Development of Simultaneous Measurement System for Strains and AE Using Multiple FBG Sensors (For Structural Health Monitoring of Solid Space Rocket Composite Motor Case)

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Research was conducted to apply fiber Bragg grating (FBG) sensors, a kind of optical fiber sensor, to structural health monitoring of solid space rocket composite motor-cases. A new measurement system was developed as a result of the research. The system possesses two light sources. When using multiple fiber ring lasers as the light source, the system can simultaneously measure strains of up to 1% and Acoustic Emission (AE) using multiple FBG sensors. When a broadband light source is used, the system can also measure very fast strains. The system was applied to a pressure test for system evaluations in the development of Epsilon Launch Vehicle.

1. Introduction

Rocket launching reliability is secured by applying various Quality Assurance (QA) procedures throughout all processes, including design, selection of materials and parts, manufacturing, transportation and rocket system assembly. The QA procedures are based on design and various test results in development stages. Rocket development tests are carried out using sufficiently reliable and time-proven measurement technologies.

Meanwhile, the Japan Aerospace Exploration Agency (JAXA) has adopted the advanced and intelligent systems to Epsilon Launch Vehicle launching procedures while maintaining their reliability. **Figure 1** shows the 1st Epsilon Launch Vehicle on the launch pad. The Epsilon Launch Vehicle is the newest three-stage solid-rocket developed by JAXA. The development of new rockets like the Epsilon Launch Vehicle brings opportunities to use and confirm advanced inspection and measurement techniques, which have been progressing in recent years.

In this research, the authors have attempted to apply optical fiber sensor-based Structural Health Monitoring (SHM) to composite motor case ground operations of solid-rocket motors. Although there are many different types of optical fiber sensors, the authors have particularly focused on FBG sensors, which are able to measure both static and dynamic strains.(1) This is because dynamic strain measurements are required in ground combustion tests of solid-rocket motors. Moreover, FBG sensors detect ultrasonic signals including AE.(2) Tsuda et al. proposed an SHM system that uses a single FBG sensor as a strain sensor and an ultrasonic sensor.(3) We have improved their proposal to match our

(Note) Taken from http://www.jaxa.jp/projects/rockets/epsilon/

Fig. 1 Epsilon-1 on the launch pad

SHM system, in which an FBG sensor measures both strain and AE simultaneously.

We have successfully developed the first (and practical) SHM system. The system can measure strains of up to 1% as well as simultaneously measure AE using multiple FBG sensors. We hereby report on our research and the newly developed system. The system was applied in the development stage of the Epsilon Launch Vehicle.

2. FBG sensor

An FBG is an inscribed periodic change in the refractive index along the core axis of an optical fiber. **Figure 2** illustrates a schematic of the FBG principle.

When a broadband light illuminates an FBG, the FBG strongly reflects the narrowband light of which the center wavelength is defined by Equation (1). The wavelength is called the Bragg wavelength λ_B. In Equation (1), n_e and Λ are the effective refractive index and the grating period.

$$\lambda_B = 2 n_e \Lambda \quad \cdots\cdots (1)$$

The Bragg wavelength λ_B varies according to changes in both the effective refractive index n_e and the grating period Λ. This is the principle that FBGs are used to as a strain sensor or a temperature sensor. **Figure 3** shows an example of the relationship between strain and the Bragg wavelength, and **Fig. 4** shows the relationship between temperature and the Bragg wavelength.

Because optical fiber is lightweight and highly rigid, it is possible to measure high-speed strain change up to 100 kHz[4] as well as static strain change. The authors have succeeded in simultaneously measuring both strains and AE signals applying the technique of using a fiber ring laser as proposed by Tsuda.[5] **Figure 5** illustrates a schematic diagram of Tsuda's method (the ultrasonic detecting method using a fiber ring laser as a light source for the FBG sensor measurement system).

3. Collaborative research system

This research was conducted as a collaborative team with members from the Institute of Space and Astronautical Science/JAXA (ISAS/JAXA), the National Institute of Advanced Industrial Science and Technology (AIST), IHI Aerospace Co., Ltd. (IA) and IHI Inspection and Instrumentation Co., Ltd. (IIC). AIST and IIC are well experienced with measurement techniques using FBG sensors, and ISAS/JAXA and IA are engaged in aerospace research and development. **Figure 6** illustrates the

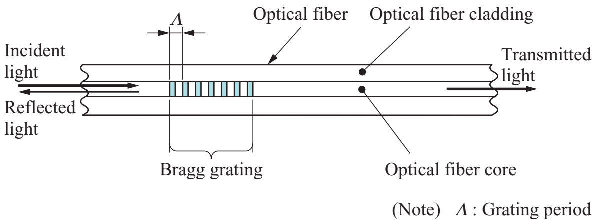

Fig. 2 Schematic of FBG principle

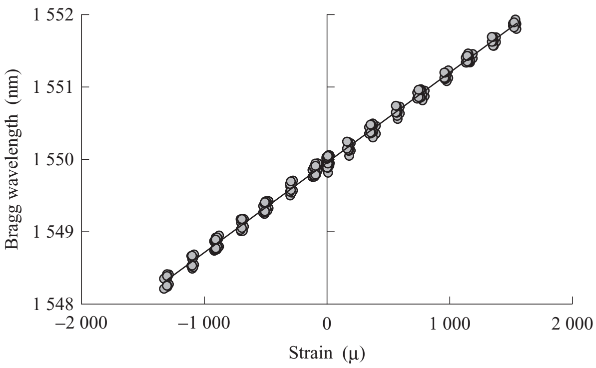

Fig. 3 Relationship between strain and Bragg wavelength

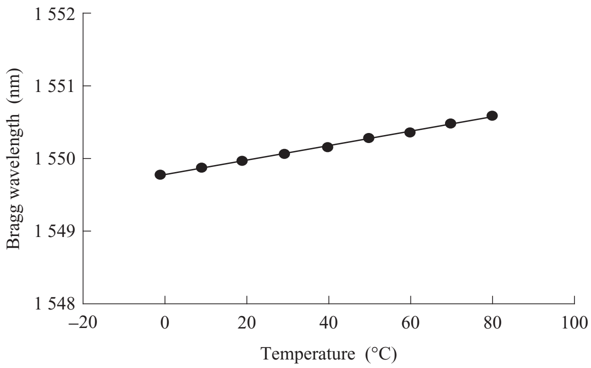

Fig. 4 Relationship between temperature and Bragg wavelength

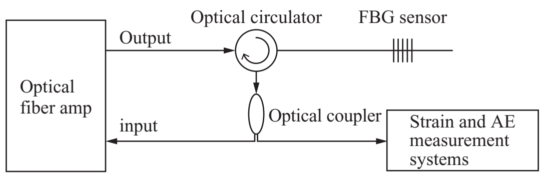

Fig. 5 Block diagram of measurement system using an FBG sensor and a fiber ring laser

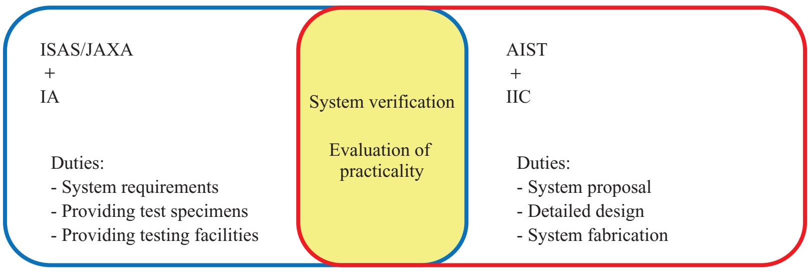

Fig. 6 Collaborative research system and roles

collaborative research system and roles of each organization. ISAS/JAXA and IA have provided the system requirements and measurement conditions for strain measurement and AE measurement of composite motor cases, while AIST and IIC have proposed the configurations and specifications of a measurement system suitable for the requirements and conditions. The system design reviews and data reviews were held frequently to discuss whether the system specifications met the conditions and preliminary test results supported the design conditions. IIC was primarily responsible for the detailed design and fabricating the system based on the discussions.

The developed system evaluations were conducted by collaborations with all members. ISAS/JAXA and IA provided test specimens and testing facilities, while AIST and IIC were responsible for operation of the system and data analysis. The obtained data were evaluated and discussed through effective collaborations.

Throughout the course of the research, all members provided respective technologies and resources, and frequently shared new insights and exchanged opinions. As a result, the research proceeded smoothly.

4. Research goal

FBG sensors are employed to various structural monitoring systems. In most cases, FBG sensors are used as strain sensors. Meanwhile, various ultrasonic detecting methods using FBG sensors have also been proposed.[2] However, there had not been a system that can measure strains and AE signals simultaneously using multiple FBG sensors before our research.

In conventional strain measurement technologies for multiple FBG sensors, a light source or spectrometer scanning is needed in order to identify the Bragg wavelengths. In such scanning optical systems, light does not illuminate all FBG sensors all the time, so such systems cannot be applied to AE measurement, because the occurrence of AE cannot be predicted.

Meanwhile, there is a well-known AE measurement technique using a narrow bandwidth tunable laser. This technique sets the wavelength of the laser to the half-power wavelength of the reflected light spectrum from an FBG sensor. When AE impinges the FBG sensor, a very small change in the Bragg wavelength is detected as the optical intensity change from the FBG sensor.[6] However, when there is a large change in the wavelength, the wavelength of the laser has to be changed. Thus, this technique cannot be used with structures for which the strain changes widely.

The authors recognized that the problem of the conventional FBG sensor measurement technology was attributed to the scanning of the light source or spectrometer. Consequently, it was reasonable to use a strain measurement technique that uses[7] an optical filter and a couple of photo-detectors proposed by Davis and Kersey that have been adopted by AIST and IIC. The technique would enable simultaneous strain and AE measurement without the need for a scanner in either the light source or the spectrometer. If simultaneous measurements of strain and AE using a single FBG sensor were possible, continuous monitoring would be possible against various structural environmental loads exerted on composite motor cases.

Based on this background, we set the goal of developing a measurement system capable of simultaneously measuring both strain and AE signals with a single FBG sensor, while also enabling a multiple FBG sensor configuration.

Figure 7 illustrates a schematic of the simultaneous measurement concept for strain and AE for the case of a single FBG sensor. In **Fig. 7**, the light from the FBG sensor is divided into a strain measurement system and an AE measurement system by an optical coupler. The strain measurement system measures large Bragg wavelength changes at a comparatively low frequency, while the AE measurement system measures optical intensity changes due to Bragg wavelength changes at a comparatively high frequency. As a result of this configuration, simultaneous measurement of strain and AE with a single FBG becomes possible. The concept has been verified through testing.

5. Developed FBG sensor measurement system[8]

Figure 8 illustrates a block diagram of the developed FBG sensor measurement system and **Fig. 9** shows the appearance of the system. The system possesses two light sources: one is a broadband light source and the other is multiple fiber-ring-lasers using custom-build Erbium-Doped optical Fiber Amplifiers (EDFA) for this research. **Table 1** shows the main specifications of the developed system. The strain measurement range is designed to cover strain changes of up to 1% that is the anticipated maximum strain in the pressure tests of the composite motor cases of solid-rockets.

6. Conclusion

A simultaneous measurement system for strain and AE using multiple FBG sensors was developed in conjunction with the development of the Epsilon Launch Vehicle, which is equipped with an advanced launch system. This measurement system is designed to be applied to the structural health monitoring of the ground operations of composite motor cases, which are major structural element of solid rockets. As a part of the system evaluations, the developed system was used in the development stage of the Epsilon Launch Vehicle. In addition, we used the developed system to measure the vibrations of a mechanical element in

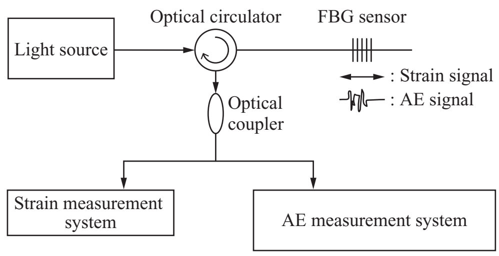

Fig. 7 Schematic of simultaneous measurement for strain and AE using an FBG sensor

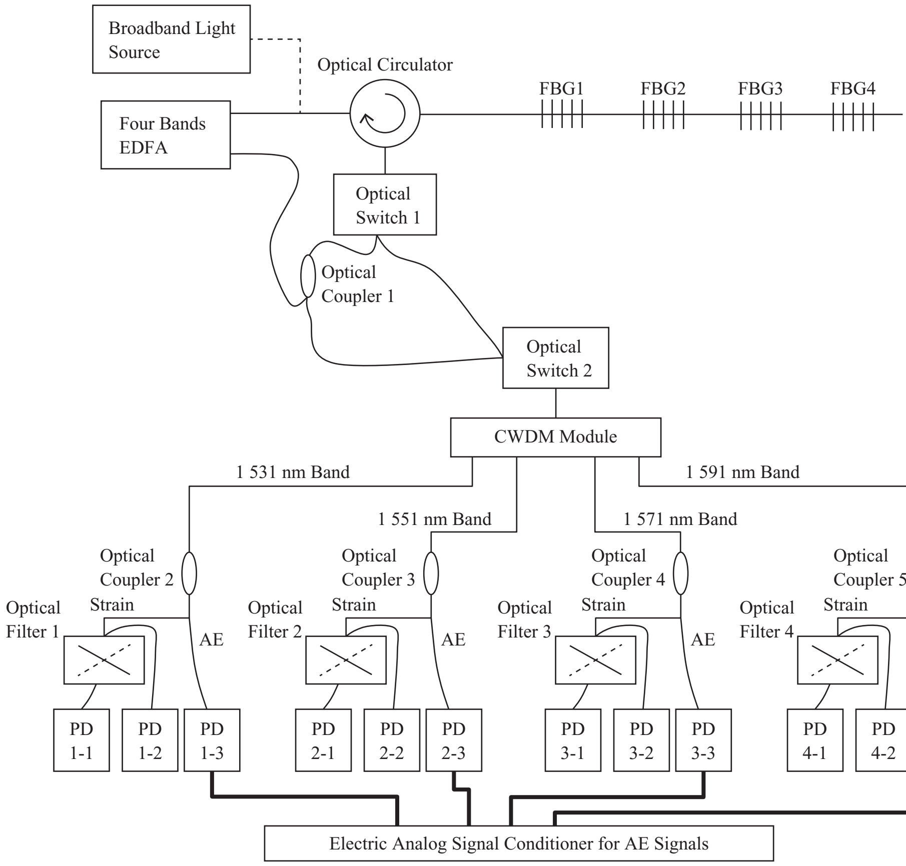

Fig. 8 Block diagram of the developed measurement system[8]

Fig. 9 Appearance of the developed measurement system

Table 1 Main specifications of the developed system

Item	Broadband light source	Optical fiber ring laser
Strain measurement frequency	DC to 100 kHz	DC to 1 kHz
Strain measurement range	0-1%	0-1%
AE measurement	N/A	Applicable (AE frequency 100-250 kHz)
FBG points	4	4

liquid hydrogen, where electric sensors cannot be used. We were able to obtain very good results.[9]

The research reported in this article is a part of the findings of the research conducted from 2008 to 2010 under the JAXA Space Open Lab Program “Study of Structural Health Monitoring for Large Structures.” The research findings have been published from the perspective of each of the collaborators.[10], [11]

This article is a revised and corrected version of the article previously published as “Development of Simultaneous Measurement System for Strain and AE Using Multiple FBG Sensors for Structural Health Evaluation of Solid Rocket Motor Composite Chamber”[12] in the IIC REVIEW published by IIC.

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