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# Theoretical and Experimental Investigation of Fiber Bragg Gratings With Different Lengths for Ultrasonic Detection

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**Abstract:** In this paper, the response of fiber Bragg gratings (FBGs) subjected to the ultrasonic wave has been theoretically and experimentally investigated. Although FBG sensors have been widely used in the ultrasonic detection for practical structural health monitoring, the relationship between the grating length and ultrasonic frequency is not yet to be obtained. To address this problem, an ultrasound detection system based on FBGs is designed and the response sensitivity of different lengths gratings are detected. Experimental results indicate that the grating with 3 mm length has a higher sensitivity when detecting high frequency ultrasonic wave, and the amplitude can be up to 0.6 mV. The 10 mm length grating has better detection sensitivity for low frequency ultrasonic wave and the amplitude is 0.8 mV. The results of this analysis provide useful tools for high sensitivity ultrasound detection in damage detection systems.

**Keywords:** FBG; nondestructive testing; ultrasonic detection

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## 1. Introduction

The ultrasonic detection based on fiber Bragg gratings (FBGs) is a new nondestructive testing technology being developed in recent years [1]. The basic idea is to use FBG sensors as ultrasonic detectors to analyze the injury condition of the construction. Compared with classical electronic detection sensors, FBGs have unique advantages such as immunity to electromagnetic interference, lightweight, high temperature corrosion resistance, stability, and durability in harsh environment. FBGs-based ultrasonic sensors have been indicated as the ideal candidate for practical structural health monitoring in light of their unique advantages over conventional sensing devices [2, 3].

At present, the use of FBG sensors for the detection of ultrasound has been widely reported in literature. Sorazu presented the results of theoretical and experimental investigations into the interaction between ultrasonic waves and fiber optic sensors, focusing on the birefringence introduced within an optical fiber placed with its axis parallel to the ultrasonic wave front [4]. Lam proposed that fiber Bragg grating sensors could be embedded in the laminate material to detect the signal of ultrasonic Lamb wave, and the damage assessment of the composite material could be found out [5]. Lee designed a new type of FBG ultrasonic receiver based on the embedded system, which detected the impact damage of carbon fiber reinforced plastic laminates by shockwave. They described the design

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of the structure of the FBG sensors and analyzed characteristics of the ultrasonic [6]. The FBG performance has a great influence on the test results, Liu and Han investigated the affection of the FBG sensors directivity, and their analysis revealed several unique FBG response characteristics [7]. Wild presented results for the spatial performance of fiber Bragg grating sensors to continuous-wave acousto-ultrasonic (AU) signals [8]. However, these researches mainly focused on health monitoring, location defection, and damage degree evaluation of the material structure [9]. There were only a few studies concerning the effect of different grating lengths on the sensitivity. The relationship between the grating length and ultrasonic frequency has not a clear conclusion.

Based on this argument, an ultrasound detection system based on FBGs is designed in this paper, and the response of FBGs to the ultrasonic wave is investigated in terms of gratings length changes. The results of the experiment have a good effect, meanwhile the qualitative relationship between the grating length and ultrasonic frequency is obtained.

## 2. Theoretical analysis

In this section, the interaction between the Bragg grating length and ultrasonic wave frequency is theoretically analyzed. FBGs consist of a periodic modulation of the refractive index in the core of a single mode fiber. According to the mode coupling theory, the central wavelength of the reflected narrowband light namely $\lambda_B$ can be described by the Bragg condition [8]:

$$\lambda_B = 2n_{\text{eff}}\Lambda \tag{1}$$

where $n_{\text{eff}}$ is the effective refractive index of the optical mode propagating along the fiber, and $\Lambda$ is the periodicity of the grating. When the Bragg condition is satisfied, the FBG reflects a narrow band of wavelengths, creating a stop band in the transmission spectrum and all of the other wavelengths not meeting the resonant condition are transmitted. The resonance depends on the periodicity of the grating and the effective refractive index of the fiber. In all of the external factors, the strain, temperature, and ultrasonic field are the most common factors that cause the Bragg wavelength shift [10, 11].

In our hypothesis, the ultrasonic wave can be modeled by a longitudinal strain wave, propagating along the axis of the optical fiber. Moreover, the time dependence is assumed to be sinusoidal. Hence, it can be expressed as an equation:

$$\varepsilon(t) = \varepsilon_m \cos(kz - w_s t) \tag{2}$$

where $w_s$ is the ultrasonic wave frequency, $\varepsilon_m$ is the amplitude of sound wave, $z$ is the sound path, and $k=2\pi/\lambda$s is the ultrasonic wave number [12]. The transfer matrix method is utilized to analyze the FBG multilayered structure. When the length of FBG is much smaller than the ultrasonic wavelength, the whole length of the gratings and the refractive index changes caused by the photo elastic effect are uniform [13, 14], and the wavelength shift of the FBG can be given by

$$\Delta\lambda(t) = \lambda_B \varepsilon_m \left[1 - \left(\frac{n_{\text{eff}}^2}{2}\right)[p_{12} - \nu(p_{11} + p_{12})]\right]\cos(w_s t) \tag{3}$$

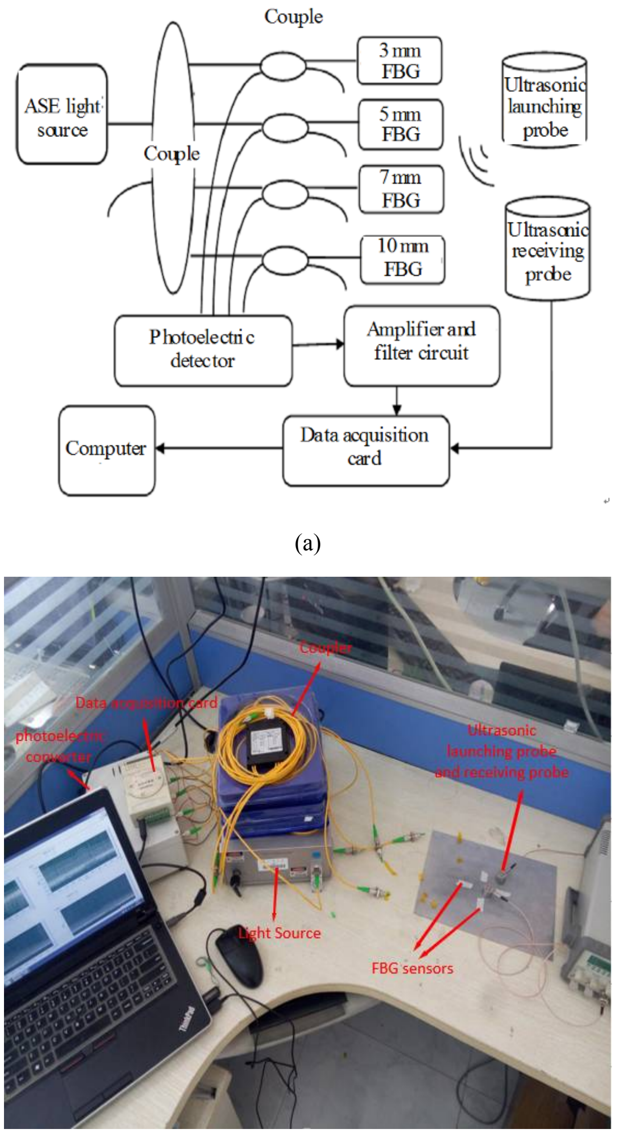
where $\nu$ is Poisson's ratio, and $p_{11}$ and $p_{12}$ represent elastic coefficient of the material, respectively.

In ultrasonic testing, the length of the grating, the reflectivity, and other parameters have a great influence on the detection of signal. In order to obtain a better detection effect, FBG length is less than 1/2 of the ultrasonic wavelength and its reflectivity is more than 0.9 [15, 16]. This can make sure that the FBG can not be affected by the non-uniform stress field of ultrasonic. When the distance between the FBG and the ultrasonic emission source is constant, the relationship between the response amplitude of sensor and the angle is a kind of approximate cosine [10]. The angle is formed by the grating axial and the ultrasonic wave propagation direction. Therefore, the FBG should be arranged in the coaxial direction with the ultrasonic transmission line and avoid the far field.

## 3. Design and analysis of the experimental test system

### 3.1 Design of the experimental test system

In order to observe the effect of different length gratings for ultrasonic detection, an ultrasound detection system was set up. The test system consisted of the high frequency signal part, the FBG optical sensing detection part, and the computer processing part. Figure 1 presents the specific experimental platform.



(a)

(b)

Fig. 1 Experimental setup for FBG sensing system (a) experimental device flow chart and (b) measurement instrument.

In this test system, the FBGs and the ultrasonic transducers were all surface-attached to the aluminum alloy plate. The grating lengths were 3 mm, 5 mm, 7 mm, and 10 mm. The 3 dB bandwidths were 0.524 nm,0.49 nm, 0.254 nm, and 0.235 nm, while the reflectivity were 89.38%, 89.06%, 91.61%, and 95.28%. All gratings were placed at an equal distance (100 mm) from the ultrasonic transducers in order to ensure the same acoustic amplitude. Specific layout position is shown in Fig. 2. The responses of different length gratings excited under the same frequency ultrasonic input wave were detected with their frequency range from 100 kHz to 800 kHz. Furthermore, the resonant piezoelectric sensor was measured at the same time. In order to make sure the experiment goes well, the temperature of the room was monitored and held constantly at 21℃. So the effects of temperature changes were eliminated.

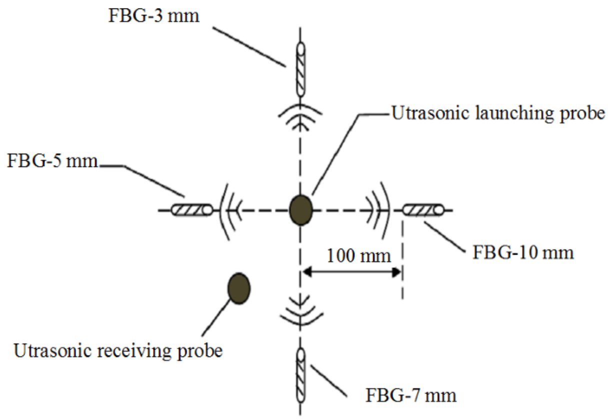
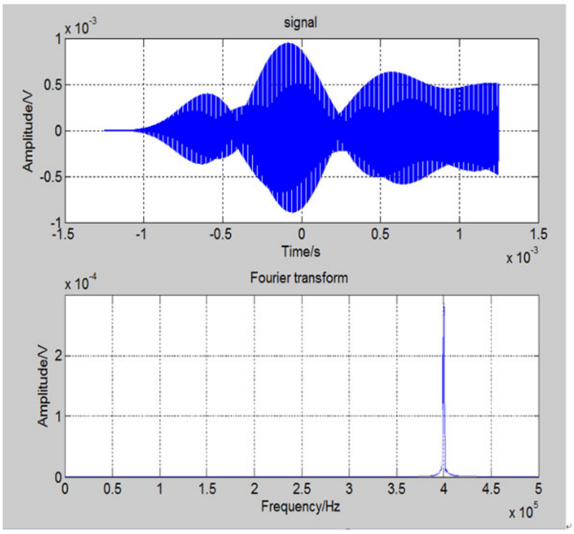


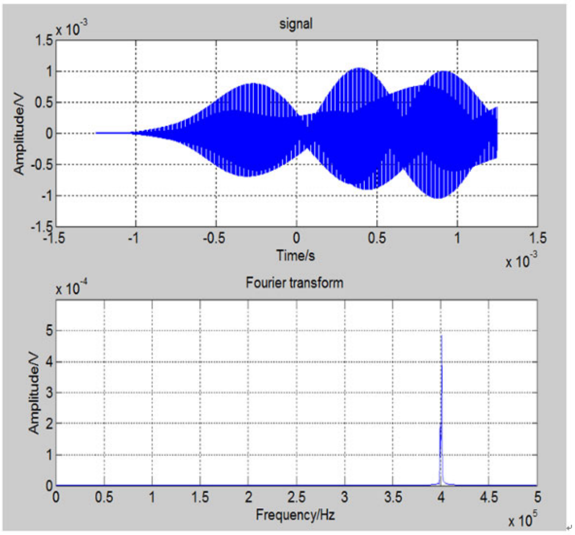
Fig. 2 Position of FBG sensors and the ultrasonic transducers.

### 3.2 Analysis and results

In the experiment, the ultrasonic frequency range from 100 kHz to 800 kHz and the data were detected at a 100 kHz interval. Under the 400 kHz frequency excitation, the signal responses of five sensors channels (3 mm, 5 mm,, 7 mm, 10 mm, and ultrasonic receiving probe) were obtained. After filtered and Fourier transformed by MATLAB software, the time and frequency domains of response are shown in Fig. 3.



(a)



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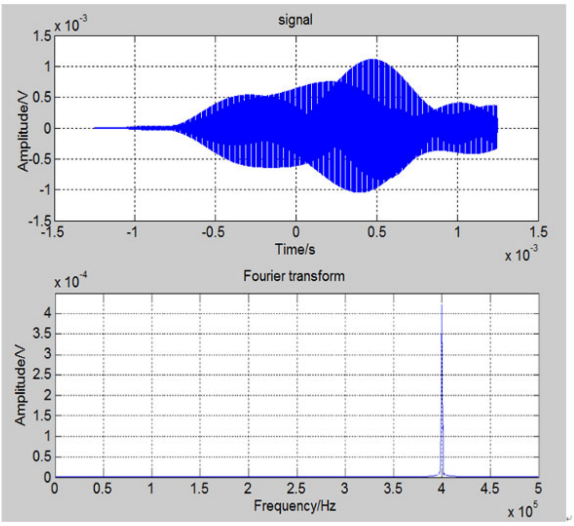

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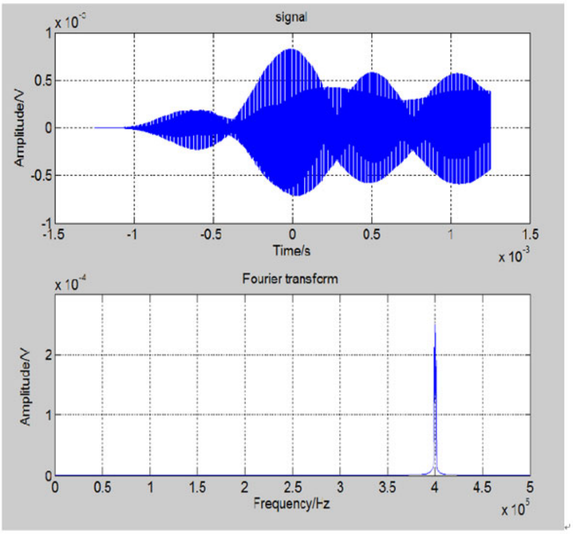

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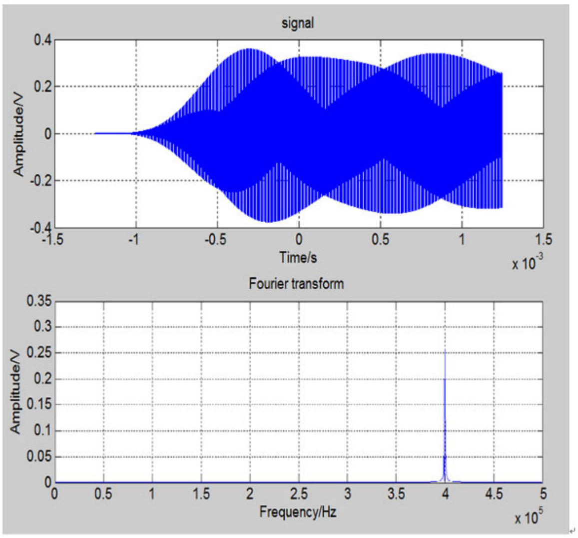

(e)

Fig. 3 Time and frequency domains of signal responses: (a) 3 mm FBG sensor, (b) 5 mm FBG sensor, (c) 7 mm FBG sensor, (d) 10 mm FBG sensor, and (e) ultrasonic receiving probe.

Since the FBG sensors have a smaller contact area than the piezoelectric sensor with the aluminum, the response amplitude detected by ultrasonic receiving probe was much larger than the grating detection. Using the origin to integrate data as shown in Fig. 4, we could see that gratings with 5 mm and 7 mm length had obvious effect under 400 kHz ultrasonic excitation, and the detection amplitude of 7 mm grating could be up to 1.2 mV.

The excitation signal was applied from 100 kHz to 800 kHz in turn, and the eight groups of data are presented in Table 1 and Table 2.

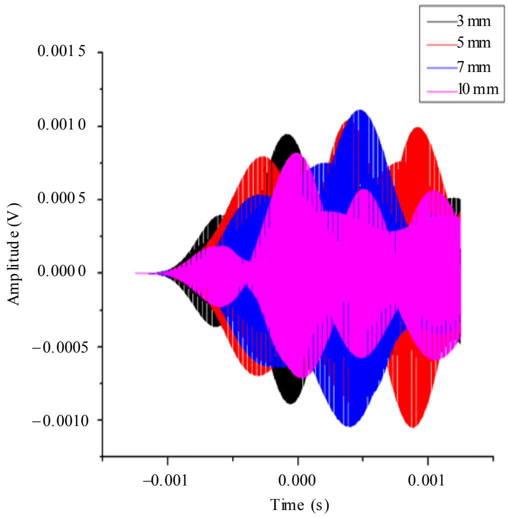

Fig. 4 Integrate data of sensors detection in five channels.

Table 1 Results of ultrasonic signal detection in five channels.

| Length of FBG<br>Amplinude ($10^{-4}$ V)<br>Frequercy | 3 mm | 5 mm | 7 mm | 10 mm | Ultrasonic receiving probe |
|---|---|---|---|---|---|
| 100 kHz | 5 | 5 | 11 | 8 | 2500 |
| 200 kHz | 9 | 9 | 8 | 6 | 4000 |
| 300 kHz | 4 | 4 | 6.5 | 5 | 3500 |
| 400 kHz | 9 | 9 | 11 | 12 | 6500 |
| 500 kHz | 2.5 | 2.5 | 2.8 | 6.5 | 3500 |
| 600 kHz | 1.5 | 1.5 | 1.8 | 2.6 | 3500 |
| 700 kHz | 2 | 2 | 4 | 2.2 | 1500 |
| 800 kHz | 6 | 6 | 2 | 3.5 | 2000 |

Table 2 Normalization process of the data.

| The length of FBG<br>Amplinude ($10^{-2}$ V)<br>Frequercy | Data processing | 3 mm | 5 mm | 7 mm | 10 mm |
|---|---|---|---|---|---|
| 100 kHz | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 |
| 200 kHz | 4 | 2.5 | 1.8 | 1.9 | 2.2 |
| 300 kHz | 3.5 | 2 | 1.5 | 1.6 | 2.5 |
| 400 kHz | 6.5 | 4.5 | 2.5 | 3.75 | 2.2 |
| 500 kHz | 3.5 | 1.25 | 0.6 | 2 | 1.25 |
| 600 kHz | 3.5 | 0.75 | 0.4 | 0.8 | 1.4 |
| 700 kHz | 1.5 | 1 | 0.9 | 0.69 | 0.7 |
| 800 kHz | 2 | 1.5 | 0.45 | 1.1 | 0.69 |

The data detected by the ultrasonic probe were compared with FBGs, and the relationship between the normalized FBG response and the ultrasonic frequency is shown in Fig. 5.

The experimental results of four grating sensors and the ultrasonic transducer showed very similar trends in both sensitivity and directivity. Although FBG sensors had a weak response amplitude, they were still showing high sensitivity for ultrasonic detection. In addition, when the range of frequency was from 100 kHz to 800 kHz, the grating with a 3 mm length had the highest sensitivity, and when the detection frequency was 800 kHz, the amplitude could be up to 0.6 mV. The 10 mm length of the grating had the highest sensitivity when the detecting frequency was low, and the amplitude was 0.8 mV as the frequency was 100 kHz. The gratings with the length of 5 mm and 7 mm had a better detection sensitivity for intermediate frequency ultrasonic wave.

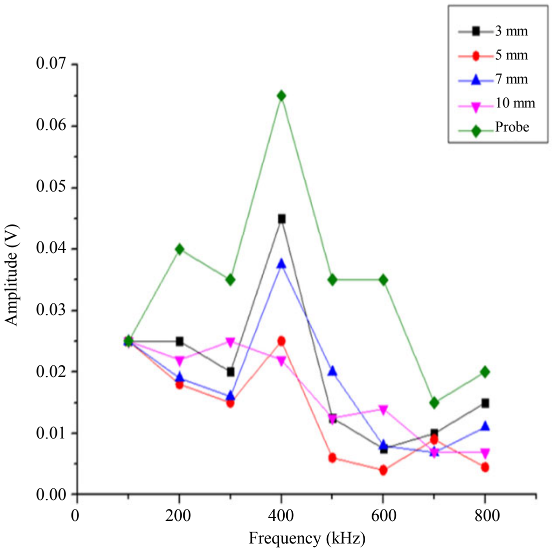

Fig. 5 Normalization of data.

## 4. Conclusions

In this paper, an ultrasound detection system based on FBGs is designed to analyze the effects of the grating length on the quality of ultrasonic resonance. The detection of different frequency ultrasonic signals in the aluminum plate is further explored, and a clear relationship between the grating length and ultrasonic frequency is obtained. Quantitative analysis has been carried out for uniform gratings, showing a better suitability in using gratings as ultrasound detectors. The theoretical analysis would be useful for sensitivity improvement of the FBG-based ultrasonic and acoustic emission sensing system. Because this experiment is a preliminary study on the response sensitivity of different length gratings to detect different wavelengths ultrasonic, deficiencies cannot be avoided in the experimental plan, which will be optimized in the further research.

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