A High-Sensitivity Fusion Index for Delamination Identification of Composite Laminate Structures

Xin LIU¹, Xiao-jun WANG²*, Qing-he SHI², Zheng LV² and Yu-jia MA²

¹National Laboratory for Aeronautics and Astronautics Large Aircraft, Beihang University, Beijing, China
²School of Aeronautics and Astronautics, Beihang University, Beijing, China

*Corresponding author

Keywords: High-sensitivity fusion index, Information fusion, Delamination, Damage identification, Structural health monitoring.

Abstract. A significant obstacle that hinders the extensive application of large composite structures in the aerospace industry is the lack of valid identification methods for composite damage, where the delamination damage is the most common one. In this paper, a high-sensitivity fusion index (HSFI) is proposed for detecting, locating, and quantifying damages in aerospace polymer composite structures. The proposed fusion index is developed based on modern information fusion of three vibration-based indexes: modal strain, modal flexibility and static strain indexes. And its advantage is high sensitivity and strong noise immunity. By detecting the delamination damage in a composite laminate plate, it is verified that this fusion index is highly sensitive for delamination position and size in both cases of little and large damage in the presence of 2% level noise.

Introduction

Because of their high specific strength and stiffness, corrosion resistance, and ability to be molded into complex shapes, laminated composite structures are being increasingly used in aerospace industry in these years. Especially, both of Boeing and Airbus use more than fifty percent composite structures for their latest commercial aircrafts B787 and A350XWB respectively. However, during service of aircrafts, it is inevitable to meet a considerable amount of sever loads such as long-time fatigue loads and accidental impact loads which must contribute to a host of composites failure modes (delamination, disbanding, fiber breakage, matrix cracking, etc.), thereby challenging performance benefits from these composite structures. Among these failure modes, delamination is the most common and severe one.

A wide range of technologies are currently employed to detect composite structures damage. In the works [1-4], modified structural dynamic models are used to predict the dynamic response of structures accurately and the structural damage detection and residual life evaluation are carried out by combining the measured results. In 2006, Zhuang [5] located the damage of self-reinforced polyethylene composites accurately by means of acoustic emission technology. In 2012, Azmi [6] proposed that the acoustic emission method can effectively detect the initial firing crack of three dimensional braided composites. But his method has difficulty to distinguish between damage signals and noise signals, which means that the result of this method can be easily disturbed. All of these methods above can recognize the damage of composite structures, but they are unable to monitor structure health condition on line and real time. Besides, they are too expensive and time-consuming to be developed to detect damage of full-size engineering structures.

In this case, research and development of on line and real time structural health monitoring (SHM) systems are pressingly needed for operation optimization, maintenance planning and overall life cycle cost reduction. These years, vibration-based damage detection method has been widely applied to detect damage in composite structures. Where damage occurs in the structure, the modal parameters such as eigenfrequencies, mode shapes, and damping ratios are affected. Thus, damage can be detected by comparing the modal parameters of the original undamaged structure to those of
the damaged structure. In 1992, Grady [7] used composite modal shape curvature as a damage identification index to detect delamination damage in composites and found that localized delamination could hardly affect structure modal shape which indicate that modal shape curvature could not be used to detect damage. Ratcliffe [8] studies the damage of structure under the condition of small damage by using the curvature of modal shape directly. In his method, the two-order difference of vibration mode of adjacent points of discriminant points was interpolated three times. Then the difference between the interpolation function and the two-order difference at the discriminant point was calculated. This value can reflect the approximate location of the damage in the beam structure. In 2007, Sohn [9] studied the change of specific damping capacity when there existed a matrix transverse cracking in orthogonal ply composite then he found that damages from different locations could contribute to corresponding damping changes of composite structures. However, there are few methods to develop a damage index highly sensitive to delamination of composite laminate structures.

This paper focuses on delamination damage identification in composite structures. In order to detect the location and size of delamination damage in the composite structures, a high-sensitivity fusion index (HSFI) is proposed based on modal strain, modal flexibility and static strain indexes. The results of numerical examples show that HSFI is reliable to be used for delamination damage identification and has higher sensitivity and stronger noise immunity than single vibration-based indexes.

**Strain-Based Index**

Delamination damage can change inherent properties of structure. Thus, by comparing change of intrinsic property parameters, damage can be detected. Strain mode is calculated by finite element method in this paper.

Many researchers have proposed coordinate strain modal identification criterion for damage detection seen as Eq.(1).

\[
I_{COSMAC} = \frac{\sum_{r=1}^{n} [\psi^e_{u_r}(k) \cdot \psi^e_{d_r}(k)]}{\sqrt{\sum_{r=1}^{n} (\psi^e_{u_r}(k))^2 \sum_{r=1}^{n} (\psi^e_{d_r}(k))^2}}
\]  

(1)

in which, \(\psi^e_{u_r}(k)\) and \(\psi^e_{d_r}(k)\) are components of undamaged strain mode \(\psi^e_{u_r}\) and damaged strain mode \(\psi^e_{d_r}\) at the \(k\) point. In fact, the effects of damage on each order strain modes are different. But \(I_{COSMAC}\) consider them equally. So, in fact, it is not a reasonable method for damage locating. Because strain mode has high sensitivity for local damage, we can locate damage by change of local feature, which can be displayed as:

\[
I_{COSMAC_r}(k) = \frac{\sum_{i=1}^{\delta(k)} [\psi^e_{u_r}(i) \cdot \psi^e_{d_r}(i)]}{\sqrt{\sum_{i=1}^{\delta(k)} (\psi^e_{u_r}(i))^2 \sum_{i=1}^{\delta(k)} (\psi^e_{d_r}(i))^2}}
\]  

(2)

where, \(I_{COSMAC_r}(k)\) is the \(r\) th order strain mode index at \(k\) point, \(\delta(k)\) is a local value that reflect local feature variations and \(\sum_{i=1}^{\delta(k)}\) means to sum coordinate \(k\) and other coordinates from its neighborhood \(\delta(k)\).

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Based on same method, static strain-based index can also be derived:

\[ J_{COSMAC}(k) = \frac{\sum_{i=1}^{n} \left| e_{u_i}(i) \cdot e_{d_j}(i) \right|}{\sqrt{\sum_{i=1}^{n} \left( e_{u_i}(i) \right)^2 \cdot \sum_{j=1}^{n} \left( e_{d_j}(i) \right)^2}} \]  \hspace{1cm} (3)

where, \( J_{COSMAC}(k) \) is the static strain-based index at \( k \) point, \( \delta(k) \) is local value that reflect change of local feature and \( \sum_{i=1}^{n} \delta(k_i) \) is the sum of coordinate at \( k \) point and its neighborhood \( \delta(k) \).

**Modal Flexibility-Based Index**

Flexibility matrix is the reciprocal of the stiffness matrix and can be obtained by vibration theory. For multi-degree of freedom systems, flexibility matrix can be built by parameters such as natural frequencies, damping ration and modal shapes etc. that can be obtained by vibration theory.

Modular flexibility can be expressed as:

\[ F = \sum_{i=1}^{n} \frac{1}{w_i} \phi_i \phi_i' = \begin{bmatrix} \sum_{i=1}^{n} \phi_{1i} \phi_{1i} & \sum_{i=1}^{n} \phi_{1i} \phi_{2i} & \cdots & \sum_{i=1}^{n} \phi_{1i} \phi_{mi} \\ \sum_{i=1}^{n} \phi_{2i} \phi_{1i} & \sum_{i=1}^{n} \phi_{2i} \phi_{2i} & \cdots & \sum_{i=1}^{n} \phi_{2i} \phi_{mi} \\ \vdots & \vdots & \ddots & \vdots \\ \sum_{i=1}^{n} \phi_{mi} \phi_{1i} & \sum_{i=1}^{n} \phi_{mi} \phi_{2i} & \cdots & \sum_{i=1}^{n} \phi_{mi} \phi_{mi} \end{bmatrix} \]  \hspace{1cm} (4)

where modal matrix \( \Phi = [\phi_1, \phi_2, \ldots, \phi_n] \), and \( \phi \) is the characteristic vector and each \( w_i \) vector corresponds to one \( \phi_i \).

Generally, with the increase of the modal order, the contribution of the mode to the modal flexibility matrix becomes smaller, which means that the flexibility matrix converges quickly with the increase of modal order.

In Eq.(4), high frequency term can be neglected and only the first three orders modal parameters need to be measured. So the difference of flexibility matrix of the undamaged and the damaged structure is widely used for damage detection:

\[ \Delta F = F_d - F_u \]  \hspace{1cm} (5)

where, \( F_d \) is the flexibility matrix of the damaged structure and \( F_u \) is the flexibility matrix of the undamaged structure.

**High Sensitivity Fusion Index**

The data fusion of information is multi-level processing of multi-source data, and each level of processing represents a different degree of abstraction of the raw data. It involves the detection, association, estimation, and combination of data. So information fusion can be divided into three levels according to their degree of abstraction in the level of sensor information processing: data-level fusion, feature-level fusion and decision-level fusion. Data-level fusion (low-level or pixel-level),
first of all, fuse all sensor data. Then, the feature vectors are extracted from the fused data, and then
the recognition or detection is performed. This requires that the sensors should be homogeneous
(observed information from these sensors belong to the same physical phenomena). Feature-level
fusion (intermediate-level or feature-level) belongs to the middle level. It firstly extracts the feature
from sensor original information. The feature may be the edge, direction, speed, etc. of the target.
Then, the feature information is synthetically analyzed and processed. Decision-level fusion
(advanced-level or decision-level) observe the same target through different types of sensors, and
each sensor completes the basic processing locally which includes preprocessing, feature extraction,
identification, or judgment to establish a preliminary conclusion of the observed object. Then the
decision-level fusion is carried out by association processing. Finally, joint inference results can be
obtained. Here, HSFI is carried out by feature-level fusion technology showed in Fig.1.

![Feature-level Fusion Diagram](image)

In this work, all data are obtained by the damaged and undamaged three-layer composite plates
FEM. Firstly, related features such as strain mode, static strain and modal flexibility are calculated
and strain mode-based index, modal flexibility-based index and static strain-based index are built.
Then, HSFI is built based on these three indexes.

As shown in the following numerical example ‘Sensitivity Analysis of Single Indexes’, it is not
difficult to find that these three indexes have different features when applied to delamination damage
detection. Strain mode-based index and static strain-based index have high accuracy when they are
applied to damage location detection but low accuracy for damage area detection of delamination.
However, by a considerable amount of numerical simulation, it is proposed that the first derivative of
modal flexibility-based index is an ideal candidate for damage area detection.

According to what is illustrated above, now, we may safely propose a HSFI for identification of
delamination in composite structure as following form:

\[ HSFI = \frac{I_{\text{COSMAC}}(k) \cdot J_{\text{COSMAC}}(k)}{\partial(F_a - F_s)} / \partial x \]

where, \( x \) is the coordinate of monitoring point.

**Numerical Examples**

**Sensitivity Analysis of Single Indexes**

In this section, we test three single indexes’ sensitivity for delamination in a 400mm×16mm
composite plate which contains three 0.3mm thick layers.
Fig. 2 is the diagrammatic sketch of this composite plate, in which DCB_Y represents the width of the plate, DCB_L represents the length of the plate, and h represents the thickness of the plate. And the location and length of delamination region are represented as x_l and d_l respectively. Because all damage region widths equal to DCB_Y, we set d_l as the area of damage.

Figure 2. Composite plate delamination FEM.

Sensitivities of location and area identifications are tested with each single index. Clamped supported region is always fixed. But another end is free when modal calculations are performed, and a displacement load is applied to it when static calculations are carried out. When sensitivity for location is tested, the location is increased by variation values from initial location and the area is a fixed value which equals to initial area. Similarly, when sensitivity for area is tested, the area is increased by variation values from initial area and the location is a fixed value which equals to initial location. All initial values and variation values are showed in Table 2.

Table 1. Initial Values of Location And Area.

<table>
<thead>
<tr>
<th>Single Index</th>
<th>Change of Damage Location(mm)</th>
<th>Change of Damage Area(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial Location</td>
<td>Initial Area</td>
</tr>
<tr>
<td>Strain mode-based index</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>Modal Flexibility-Based Index</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>Static strain-based Index</td>
<td>80</td>
<td>20</td>
</tr>
</tbody>
</table>

As showed in Fig. 3 and Fig. 5, two peaks of every curve indicate two ends of delamination region. As for the modal flexibility-based index, here, first order derivation of Eq.(5) is used for delamination damage detection. So, in Fig. 4 maximal slope change points of every curve indicate two ends of delamination region. And all data were normalized.

When they are used to detect the damage locations of delamination in different positions, strain mode-based index and static strain-based index have relatively better performance than modal flexibility-based index. But it is also obvious that, when used to detect the damage area of delamination in different areas, these two strain-based indexes perform really badly. Especially when damage area is larger than 100mm, they can hardly identify the area as showed in Fig. 3(b) and Fig. 5(b).
Sensitivity Analysis of HSFI

In this section, the initial location of all damages is 80mm, only the area of damages is changed by different cases. We firstly test the performance of the HSFI for both of little and large size delamination damages in the composite structure. As showed in Fig.6, two peaks of every curve
indicate the two ends of delamination region, so both of little and large size delamination damages can be successfully identified with proposed HSFI.

Furthermore, in order to test the robustness of the proposed HSFI, white Gaussian noises with a level of 2% are added to all simulated responses and then performance of HSFI and three single indexes are compared. The results (shown in Fig.7(a) and Fig.8(a)) indicate that the accuracy and the resistance to noise of delamination identification via HSFI are pretty satisfactory.

It can be easily found that responses with noise influence the validity of three single indexes significantly. As illustrated above, two highest peaks of the curve are needed to indicate two ends of the delamination region. However, these peaks are submerged easily by other peaks caused by noise. Fig.7(b) and Fig.8(b) indicate that modal-flexibility based index is not valid whatever it is used for declaration of little or large damage. Fig.7(c) and Fig.8(c) indicate that strain mode-based index is valid in the case of identification of little damage but invalid when it comes to identification of large damage. On the contrary, Fig.7(d) and Fig.8(d) indicate that static-strain based index is invalid in the case of identification of little damage but valid when it comes to identification of large damage.

So it is not reliable to detect delamination damage by one of these three single indexes in case of this level of noise. But the HSFI proposed in this paper shows its superiority: two peaks at two ends of delamination region are still clear and the result is highly convincing no matter the damage is of little or large size.
Summary

This study presents a high-sensitivity fusion index (HSFI) for delamination damage in composite laminate structures in a strategy of combing several different vibration-based indexes with different strengths and weaknesses. Analysis reveals that strain mode-based index, modal flexibility-based index and static strain-based index are needed and suitable for building fusion index whose procedure
and validity is demonstrated by numerical examples. Also, numerical results show that the proposed HSFI has remarkable superiority: direct utilization of the single index in a case of 2%-level noise cannot identify the damage, while the HSFI can identify the location and size of the delamination region, whatever the size of the damage is little or large, which reveals that the HSFI is valid and sensitive for both of little and large size delamination damages in presence of noise in raw data.

Acknowledgement

This work is supported by the National Nature Science Foundation of the P.R. China (No.11372025, No.11432002, No.11602012), the China Postdoctoral Science Foundation (No. 2016M591038), ‘111’ Project (No. B07009), the Major Research Project (No. MJ-F-2012-04) and Defense Industrial Technology Development Program (No. JCKY2013601B001, No. JCKY201 6601B001) for the financial supports. Besides, the authors also would like to thank the editor and reviewers for their valuable suggestions.

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