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Impact localization on composite laminates using fiber Bragg grating sensors and a novel technique based on strain amplitude

Gang Zhao[a,b], Shuxin Li[a,c,*], Haixiao Hu[c,*], Yucheng Zhong[c], Kun Li[a,b]

[a] School of Science, Wuhan University of Technology, Wuhan 430070, China
[b] School of Mathematics and Information Sciences, Nanchang Hangkong University, Nanchang 330063, China
[c] State Key Laboratory of Advanced Technology for Materials Synthesis and Processing, Wuhan University of Technology, Wuhan 430070, China

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ABSTRACT

Carbon fiber reinforced composite materials have been widely used in aerospace and other high-tech fields because of their excellent performance. However barely visible impact damage can be introduced by low velocity impact, which might bring out tremendous risk. In this paper, a new method is proposed to predict the position of low velocity impact. The dynamic strain signal that is caused by low velocity impact is obtained by the fiber Bragg grating (FBG) sensor. The amplitude of the first K order natural frequency is extracted by Fast Fourier Transform (FFT). The amplitude data is normalized, and then establish k order vector matrix model is established. It is proposed that K order sum of squares of deviations can be used as the basis to predict positioning. Two different validation tests were performed. The experimental model was made of different layers. FBG were used to embed and paste type method, experiments were conducted with impact of different energy levels. The results show that proposed method is feasible.

1. Introduction

Composite materials occupy an important position in the automotive, shipbuilding, aviation, aerospace and other engineering fields. Especially they have been widely used in military and civil aircraft as the properties of the materials can be designed and they have good fatigue resistance, high specific stiffness, high specific strength and a series of other advantages. However, the brittleness of composite resin matrix and reinforcing fiber is very sensitive to impact load. Fiber reinforced composite materials in its life cycle, that is, manufacturing, applying and maintaining process will inevitably be affected by the impact of external objects manufacturing which can bring about a decline in bearing capacity and structural damage [1,2]. The effects of low velocity impact on composite structures have attracted more and more attention.

A slight impact to composite structures and a falling object impact belong to low velocity impact, which are often encountered during the applying and maintaining process. The strain rate of low velocity impact is pretty low. Low velocity impact to a composite structure can introduce the occurrence of barely visible impact damage (BVID) [3]. This damage will bring unimaginable consequences. The failure form that makes up of partial failure and total failure is more complex. Therefore, the study on the structural health of composite materials is quite significant. At present, there are many traditional nondestructive testing techniques, such as ultrasonic, X-ray, thermal stress field and potential measurement. However, traditional detection methods have the disadvantages such as complex equipment, inconvenient and time-consuming. Moreover, the initial damage location needs to be known in advance.

During the past three decades, some scholars have done a lot of research work on the damage location of composite materials induced by low velocity impact, and put forward some meaningful positioning methods. In those paper, a variety of sensors, signal processing methods and impact location methods are proposed. In order to obtain the acoustic signal, piezoelectric sensors (PZT), Polyvinylidene Fluoride (PVDF) piezoelectric sensor, accelerometer, acoustic emission, magnetic sensor and laser interferometer, and doppler laser velocimetry were applied in their experiment. At present, because of the excellent performance of FBG sensors, many scholars choose FBG sensors to obtain the impact signal [4]. Optical fiber sensor is proposed at the end of the twentieth century. FBG technology can be considered one of the fastest growing technology. Now it has become a very good application prospect of Structural Health Monitoring (SHM) technology. Fiber optic technology was originally used for static measurement. Dynamic sensor using FBG sensor was a new technology, related research has developed rapidly. Since one decade ago, FBG dynamic sensing system has been

* Corresponding authors at: School of Science, Wuhan University of Technology, Wuhan 430070, China (S. Li).
E-mail address: shuxinli_01@163.com (S. Li).

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used in many fields, such as the health monitoring of composite materials [5], mechanical testing and nondestructive evaluation [6–8]. The FBG sensor can be embedded in the composite laminate without significantly affecting its mechanical properties, because of its smaller size [9]. Furthermore, it also has the advantage that it can be reused which other sensors do not have, and can detect defects between the composite layers [10]. In addition, another advantage of using the FBG sensor in the composite structure is that it can integrate advanced optical transmission system technology in nondestructive testing. It is an undeniable fact that light wave communication systems are very successful in telecommunication applications. In addition to its low transmission loss, the system has advantages of small volume and light weight.

Lamb wave [11–15], frequency response function [16,17], triangulation technique [18] and artificial intelligence algorithm [19] are used to detect the damage location of composite materials. In general, the current method of impact monitoring technology mainly includes the following three categories. The first class of algorithms based on time-of-arrival location technology was widely used, which realize the positioning of impact via the proper distance and angle of arrival time. A better approach is the use of more advanced signal processing methods to transform the acoustic emission signal, such as wavelet transform [20], time domain filtering a signal of a certain frequency, extracted from more accurate information on the time of arrival. For the wave velocity, many measuring methods are introduced in the literature, such as measuring the different direction of speed, and then using the average value instead; or using the Lamb dispersion equation to calculate group velocity [3], or analysing of velocity profile [1] to determine the speed and using the Mindlin plate theory [20] to calculate the speed [18]. However, it is difficult to accurately determine the time of arrival and velocity in the composites, due to the influence of reflection and propagation of stress wave in the process of refraction, scattering and noise. The second category is the method of system modeling based on the model. The method of the model is usually based on the comparison between the measured and simulated signal features. The final damage location is based on the minimization of the difference between the measured and simulated structural characteristics. Different distance can be used to measure the difference, and different techniques can be used to update the model as close as possible to measure the response parameters. Damage characteristics can be found, such as location, range or more precise size or coordinates [21]. Structures made of composite materials and composite laminates exhibit nonlinear dynamic behavior on different parameter and time series. In general, it is hard to mode of structural vibration response is difficult, especially if accurate prediction is required because the traditional modeling techniques cannot be used. There are a number of research models of the Structural Health Monitoring (SHM) method applied to composite structures. And it should be emphasized that these are based on materials and structures that are not applicable to other structures. The dynamic response of the structure is compared with the response obtained by the model. The optimization model is established. However, due to the influence of random noise and the ill conditioned characteristics of the coefficient matrix of the equation, it will lead to a large computational errors if not handled properly. The third approach is based on a variety of machine learning and fitting methods, through the establishment of complex structure of data input and output relations between impact localization, Examples of this approach include the establishment of a reference database [3], neural networks [22], particle swarm optimization algorithm [23], genetic algorithm [24], and inverse algorithm reconstruction [16]. Those methods need more data in the inversion process, and the structure of the training were workload. After the training, the structure was still unstable when the actual load was identified, and it needed to be constantly iterated during the calculation. So, it is a tough computational tasks. Therefore it still has certain degree of difficulty to apply to the actual impact monitoring.

In addition, in order to solve the problem of damage detection of composite laminates, some scholars put forward the methods of pure data-driven that use statistics and data analysis to extract the damage information from the strain signal. For the sake of detecting the delamination damage and its position, the statistical analyze method of cross-correlation is used in literature [25]. Data driven methods can be used to analysis different characteristics of the signal recorded, which are data analysis method. They can be applied to any signal analysis, including deterministic and random data. There are several papers, using multivariate data analysis methods, such as principal component analysis (PCA). PCA has been applied to delamination detection and classification, and the results prove its potential for damage detection [26]. PCA is used as a linear tool to detect structural damage associated with vibration characteristics and environmental conditions. Subsequently, they propose an extension of the nonlinear detecting method [27]. These methods are applicable to certain values of PCA or structural vibration response characteristics, such as amplitude, frequency, and impedance. Singular Spectrum Analysis (SSA) suggested [28,29] is a kind of data analysis method. It is a kind of PCA analysis, which can be used to detect the delamination of composite structure.

Based on the previous research, this paper proposes a new localization method. The dynamic strain signal which is caused by low velocity impact is obtained by the FBG sensor. The vector matrix model of the amplitude data is established. The K-order sum of squares of deviations can be used as the basis to predict positioning. Two different carbon fiber-reinforced plastics (CFRP) laminates are used to verify the model. The FBG sensors were embedded and pasted respectively. The robustness of the method is verified by using different energy impact. This paper is composed of the following parts. The second section introduces the working principle of the FBG grating sensor. The location method proposed in this paper is stated. The third section describes the composition of the experimental equipment and sample making. The fourth section includes the experimental results and discussions, the feasibility of the algorithm is verified by the impact of two different layers of the model, and the robustness of the algorithm is verified by different energy impact. The fifth section is the conclusion.

2. Theoretical principle

In this section, the principle of acquiring dynamic strain signals for FBG sensors is introduced. The localization algorithm proposed in this paper is described.

2.1. FBG sensor principle

Fiber Bragg grating sensor is a kind of single mode fiber with periodic change of refractive index along a certain length, and it can reflect the incident light which can be represented by the spectral wavelength, as shown in Fig. 1 [10]. Optical fiber sensor has the advantages of small size, light weight, corrosion resistance, good durability, resistance to

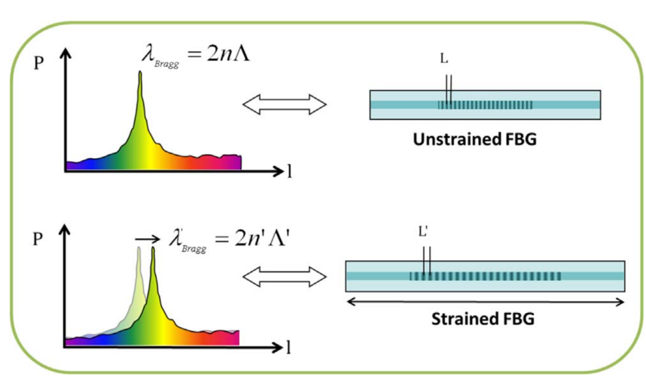

Fig. 1. FBG sensor schematic diagram.