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# Application of 1D Array FBG Configuration for Impact Localization on Composite Wing under Simulated Noise

Pratik Shrestha [1], Jin-Hyuk Kim [1], Yurim Park [1] and Chun-Gon Kim [1]

[1] *Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea*

## Abstract

Low velocity impacts on composite materials, which can cause barely visible impact damage (BVID), needs to be detected and localized in order to ensure the safety of aircraft structures. In this paper, impact localization on composite wing under simulated operating noise condition using 1D array FBG sensor configuration is presented. Composite wing of Jabiru UL-D aircraft is used for impact localization test under simulated noise conditions. The impact signals were sampled using a high speed FBG interrogator at 100 kHz, the operating noise conditions on the wing were simulated using a shaker and correlation based reference database algorithm was used for impact localization. The present study demonstrates the feasibility of 1D array FBG configuration and reference database impact localization algorithm to monitor low velocity impact on large scale structure under simulated working environment. The impact points on the composite wing were detected with localization error of less than 40 mm.

**Keywords:** Composite Wing, FBG Sensors, Impact Localization, Simulated Noise, SHM.

## Introduction

Due to composite material's high specific strength and stiffness to weight ratio, their application for aircraft components is highly desirable and therefore upward trend in the use of such materials is expected to continue in the future [1]. Currently, aircraft safety and efficiency are ensured through periodic non-destructive inspection [2]. However, composite materials have much more complex damage characteristics than isotropic materials and so conventional approach for inspecting such structure is not suitable for ensuring the safety and reliability of such structures [3]. One of the major concern in composite structure is the occurrence of barely visible impact damage (BVID) [4] which may occur due to low velocity impact. BVIDs are difficult to detect through visual inspection. Therefore, to overcome such limitation of composite structures, detection and localization of low velocity impact which can cause BVID is highly desirable for ensuring the safety and reliability of such materials.

Real-time structural health monitoring (SHM) [5] of aircraft structure can be done so that low velocity impacts, such as due to tool drop, runway debris, bird strike etc., which can cause BVID can be detected and localized instantaneously. SHM system can alert the ground engineers and the pilot of such impacts simultaneously for further inspections. Thereby, the risk of structure failures due to BVID, which might have gone unnoticed otherwise, can be minimized. Several kinds of sensors are available for SHM application, however fiber optic sensors (FOSs) [6] are of great interest for SHM. Among the different types of FOSs, fiber Bragg grating (FBG) optic sensors are highly desirable for SHM of aircraft structures as they can be multiplexed, embedded into composite materials and are also immune to electromagnetic interference.

Several researchers have demonstrated impact detection and localization using FBG sensors for SHM. Park et al., [7] used neural network algorithm to estimate the location of impact on stiffened composite plate using the signals from FBG sensors. Cristobal et al., performed localization of low velocity impact using strain amplitude information from FBG sensors [8]. Nakamura et al., implemented a FBG/PZT hybrid sensor system for impact monitoring of aircraft composite structure [9]. FBG sensor was shown to be sensitive to the direction of the signal propagation by Takeda et al., [10]. Shrestha et al., [11] demonstrated the use of 1D array FBG sensor for impact localization on composite wing using reference database impact localization algorithm. While Jang et al., demonstrated the possibility of using RMS based impact localization algorithm for impact detection under dynamic loading [12].

Detection and localization of impacts on aircraft structure under working conditions can be difficult due to variance in the response signals due to noise presence. Therefore, in this paper, impact location detection on composite wing, under simulated operational noise, using correlation comparing reference database based impact localization algorithm is investigated. The working principle of FBG sensor and the reference database impact localization algorithm is introduced. Then the experimental set-up for impact localization on composite wing and the experimental results are presented. The conclusions of the present research are presented in the final section of this paper.

## Fiber Bragg Grating Sensor Fundamentals

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

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

where, $n_e$ is the grating's effective refractive index and $\Lambda$ 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, $\alpha$ is the coefficient of thermal expansion, $\xi$ is the thermal-optic coefficient, $T$ is the temperature, $\varepsilon$ is the strain value, and $p_e$ is the photo-elastic constant. The photo-elastic constant is calculated using

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

where, $\nu$ is the Poisson's ratio and, $p_{11}$ and $p_{12}$ are the strain-optic constants. Finally, the strain can be calculated using Eqn 4, assuming there is no changes in the temperature. Similarly, changes in the temperature can be obtained using Eqn 5, assuming no strain is applied to the FBG sensor.

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

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

## Correlation Based Impact Localization Algorithm

In the present research, correlation based impact localization algorithm is used to localize the impact points. In the correlation based impact localization algorithm, the correlation coefficient between the reference signal, $S_{ref}$, and the random impact signal, $S_{ran}$, is calculated using Eqn 6**.** The correlation method used for the reference database impact localization algorithm compares the two signals, reference signal and the random impact signal, and outputs the correlation value from −1 to +1. Signals similar to each other will have correlation value closer to +1 and dissimilar signals will have low or negative correlation value.

$$Corr = \frac{\Sigma(S_{ref}-\overline{S_{ref}})(S_{ran}-\overline{S_{ran}})}{\sqrt{\Sigma(S_{ref}-\overline{S_{ref}})^2(S_{ran}-\overline{S_{ran}})^2}} \tag{6}$$

Figure 1 shows flowchart of the correlation based reference database impact localization algorithm. In this algorithm, firstly, the data normalization of the reference signal, $S_{ref(n,i)}$, obtained by FBG sensor 'i' at training reference grid point 'n' and random impact signal, $S_{ran(i)}$, acquired by FBG sensor 'i' is done to re-scale the signal. Subsequently, the correlation coefficient between the test signal, $S_{ran(i)}$, and all the reference impact signals, $S_{ref(n,i)}$, of the test specimen are calculated.

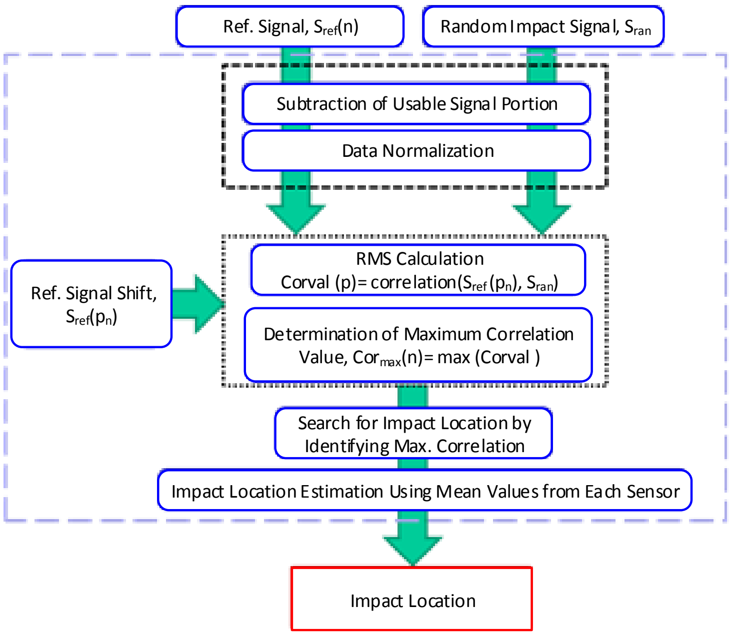


*Fig. 1: Correlation based reference database impact localization algorithm flowchart*

In order to improve the localization results the normalized reference signal is time-shifted, $S_{ref}(t_{n,i})$, from t=1 to t=200 in increments of t=1, and the correlation value between each of the time-shifted reference impact signal and the random impact signal, $S_{ran(i)}$, are computed. The algorithm then searches for the maximum correlation coefficient obtained among the correlation value computed at each reference point between the time-shifted reference impact signals and the test impact signal.

Finally, for each sensor the impact location is determined to be the location of the reference point whose reference impact signal was most similar to the random impact signal, corresponding to the maximum correlation value. The location of the impact is estimated by calculating the mean of the impact locations detected by all of the FBG sensor.

## Composite Wing Impact Localization Experimental Set-Up

Jabiru UL-D's, shown in Fig. 2, (Jabiru Aircraft Pty Ltd, Australia**)** composite wing was used for the impact localization test under simulated noise condition. The experimental set-up of the composite wing's impact localization under external simulated noise is shown in Fig. 3. The strut based wing structure of jabiru UL-D aircraft is categorized into inner and outer wing regions which are separated along the cross-section fixed with the strut. Six multiplexed acrylic coated FBG sensors (Fiberpro Inc., Korea**)**, with center wavelength ranging from 1532 nm ~ 1547 nm, were attached 600 mm apart from each other. All of the FBG sensors were attached on the wing surface with 45º angle orientation. Impact localization tests were performed on a 600 mm by 600 mm test area on the upper surface of the inner wing section.

*Fig. 2: Jabiru UL-D aircraft*

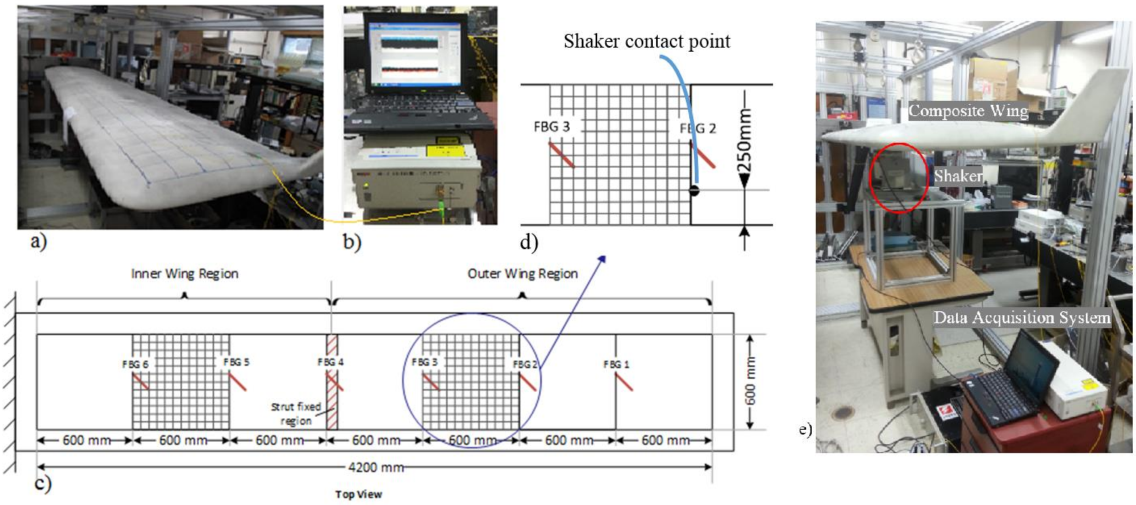


*Fig. 3: a) Composite wing, b) Data acquisition system, c) 1D array FBG configuration on composite wing surface, d) Illustration of shaker contact point and e) test set-up for simulated vibration cases.*

The noise condition was simulated through the composite wing's outer wing section using a shaker, MB Dynamics PM50A. Sinusoidal noise with frequency of 15 Hz, 17 Hz, 20 Hz and 30 Hz were generated using function generator and simulated on the composite wing. The localization tests were performed on the inner wing section of the composite wing. The impact monitoring on the composite wing is done using 6 multiplexed FBG sensors attached on the upper surface of the wing in 1D array FBG sensor configuration. High-speed interrogator, SFI-710, was used to acquire the impact signals given by impact hammer at a frequency of 100 kHz. The test signals acquired from the wing under simulated noise cases were analyzed using the correlation based reference database algorithm, with 169 reference signals, to detect the location of the impact. The reference points on the test section of the inner wing section were 50 mm apart from each other. Impact point coordinates, shown in Table 1, were used for the localization test for results comparison between composite wing without simulated noise and with simulated noise conditions.

*Table 1: Composite wing impact test point coordinates*

| Inner Wing Section Impact Coordinate | | |
|---|---|---|
| Impact Test N. | x-coordinate (mm) | y-coordinate (mm) |
| 1 | 625 | 25 |
| 2 | 625 | 225 |
| 3 | 725 | 425 |
| 4 | 850 | 275 |
| 5 | 875 | 575 |
| 6 | 975 | 175 |
| 7 | 975 | 375 |
| 8 | 1000 | 125 |
| 9 | 1050 | 325 |
| 10 | 1125 | 150 |
| 11 | 1175 | 375 |

## Composite Wing Impact Localization Results

Impact localization on composite wing under simulated noise condition was performed for the simulated noise cases from 15 kHz to 30 kHz and the results are presented in Fig. 4. All of the 11 test impact points were localized with localization error of less than 40 mm using the correlation based impact localization algorithm. The results for the localization under simulated noise conditions were found to be similar to that of the composite wing structure without simulated operating noise condition. Decrease in the localization performance was observed when the wing was excited with noise condition from 15 Hz to 30 Hz. The impact points were estimated with average localization error of 22.6 mm, compared to 14.8 mm when the localization was performed without any simulated noise conditions. However, the results are found to be satisfactory for impact detection and localization application.

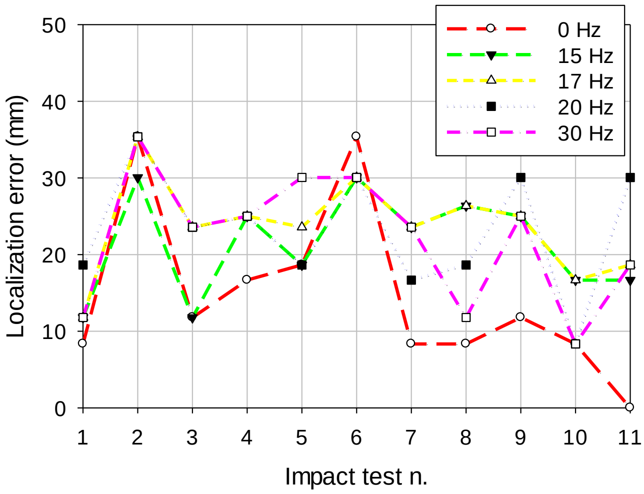


*Fig. 4: Impact localization of composite wing under simulated noise conditions.*

Though the impact localization under simulated noise conditions had average error higher than the 0 Hz case, it can be concluded that overall the impact points on the composite wing were localized effectively with close estimate from the actual impact point. From the present results it is found that correlation based reference database localization algorithm is suitable for determining the impact position on complex composite structure under simulated noise conditions.

## Conclusion

Occurrence of BVID is a major concern for application of composite materials on aircraft structures. Therefore, a SHM system is required to monitor the structure of the aircraft to detect and localize low velocity impacts on the aircraft structure under operating conditions. In this paper, feasibility of localizing impact point on composite wing under simulated noise conditions using correlation based impact localization algorithm was presented.

A shaker was used to simulate the noise on the test structures to generate sinusoidal frequency ranging from 15 Hz ~ 30 Hz. Six multiplexed FBG sensors in 1D array FBG sensor configuration were used to obtain the response signal from the composite wing for impact localization. The results shows that all of the impact points were localized effectively with maximum localization error of less than 40 mm from the actual impact location. The localization results of composite wing with and without simulated noise conditions were found to be similar. Therefore, impact localization on complex composite structures under simulated noise condition using correlation based reference database localization algorithm has been demonstrated.

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