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Strain sensing characteristic of ultrasonic excitation-fiber Bragg gratings damage detection technique

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ABSTRACT

There are good prospects for development of ultrasonic excitation-fiber Bragg gratings (UE-FBGs) damage detection techniques in the field of Nondestructive Testing (NDT). However, corresponding strain sensing theories are few and only applicable to the embedded fiber Bragg gratings (FBGs) sensors in composite structures. First, a four-cylinder sensing model for both the embedded and glued FBG sensors is established by introducing a surface-bonded effect coefficient obtained from simulation analysis in this paper. According to the shear-lag theory, an improved strain sensing function is derived from this model by considering the contribution made by the elastic modulus of host material. Then, based on above function, the strain sensing characteristics are analyzed. Finally, the system with an ultrasonic transducer to excite FBG and a demodulation device employing a tunable laser to detect FBG wavelength shifts was established to validate the theoretical analysis. The experiment results showed that the ultrasonic strain sensing ability of the FBG sensor decreased with the increase of ultrasonic frequency and glued thickness.

1. Introduction

FBG sensors are one of the most potential optical passive components which have been widely used in many engineering fields [1]. The UE-FBG damage detection is a new technique being developed in recent years. Its basic idea is to use FBG sensors as ultrasonic detectors instead of piezoelectric ceramics and analyze the injury condition of the mechanical construction by carrier ultrasonic waves with damage information achieved by FBG sensors. It has great development potential in the field of damage detection by combining the unique advantages of FBG such as distributed sensing, electromagnetic interference immunity, high axial sensibility and multiplexing capability with the ultrasonic features of good directivity and high penetrating power. Some of the researchers such as Daniel C Betz, Hiroshi Tsuda, Nobuo Takeda and Pou-Man Lam have applied this technique to the damage detection of smart composite structures and metal plates [2–6].

With main components of silicon dioxide, the shear resistance of the single-mode fiber is weak. In practice, a bare optical fiber is usually surrounded by a protective coating of high toughness and low elastic modulus. On the other hand, the FBG is often bonded on the surface or embedded in the interior of the test material to detect the ultrasonic wave of the corresponding location sensitively during UE-FBG damage detection. Therefore a fraction of the ultrasonic energy is absorbed by intermediate layers during its propagation from the test material to the fiber core, resulting in the differences between the strains of the test material and the fiber core. However, few researches on related FBG sensing theories under ultrasonic excitation are carried out so far. Duck and LeBlanc only put forth the strain sensing mechanism from the host material to the fiber core directly [7]. Ling et al. developed a four-cylinder model which was only suitable for the FBG sensor embedded in composite and plastic

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structures owing to its neglecting of the host material's elastic modulus [8].

Yet the FBG is usually pasted onto the surface rather than embedded in the test material during damage detection. In addition, the most common test materials are aluminum, steel and copper etc. with a higher elastic modulus than the fiber core, so the effect of the host material's elastic modulus on strain transfer process cannot be ignored. Therefore, in most instances the strain sensing ability and measurement sensitivity of the FBG under ultrasonic excitation are often different from that of the Ling's model [8]. Ultrasonic waves used in structural damage detection often have a high frequency but a relatively low energy and they will bright low strain amplitude in the test material. Considering the character of UE-FBG damage detection, a new strain sensing model of FBG suitable for all circumstances needs to be developed to better reflect the ultrasonic energy distribution in the FBG and provide a theoretical basis for the selections and locations of the ultrasonic source and FBGs.

Therefore, the strain distributions of the embedded FBG sensor and the pasted one under constant stress are analyzed though simulation in this paper. On these bases, the four-cylinder model is employed to study the strain sensing mechanism of the two above mentioned FBG sensors under ultrasonic excitation in UE-FBG damage detection by introducing a surface-bounded effect coefficient. By considering the host material influence, the strain sensing function is derived and the effects of ultrasonic frequency, adhesive layer thickness on strain sensing characteristic are studied systematically. Finally, the above theoretical analyses are verified by experiments.

2. FBG sensor structure in UE-FBG

The FBG is usually glued on the surface or embedded in the test material and used as an ultrasonic sensor in UE-FBG damage detection. According to Ling's theory [8], the embedded FBG sensor is modeled as a four-cylinder structure. As shown in Fig. 1a, it is considered to be composed of four parts: fiber core, protective coating, adhesive layer and host material, representing bare optical fiber, coating material, bonding adhesive and the test structure, respectively. While, the cross section of the glued FBG sensor is simplified to the structure shown in Fig. 1b of this paper. From Fig. 1b, the glued FBG sensor is also made up of the same four parts as the embedded one, however, the adhesive and host material layers are considered as a rectangle with round corners and a rectangle separately. r_m, r_a, r_c, r_f are radii from the center of the fiber to the outer faces of host material, adhesive layer, protective coating and fiber core, respectively. h is the thickness of the host material and d is the adhesive layer width of the glued FBG. Both the host materials in above mentioned models bear only axial ultrasonic strain within a certain thickness.

The software COMSOL is used to create parametric models shown in Fig. 1 and calculate the axial strain distributions of all layers under static stress. An axial stress of 5 MPa is applied to the two ends of the host material. Parameters for the basic model of FBG sensors are listed in Table 1. Suppose that the host material is made of aluminum (parameters are shown in Table 2), the width d of the adhesive layer is 20 mm, and the adhesive bond length of the FBG is 20 mm, then the simulation results are presented in Fig. 2.

Clearly, from Fig. 2a, the strain distributions of four different layers in the embedded model are non-uniform along the axis, especially at the two ends of the adhesive bond length; however, the strain of each layer within the mid-beam region (about 14.5 mm in length) is approximately uniform. As for the glued FBG model in Fig. 2b, the axial strains of the four layers decrease from the host

Table 2
Physical parameters of aluminum material.

Material	Density, ρ(g/cm^3)	Elasticity modulus, E (GPa)	Shear modulus, G (GPa)
Aluminum	2.7	71.7	27

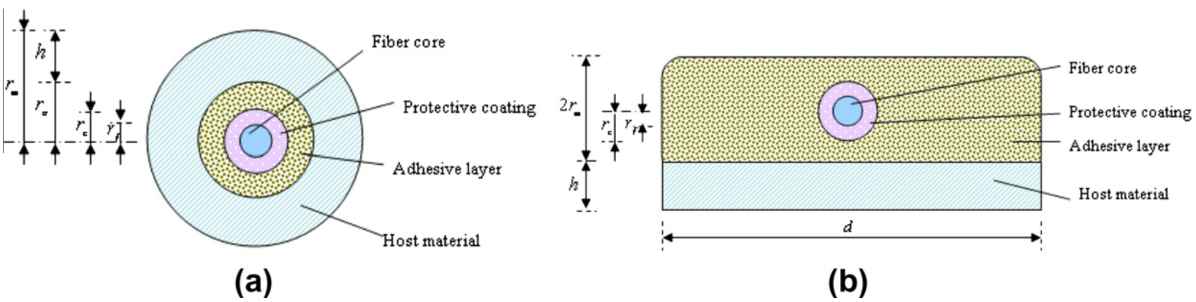

Fig. 1. (a) Cross section of embedded FBG sensor. (b) Cross section of glued FBG sensor.

Table 1
FBG sensor main parameters.

r_f (μm)	r_c (μm)	r_a (μm)	r_m (μm)	h (μm)	E_f (GPa)	E_c (GPa)	E_a (GPa)	G_f (GPa)	G_c (GPa)	G_a (GPa)
62.5	125	225	1225	1000	72	0.1	3.3	30.77	0.037	1.2