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Impact localization on a composite plate based on error outliers with Pugh's concept selection

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ABSTRACT

Many researchers have performed impact localization using multiplexed fiber Bragg grating (FBG) sensors for a unique estimation of impact position. However, the previous impact localization did not show the methodology to choose the location with the lowest error among candidate impact points, estimated from sensors. We propose an error-outlier-based algorithm with Pugh's concept selection that can choose the impact point with the lowest error among several candidate impact points. The proposed impact localization algorithm was implemented for 30 arbitrary points on a carbon-fiber-reinforced polymer composite plate with two bonded FBG sensors. The results showed that the proposed algorithm could efficiently localize all impact points. Additionally, it could successfully choose the impact point with lower error among two candidate impact points estimated from the two sensors. The accuracy of selection was 93.33% and the totally estimated averaged-error for the selected sensors by Pugh's concept selection for all tests was 6.24 mm. Therefore, we conclude that the proposed impact localization algorithm is effective in localizing the impact points with the lowest errors when multiplexed sensors are used, regardless of the type of sensor. This technique will contribute to reducing measurement errors when localizing impact points on composite structures.

1. Introduction

Composite materials have quickly replaced conventional materials in many fields, including the aerospace, maritime, civil, automobile, and wind industries, because they have outstanding specific stiffness and specific strength, low weight, low density, and corrosion and fatigue resistance [1]. However, composite structures are prone to internal or external damage from unexpected external loads. Among such external loads, low-velocity impacts (e.g., bird strike or drop of tools) are detrimental to the structural safety of composite structures because they can induce barely visible impact damage (BVID) including delamination, matrix cracking, and fiber breakage [2–4]. Generally, BVIDs do not directly result in structural failure; however, they can progress gradually and degrade mechanical properties during operation.

Many researchers have performed impact localization to reduce the risk of BVIDs in composite structures using optical-fiber sensors (OFSs) [5–15], which have several advantages [16,17]: high reliability, small size, multiplexing capability, corrosion resistance, and immunity to electromagnetic interference. Schindler et al. [5] demonstrated impact localization for an anisotropic polymer matrix composite panel with three embedded extrinsic Fabry-Pérot interferometer sensors by using a neural network algorithm. Coelho et al. [6] and Augustin et al. [7] proposed an impact localization algorithm based on the maximum strain amplitude obtained from fiber Bragg grating (FBG) sensors during impact and verified it through application to a graphite/epoxy composite wing and composite laminate structures. Sai et al. [8] developed an impact localization algorithm independent of wave velocity for a composite plate using six FBG sensor arrays. Kim et al. [9] localized the impact points for a stiffened composite panel with four FBG sensors by applying the normalized cross-correlation method. Lee et al. [10] used a root-mean square (RMS) value-based algorithm to detect the impact location for pipe structures with a large curvature by using six FBG sensors. Lu et al. [11] studied least-squares support vector machine (LS-SVM) modeling for impact localization on a carbon-fiber-reinforced polymer (CFRP) composite plate using four FBG sensors. Lamberti et al. [12] implemented the impact localization on the stiffened composite panel using the improved fast phase correlation (FPC) algorithm with a variable selective least squares (VS-LS) inverse solver approach. Of particular interest is that they successfully localized impact points using the embedded FBG sensor network. Rezayat et al. [13] also used FBG sensors and VS-LS algorithm for the impact localization and the reconstruction of impact force. Jang et al. [14] and Park et al.

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Nomenclature

AIN	arbitrary impact point number
AIS	arbitrary impact signal
AIS_N	normalized arbitrary impact signal
CLO	constant level of outlier
DE	newly defined distance error
E	error
ED_x	Euclidean distance for x coordinate
ED_y	Euclidean distance for y coordinate
FN	FBG number
I	importance value
IO	integration of outlier
IP	impact point
NR_S	number of selected reference points
O	outlier
O_{min}	minimum outlier for each reference
O_{whole_min}	minimum value of all O_{min} for each sensor
R	rank value
RN	reference number
RN_S	selected reference number
RS_N	normalized reference signal
RP	reference point
S	step value
t	time
TIS	time increment for shift
VO	variance of outlier

[15] localized the impact points on the composite structures using the multiplexed FBG sensors. They used the arrival time determination algorithm of impact wave and the neural network algorithm for impact identification. Shrestha et al. [18,19] first developed an error-outlier-based impact localization algorithm and demonstrated it for composite structures (e.g., a CFRP composite plate and an aircraft wing) using FBG sensor arrays. All researchers mentioned above successfully demonstrated impact localization for various structures using multiplexed OFSs for a unique estimation of impact position. However, the previously studied impact localization did not show the algorithms to choose the location with the lowest error among candidate impact locations estimated from multiplexed FBG sensors. The capability of selecting the appropriate sensor (or impact location with a lower error) is very important because it directly corresponds to a performance index of the impact localization algorithm.

This study proposes an alternative impact localization algorithm, i.e., an error-outlier-based impact localization algorithm with Pugh's concept selection [20] that can localize the impact point with the lowest error among the several candidate impact points estimated from multiplexed sensors. Pugh's concept selection, a type of prioritization matrix, was first proposed by Pugh in 1981 [20] and is associated with quality function deployment (QFD). Pugh's concept selection can be used to choose a more exact impact point by estimating the ranks of key parameters in the impact localization algorithm. First, we used the error-outlier-based impact localization algorithm to localize arbitrary impact points on a CFRP composite plate with two surface-bonded FBG sensors. Subsequently, we adopted Pugh's concept selection to choose the impact point with the lower error among two candidate impact points determined from two FBG sensors, and we estimated the accuracy of selection.

2. Error-outlier-based impact localization algorithm

Many impact localization methods exist, such as the RMS method [10,21,22], the correlation method [9,21], the error-outlier-based method [18,19], and the others [5–8,11–16]. Among the several different impact localization algorithms, we adopted the error-outlier-based impact localization algorithm for impact localization on a composite plate. Fig. 1 shows a flowchart of the error-outlier-based algorithm [18,19] with Pugh's concept selection [20]. This algorithm requires reference signals ($RS(t_{RN,\ FN})$) and arbitrary impact signals ($AIS(t_{AIN,\ FN})$). The RSs are acquired in advance by striking all reference points with an impact hammer, and the AISs are measured by striking arbitrary impact points. All impact signals are normalized by their maximum absolute values before comparing the RS and AIS. Moreover, the RS is time-shifted by increasing the time step from 1 to 200 (i.e., TIS = 1:200), which can improve time coherence during signal comparisons and results in better results for errors and outliers. Subsequently, the RS and AIS are compared to obtain their differences. The error-outlier-based method is a signal comparison technique that uses the difference between two signals (i.e., RS and AIS). The errors are calculated by subtracting the magnitude of AIS from that of RS as follows:

$$E\,(t_{RN,FN,TIS}) = ||RS_N\,(t_{RN,FN,TIS})|-|AIS_N\,(t_{AIN,FN})||, \tag{1}$$

(see the nomenclature list for symbol and subscript definitions). Errors are the dissimilar parts between the magnitudes of AIS and each RS. Outliers ($O(t_{RN,\ FN,\ TIS})$) are defined as the errors that exceed the limiting value of 0.325 determined by test trails. The limiting value can be altered by the other parameters of experiments and impact localization algorithm, but we experimentally verified that 0.325 it is effective for the given conditions in our study. Using this definition, the minimum outliers (O_{min}(RN,FN)) among the calculated outliers (O(RN,FN,TIS)) are estimated.

The several selected reference points (RN_S(FN)) for each FBG sensor, whose outlier values are under the summation of the smallest outlier (O_{whole_min}(FN)) and the constant level of the outlier (CLO = 115), are estimated to determine the impact location. The determination procedure of the CLO is described in Section 5.1.1. The number of RN_S can be more than one and its optimal number need to be determined. If the maximum number of RNs is four and five RNs are selected, then only four RNs with the smallest outliers are survived. The determination procedure in details of how many RN_S should be selected is described in Section 5.1.2. After calculating RN_S, the Euclidean distance threshold criterion [19] is used to reduce the area of possible locations in the error outlier algorithm. This is performed in two stages. In the first stage, the distance between the averaged coordinates (for x and y) of RN_S and each coordinate of RN_S are estimated. Subsequently, RN_S values with distances greater than a predetermined threshold distance ($ED_x = ED_y$ = 200% of the grid size = 90 mm) are excluded from the next step of the calculation. In the second stage, the Euclidean distances are estimated by calculating the distances between the averaged coordinates of RN_S and each coordinate of RN_S that has survived the first stage. Then, RN_S values with a Euclidean distance greater than 54 mm (i.e., 120% of the grid size) are excluded from the final procedure of impact localization. Finally, the locations of the impact points are determined by averaging the x and y coordinates of the surviving RN_S values.

3. Pugh's concept selection

Pugh's concept selection, a type of prioritization matrix, is associated with QFD. The procedure followed in Pugh's concept selection for impact localization in the proposed algorithm is Fig. 1. In Pugh's concept selection algorithm, the evaluation items must be determined and their importance value (I-value) and step value (S-value) must be constructed in advance. The number of the selected reference points (NR_S) is determined as a first evaluation item because impact localization is