Impact Localization on Composite Wing Using a Single FBG Sensor and Error Outlier Based Impact Localization Algorithm

Pratik Shrestha[1], Yurim Park[2], Hyunseok Kwon[3] and Chun-Gon Kim[4]

[1,2,3,4]Department of Aerospace Engineering, Korea Advanced Institute of Science and Technology,
291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea

pratik@kaist.ac.kr
yurimpark@kaist.ac.kr
khskr2000@kaist.ac.kr
cgkim@kaist.edu

ABSTRACT

Low velocity impact on composite structure can result in occurrence of barely visible impact damage (BVID) which are difficult to detect. Aircraft structures are vulnerable to such BVID because of low velocity impact due to runway debris, bird strike, tool drop, etc. Therefore, low velocity impact monitoring of composite structure is highly desirable for impact detection and localization. Additionally, SHM of large-scale structures with fewer numbers of sensors is desirable to reduce the complexity involved with the data-acquisition and processing. In this paper, feasibility of localizing low velocity impact on composite structure using a single sensor was investigated. Three FBG sensors were attached on the surface of the full-scale composite wing and the signal from each of the FBG sensor was processed using the error outlier based impact localization algorithm to predict the location of the impact. The localization results demonstrated the feasibility of localizing impact on composite structure using a single FBG sensor; overall, the impacts were localized with average error of about 26.6 mm.

1. INTRODUCTION

There has been considerable increase in the use of composite materials for manufacturing aircraft components and this upward trend is expected to continue in the future (Roeseler, Sarh, & Kismarton, 2007). Although there are many benefits of using composite materials, when these materials are impacted by foreign objects they are prone to barely visible impact damage (BVID) (Baker, Dutton, & Kelly, 1986). Undetected BVID can lead to catastrophic events, therefore BVID phenomenon is of major concern when using composite materials. As a result, structural health monitoring (SHM) is needed to inspect and detect any impact before they can cause failure of the aircraft.

There are several kinds of sensors available for SHM application, however fiber optic sensors (FOSs) (Measures, 2001) are of great interest for SHM. Among different types of FOSs, fiber Bragg grating (FBG) optic sensors are highly desirable for SHM of aircraft structures. These sensors can be embedded into composite materials, multiplexed and are also immune to electromagnetic interference. Furthermore, many previous research show promising capability of FBG sensors for performing SHM (Shrestha, Kim, Park, & Kim, 2015) (Kim, Park, Kim, Shrestha, & Kim, 2015) (Kim, Kim, Park, Shrestha, Kwon, & Kim, 2016).

In this paper, low velocity impact localization on composite wing done using FBG sensor together with error outlier based impact localization algorithm is presented. The materials and methods are presented in section two. Subsequently, the results are presented in the third section. Finally, the conclusions are presented in the fourth section.

2. MATERIALS AND METHODS

2.1. FBG Sensing Principal

FBG sensors consists of grating with periodic variation in the refractive index that reflects certain wavelengths of light and the remaining wavelengths are transmitted. The reflected wavelength can be calculated using the Bragg wavelength,

$$\lambda_B = 2 n_e \Lambda \tag{1}$$

where, n_e is the grating's effective refractive index and Λ is the grating period. Bragg wavelength is sensitive to any changes in strain or temperature. Therefore, the changes in temperature or strain shift can be measured using the shift in Bragg wavelength,

$$\Delta\lambda_B = \lambda_B\left[(\alpha + \xi)\Delta T + (1 - p_e)\varepsilon\right] \tag{2}$$

where, α is the coefficient of thermal expansion, ξ is the thermal-optic coefficient, T is the temperature, ε is the strain value, and p_e is the photo-elastic constant. The photo-elastic constant is calculated using

$$p_e = \left(\frac{n_e^{\,2}}{2}\right)\left[p_{12} - \nu\left(p_{11} + p_{12}\right)\right] \tag{3}$$

where, ν is the Poisson's ratio and, p_{11} and p_{12} are the strain-optic constants.

Finally, the strain can be calculated using equation (4), assuming there is no changes in the temperature. Similarly, changes in the temperature can be obtained using equation (5), assuming no strain is applied to the FBG sensor.

$$\varepsilon = \frac{1}{1-p_e}\cdot\frac{\Delta\lambda_B}{\lambda_B} \tag{4}$$

$$\Delta T = \frac{1}{\alpha+\xi}\cdot\frac{\Delta\lambda_B}{\lambda_B} \tag{5}$$

2.2. Experimental set-up

Figure 1. Experimental set-up: a) Jabiru UL-D aircraft, b) Jabiru's composite wing structure and c) data acquisition system.

Jabiru UL-D's, shown in Figure 1, (Jabiru Aircraft Pty Ltd, Australia) composite wing was used for the impact localization test. The experimental set-up of the composite wing used for the impact localization is shown in Figure 1. Three-multiplexed acrylic coated FBG sensors were attached on the upper surface of the wing with 45º angle orientation. Each of the sensor was used to localize the 20 impact delivered on the impact test region of the wing.

High-speed interrogator, SFI-710 (Fiberpro Inc., Korea), was used to acquire the impact signals at a frequency of 100 kHz, and the impact was delivered using impact hammer. The test impact signals acquired from the FBG sensors were analyzed using the error outlier based impact localization algorithm (Shrestha, Kim, Park, & Kim, 2016) (Shrestha, Park, & Kim, 2017).

2.3. Impact localization algorithm

The impact response signals obtained from the FBG sensors are processed using the error outlier with Euclidean threshold based impact localization algorithm (Shrestha et al, 2017). The impact location on the test structure is determined by comparing the normalized impact signal with the normalized reference signals, through Step 1 and Step 2, by setting the error threshold limit to 1.0 nm. Once all the possible location points 'N' are identified in Step 3, in the next step the algorithm evaluates whether to include any possible detected location that can be used to determine the final impact location.

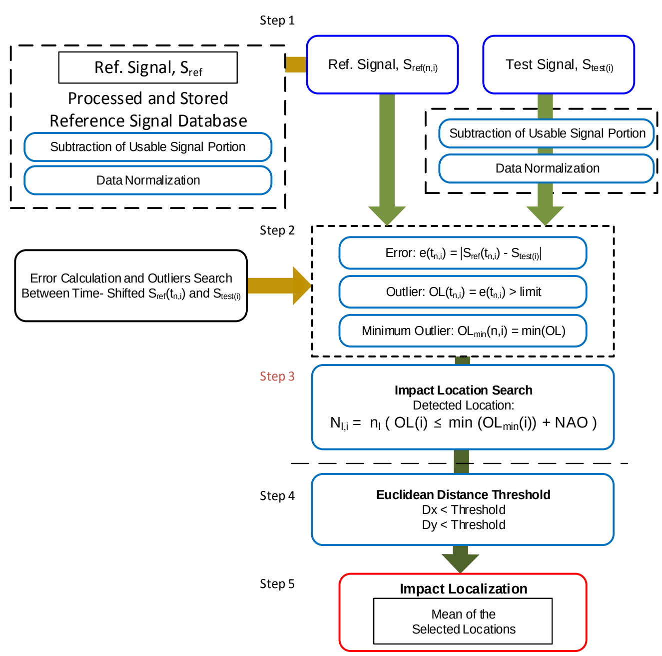

Figure 2. Impact localization algorithm flowchart.

In Step 4, selection of the most likely impact locations are done by comparing the Euclidean distances between the x-coordinate and the y-coordinate of each of the detected locations with the mean of the x-coordinate and the y-coordinate, 'Dx' and 'Dy', respectively, for all the detected locations. Finally, in Step 5, the location of the impact is predicted by calculating the mean of the selected locations.

3. RESULTS

The test impact points on the composite wing were successfully localized using a single FBG sensor and the error outlier based impact localization algorithm. The three FBG sensors were able to localize the 20 impact test points with average error of 24.3 mm, 26.3 mm and 29.3 mm. Moreover, the impacts on the wing structure were localized with average error of 26.6 mm. Therefore, the feasibility of using a single sensor to localize the low velocity impact with error outlier based impact localization has been demonstrated.

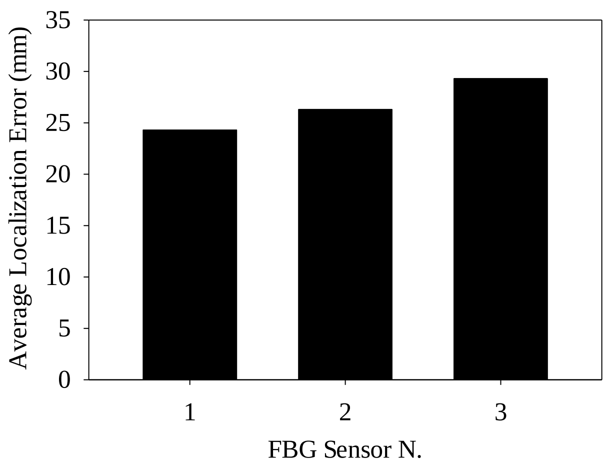

Figure 3. Single sensor localization results.

4. CONCLUSIONS

A SHM system capable of localizing low velocity impact using few numbers of FBG sensor is highly desirable in order to reduce the complexity and cost associated with the data acquisition and processing of signals for real-time health monitoring of aircraft structure. In this paper, the feasibility of low velocity impact localization on complex composite wing structure done using a single FBG sensor and error outlier based impact localization algorithm was presented. The single sensor impact localization parametric study results presented in this paper show that the impact monitoring on composite structure can be performed using a single FBG sensor with consistent localization performance.

ACKNOWLEDGEMENT

This work was supported by the Technology Innovation Program (10074278, Development of a SHM system for UAV using CNT/Polymer hybrid fiber sensor network and simultaneous proof-of-concept of autonomous flight and diagnosis) funded By the Ministry of Trade, Industry & Energy (MI, Korea).

REFERENCES

Baker, A., Dutton, S., & Kelly, D. (1986). *Composite Materials for Aircraft Structures*. AIAA.

Kim, J.-H., Park, Y., Kim, Y.-Y., Shrestha, P., & Kim, C.-G. (2015). Aircraft health and usage monitoring system for in-flight strain measurement of a wing structure. *Smart Materials and Structures*, *24*(10), 1–12. http://doi.org/10.1088/0964-1726/24/10/105003

Kim, Y. Y., Kim, J. H., Park, Y., Shrestha, P., Kwon, H. J. and, & Kim, C. G. (2016). Low-speed impact localization on a stiffened composite structure using reference data method. *Composites Research*, *29*(1), 1–6.

Measures, R. M. (2001). *Structural Monitoring with Fiber Optic Technology*. San Diego, Calif.: Academic Press.

Roeseler, W. G., Sarh, B., & Kismarton, M. U. (2007). Composite structures: The first 100 years. In *16th International Conference on Composite Materials* (pp. 1–10).

Shrestha, P., Kim, J. H., Park, Y., & Kim, C. G. (2015). Impact localization on composite wing using 1D array FBG sensor and RMS/correlation based reference database algorithm. *Composite Structures*, *125*, 159–169. http://doi.org/10.1016/j.compstruct.2015.01.029

Shrestha, P., Kim, J. H., Park, Y., & Kim, C. G. (2016). Impact localization on composite structure using FBG sensors and novel impact localization technique based on error outliers. *Composite Structures*, *142*, 263–271. http://doi.org/10.1016/j.compstruct.2016.01.088

Shrestha, P., Park, Y., & Kim, C.-G. (2017). Low velocity impact localization on composite wing structure using error outlier based algorithm and FBG sensors. *Composites Part B: Engineering*, *116C*, 310–324. http://doi.org/http://dx.doi.org/10.1016/j.compositesb.2016.10.068

BIOGRAPHIES

Pratik Shrestha was born in Nepal in 1990. He received his PhD in Aerospace Engineering from KAIST, South Korea, in 2017. He is currently working as a post-doctoral researcher at Smart Structures and Composites Lab., KAIST. His research interest is in the area of low-velocity impact localization & damage monitoring on composite structures using fiber optic sensors.

Yurim Park received his undergraduate and master's degree from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 2011 and 2013, respectively. He is currently pursuing his PhD at KAIST and his research interests are fiber Bragg grating sensors for structural health monitoring in space applications including hypervelocity impact and composite materials.

Hyunseok Kwon was born in Korea in 1989. He received his MSc degree in Aerospace Engineering from KAIST, South Korea, in 2017. He is currently a PhD candidate in the Department of Aerospace Engineering at KAIST. His research interest is in the area of multifunctional composite structure & structural health monitoring of the composite structures using fiber optic sensors.

Chun-Gon Kim is a professor of Aerospace Engineering at Korea Advanced Institute of Science and Technology. He received his PhD degree in Aeronautical Engineering from KAIST in 1987. He has been a faculty member in Aerospace Engineering at KAIST since 1991. His primary research interest is in the area of smart structure design using optical fiber sensors, stealth structure, composite material properties in space environment and structural battery.