on around weight reduction hole are shown in Fig.7. The x-axis indicates optical fiber sensor position from the BOCDA system. The optical fiber positionA-1 (see Fig. 4(a)) was 0.35m of optical fiber position, and the optical fiber position A-2 was 0.95m.The strain concentration was observed clearly from the BOCDA measurement results. The strain value at uniform strain area where far from weight reduction hole, was same as calculation value. The strain value of stress concentration portion (point A-2) is good agreement with strain gage. However the strain value of the point A-1 position has about 10% of difference by that of the BOCDA system and strain gages. This difference is considered influence of optical fiber coating. The coating material is UV cured resin, which is very low elastic modulus (about 1.5 GPa). This UV cured resin coating protects optical fiber sensor from the disturbance, such as axial asymmetric load and micro bending [8]. The disturbance is reduction Brillouin scattering light power and measuring accuracy. But the coatings reduce strain-measuring sensitivity of BOCDA.

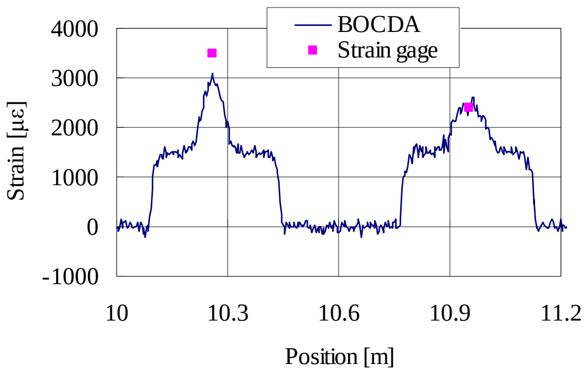
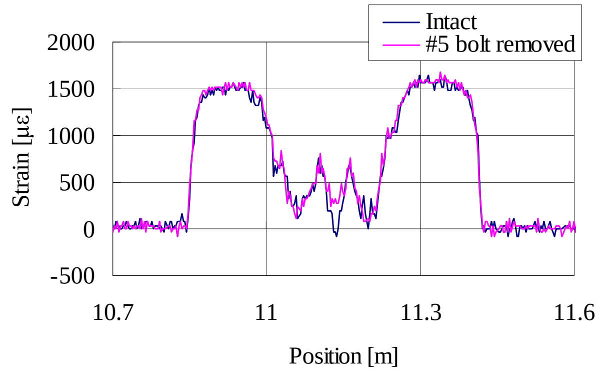


Fig. 7 strain distribution result of the test article A (weight reduction hole)

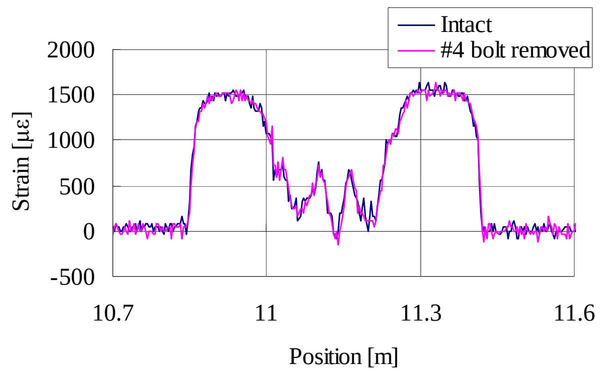
4.1 Test article B (bolted joint portion)

The strain distribution results on around bolted joint portion are shown in Fig. 8. The x-axis indicated optical fiber sensor position from the BOCDA system. From the BOCDA measurement results, a complicated strain distribution is observed.

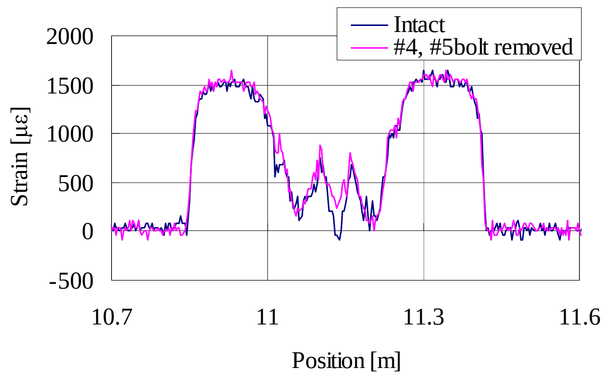
The strain distribution result of missing bolt simulation case is also shown in Fig. 8. At the #5 bolt removed case, the strain distribution was clearly changed. This result shows the BOCDA system has the potential to monitor missing bolts. However, at the #4 bolt removed case, the strain distribution change is hardly discriminable. It is possible to be affected from optical fiber sensor coating and/or optical fiber sensor route. At the #4 and #5 bolt removed case, strain distribution result is similar to #5 removed case. Around #4 bolt portion is seemed to hardly detect portion.



(a) #5 bolt removed condition



(b) #4 bolt removed condition



(c) #4, #5 bolts removed condition

Fig. 8 BOCDA measuring results at bolted joint test article

5 Discussions

Comparison with a BOCDA measurement and the FEM analysis result in test article A is shown in Fig. 9. The comparison of test article A is almost good agreement. In comparison of strain distribution with BOCDA measurement in the state where all the bolts were combined, and FEM analysis, a difference is accepted in the peak position value of strain like the measurement result around a weight reduction hole.

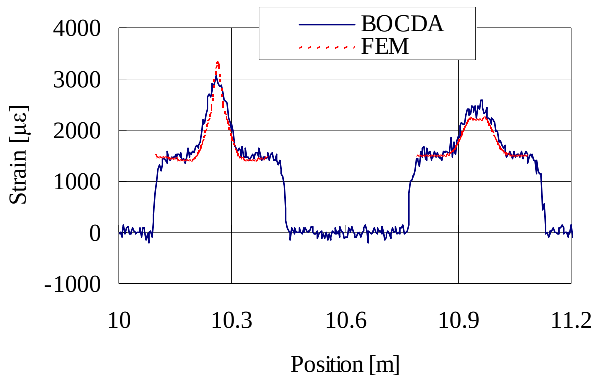
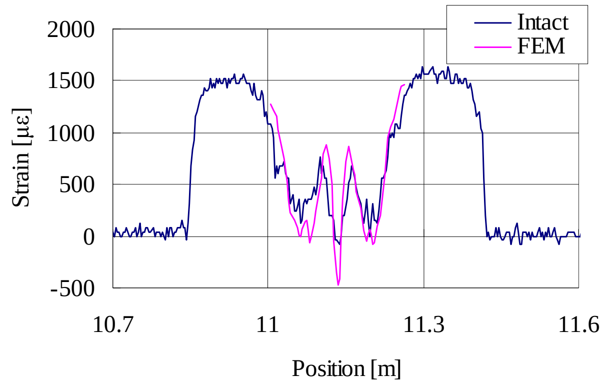
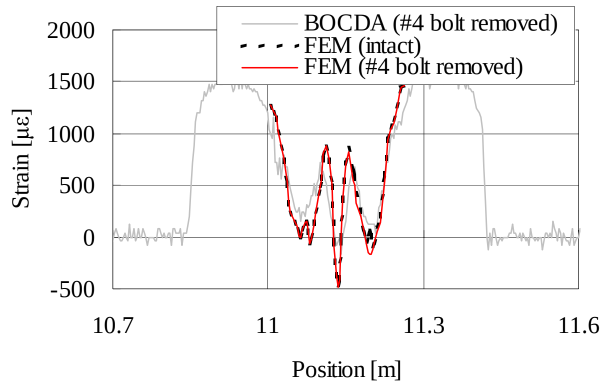


Fig. 9 Strain distribution comparison between BOCDA and FEM analysis

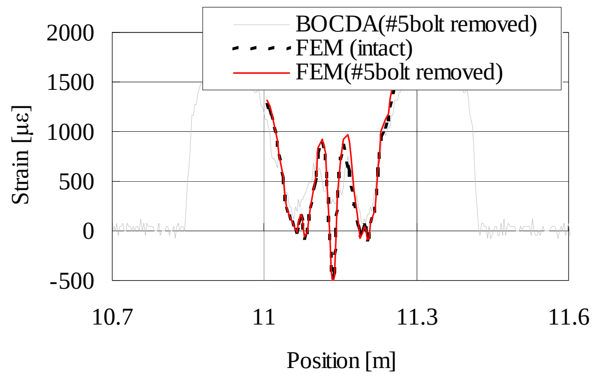
Comparison with a BOCDA measurement and the FEM analysis result in test article B is shown in Fig. 10. These results indicate similarly strain distribution, but strain peak and negative value is slightly deferent. This difference is also caused by optical fiber coating influence. In the missing bolts simulation case (Fig. 10 (b), (c)), removing #5 bolt occurs clearly strain distribution change around #5 bolt. But removing #4 bolt is not clearly change. Therefore, optical fiber route in this test hardly detected #4 bolt missing. Consequently, in order to monitor bolted joint portion with the BOCDA system it is necessary to optimize fiber coating such as material and thickness and optical fiber sensor routing.



(a) Intact condition



(b) #4 bolt removed condition



(c) #5 bolt removed condition

Fig. 10 comparison between BOCDA measuring results and FEM analysis

6 Conclusions

The subcomponents test simulated structure critical portion was conducted and measured distribution strain with the high spatial resolution BOCDA system. Results obtained in this work are summarized as follows:

- The high spatial resolution BOCDA system has a potential monitoring weight reduction hole and bolted joint portion.

- An optical fiber sensor coating should be optimized to detect steep strain distribution.
- A route of optical fiber sensor around of bolts should be optimized to detect missing molt.

Future studies for applying BOCDA system to aerospace SHM is optimization optical fiber coating and sensor route. And next step is application the BOCDA system to monitor composite structure

Acknowledgment

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.

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