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Using Embedded Fiber Bragg Grating (FBG) Sensors in Smart Aircraft Structure Materials

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Abstract

This paper describes the process of developing a smart material with monitoring application to the aircraft structures. A part of vertical stabilizer was selected and reproduced using carbon fiber honeycomb core sandwich panels. The sandwich panels reproduced were fabricated in accordance to the generic sandwich structure and aviation industry standards, including the materials and also the method of construction. Using a carbon fiber from Hexcel as the face-sheet, Nomex honeycomb as the core, the sandwich panel was cured using Hysol EA9330 resin according to aviation industry standard curing process. In order to make the sandwich panel as smart materials, optical sensor which has fiber bragg grating arrays, FBG, were embedded between the carbon fiber plies during the lay-out process. Using an FBG data logger, the FBG sensor signals were read before and after the FBG arrays were installed in the sandwich panels. From the initial measurement, the experiment was a success since the FBG sensors were readable and the difference in the signals was less than 1 nm. In the future, the specimen will be used for further experiment for measuring strains and establishing the existence of damage in the panel.

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Keywords: embedded fiber bragg grating arrays, optical sensors, honeycomb core sandwich panel

1. Introduction

The aircraft manufacturers started to use composite materials in aircraft components since early 1980s however the applications were limited to certain components only\textsuperscript{1}. The initial problem with the implementation of composite materials were high development cost including research and manufacturing cost as composite was relatively new at that time. There is a need to replace aluminum with composites for the following three reasons: fatigue problem with aluminum, lightness of composites, and corrosion problem in aluminum \textsuperscript{2}. The main reason of aircraft manufacturers changed the technology from steel and wood to aluminum in the 1920s was to get a lighter, more speed and comfort. The stressed-skin construction and compressed fuselage was developed to be lighter so that the aircraft could fly higher while burning less fuel and at the same time adding more speed to the aircraft \textsuperscript{3}. In order to get a lighter, stronger, more fuel efficient, and aerodynamically good performance aircraft, new composite materials must be adopted and researched. Van Tooren \textsuperscript{2} had proposed sandwich composite fuselage design for a lighter aircraft and Takeda et.al \textsuperscript{3} had proposed a smart composite sandwich structure for aerospace application with structural health monitoring (SHM) embedded in the composite in order to monitor the integrity of the structure. Herrmann et.al \textsuperscript{4} talked about the future of sandwich materials in commercial aviation. Stickler \textsuperscript{5} explained that the use of advanced composite materials in secondary structure in aircraft has been in practice since the last 30 years. The aircraft manufacturers have been using composite materials in various parts of the aircraft. The honeycomb sandwich composite, mainly non-metallic, has been used in larger parts in aircraft especially in the main box of the vertical and horizontal stabilizers. Figure 1 shows a diagram showing various components on the aircraft made out of composite materials.
1.1. The application of optical sensor in aircraft composite smart materials

The current technology of structural health monitoring (SHM) in composite materials is done using sensors especially optical sensors [6] and [7]. This is due to the fact that the traditional strain gauge is sensitive to lightning, current leakage and corrosion, whereby inaccurate reading will be shown. The main problem with sandwich composite is delamination between the core and the facesheet, and this failure occurs underneath the skin and cannot be seen with naked eye. Therefore, a smart material with embedded fiber bragg grating (FBG) optical sensor has been developed to monitor the delamination between the face-sheet and the honeycomb core. Takeda et.al [3] has been doing an extensive research in smart materials, damage detection using optical sensor [8, 9], health structural monitoring in aircraft honeycomb composite sandwich panel [10] and also the delamination of the face-sheet detection using FBG [11]. Other researchers have also been doing research on the aircraft composite structures monitoring using optical sensor. Riccio et.al [12] was conducting study on the stiffened composite panel, while Giurgiutiu et.al [13] were developing a smart structure with embedded optical sensor for better health monitoring. The recent development in the application of optical sensor especially fiber bragg grating can be seen through the works of Takeda et.al [9], Liu et.al [14] and also Giurgiutiu et.al [14]. K. Diamanti and C. Soutis had compiled the most recent works in structural health monitoring using optical sensor [15]. In Malaysia, FBG optical sensor is used to monitor a civil structure performance [16]. A fully operational airframe fatigue monitoring is conducted in Malaysia to its fighter airplanes although still based on strain gauges [17]. The works reported in this paper is part of an effort to make use FBG as part of the sensor system in aircraft structural integrity monitoring.

The type of FBG sensor used in this research is an array of two sensors in a single optical fiber. It is identified with the wavelength grating of 1550 nm and 1555 nm each. An Optical Spectrum Analyzer, OSA, and FBG scanner were used to measure the signal wavelength of the FBG sensors.

2. The objective of the paper

The objective of this paper is firstly to describe the construction of a smart aircraft structure material, constructed from honeycomb core-carbon fiber facesheet sandwich composite panel embedded with fiber bragg grating (FBG) sensor; and secondly to characterize the wavelength signals of the FBG sensor before and after embedded in the composite sandwich panel.

3. Theory of Fiber Bragg Grating (FBG) Sensors

Fiber Bragg grating, which is an in-fiber component, consists of a periodic modulation of the index of refraction along the fiber core, as shown in Figure 2. FBG functions like a filter when a broad-band light is transmitted into the fiber core, reflecting light at a single wavelength, $\lambda$, and a single wavelength is filtered in the transmitted light spectrum.
When there is a force exerted on the FBG, it will compress or expand, thus the grating spectral response is changed. The wavelength of the light source is related to the Bragg Grating period $d_o$ through the equation below:

$$\lambda_0 = 2n_0 d_o$$  \hspace{1cm} (1)

and

$$\Delta \lambda = 2n_0 \Delta d + 2d_o \Delta n$$  \hspace{1cm} (2)

The strain dependence of the Bragg wavelength arises from the physical elongation/retraction of the sensor and the change in refractive index due to photoelastic effects. The wavelength shift due to axial strain can be obtained by equation below:

$$\Delta \lambda = (1 - p_e) \lambda_0 \epsilon$$  \hspace{1cm} (3)

where $\epsilon$ is the applied strain, and $p_e$ is the photoelastic coefficient term given by

$$p_e = (n_0^2/2)(p_{12} - \nu(p_{11} + p_{12}))$$  \hspace{1cm} (4)

where $p_{ij}$ coefficients are the Pockel’s coefficient of strain-optic tensor and $\nu$ is the Poisson’s ratio.

4. The construction of the smart sandwich panel with embedded optical sensor

There were 14 specimens altogether prepared in this research. The specimen was a rectangular shape of size 300 mm long by 200 mm wide and 20 mm thick. It was constructed from a 20 mm thick, 3.2 mm cell size Nomex honeycomb core, sandwiched between two plies of carbon fiber from Hexcel at top and bottom sides. The composite panel was impregnated with Hysol 9330 resin. The fiber bragg grating sensor was laid on between the plies of the carbon fiber on one side of the panel. The specimen was cured at 82.2 degrees Celsius for 90 minutes under 110 kPa of vacuum pressure using Heatcon curing system. Figure 3 below shows the work flow of preparing the smart aircraft structure materials.

![Fig 3. The work flow process of preparing the smart aircraft structure](image)

The detail process in the workshop is shown in the Figure 4 below. The process was done in a controlled environment where the room temperature was kept at 25 degrees Celsius. The preparation and curing of the smart structure was done according to the airline standard procedures and in this case all specimens were constructed at Malaysia Airlines Composite Workshop at MAS Engineering Complex A at Subang, Malaysia.
Fig. 4. Specimen preparation. (a) wet lay-up cut-out, (b) laying down the FBG array in the middle of the carbon ply outer layer, (c) curing process of the panel, (d) completed smart structure sandwich panel with embedded FBG sensor.

Before the FBG sensors were embedded inside the smart structure, the wavelength signals were taken first, and after cured (Figure 4 (d)), the signals were once again taken to ensure that the FBG sensors system was working in the smart structure. Using FBG-SCAN 700/800 scanner from FBGS, the signals were read in both conditions (before and after embedded). Figure 5 below shows the schematic diagram of the experimental procedure.

Fig. 5. Schematic diagram showing FBG sensor connected to the measuring instruments (a) before embedded, (b) after embedded.
The signals taken were the peak wavelength in nanometer, nm, of the FBG in each optical array. There were two (2) FBG sensors in a single array. The optical sensor connector was connected to the FBG scanner, and the output data was taken directly in the output computer as shown in Figure 5 (a). The same procedure was done after the sensor was embedded in the smart structure as shown in Figure 5 (b). The following Table 1 shows the condition of the optical sensors after they were embedded.

Table 1. Sensor condition before and after embedded

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Sensor Condition Before Embedded</th>
<th>Sensor Condition After Embedded</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Good</td>
<td>One side broken but readable</td>
</tr>
<tr>
<td>2</td>
<td>Good</td>
<td>One side broken but readable</td>
</tr>
<tr>
<td>3</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>4</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>5</td>
<td>Good</td>
<td>One Side broken but readable</td>
</tr>
<tr>
<td>6</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>7</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>8</td>
<td>Good</td>
<td>One side broken but readable</td>
</tr>
<tr>
<td>9</td>
<td>Good</td>
<td>Broken in the middle. Need to read</td>
</tr>
<tr>
<td></td>
<td></td>
<td>from both sides</td>
</tr>
<tr>
<td>10</td>
<td>Good</td>
<td>One side broken but readable</td>
</tr>
<tr>
<td>11</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>12</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>13</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>14</td>
<td>Good</td>
<td>One side broken but readable</td>
</tr>
</tbody>
</table>

5. The results and discussion

The results of the signal readings of all 14 FBG sensor array is displayed in the Figure 6 and Figure 7 below. Figure 6 shows the signal reading of each of the 14 FBG’s before and after the FBG arrays were embedded in the sandwich composite panel. Figure 7 shows the difference of peak wavelength changes after the FBG arrays were embedded inside the sandwich composite panel. Positive difference means the sensor was stretched while negative difference means the sensor was contracted.

![Graph showing the peak wavelength of the 14 FBG arrays](image)

From Figure 6, it can be seen that the signal reading before and after embedded is not very much different. The bar on the left of each couple of bars is the signal taken before embedded, while the bar on the right side is the signal taken after embedded. The first series of arrays for example, An.1 (where n is the number from 1 to 14) is the grating wavelength of 1550 nm, while the second series An.2 (where n is the number from 1 to 14) is the grating wavelength of 1555 nm. From the figure, it can be seen that the signal reading after the embedded is almost identical to the signal before it was embedded in the specimen. The exact differences of the signal reading can be seen in the Figure 7.
From Figure 7, it can be seen that peak wavelength shift generally was less than 1 nm. Most of the FBG sensors show a stretched condition as indicated by the positive differences while only three FBG (sensor A7.1 & A7.2, A11.1&A11.2, and sensor A 14.1&A14.2) sensor arrays were compressed as indicated by the negative difference. The compression or extension of the FBG has no significant consequences in this experiment since the main intention of this experiment is the sensors are functional as it is supposed to be. Figure 8 shows the example of peak shift using Optical Spectrum Analyzer, OSA. In the figure, the left side of the each peak is the one before embedded while the right side of each peak is the one after embedded. The second line is a bit lower than the first line shows a power drop inside the optical fiber.

6. Conclusion

This paper has described the process of developing a smart material in the application of the aircraft structures. The material being developed in this research was a honeycomb core-carbon fiber skin sandwich composite panel with embedded FBG sensor for structural health monitoring. In this paper, the process of preparing the specimen was presented. Before the FBG sensor arrays were embedded, the signals were measured using optical FBG scanner. These signals were once again measured using the same equipment after they were embedded in the specimen. The signals were also recorded using Optical Spectrum Analyzer, OSA, to see the wavelength peak shift before and after embedded condition. From the initial measurement, the experiment was a success since the FBG sensors were readable and the difference in the signals was less than 1 nm. In the future, the specimen will be used for further experiment for measuring strains and establishing the existence of damage in the panel.
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Reference