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Design and performance analysis of a fiber ultrasonic hydrophone based on a phase-shifted fiber Bragg grating-thin plate coupled structure

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Abstract: To improve the sensitivity of a phase-shifted fiber Bragg grating (PS-FBG) for ultrasonic sensing, a coupled structure is proposed innovatively. The coupled structure is composed of a PS-FBG and a thin plate. The coupling mechanism between the plate's bending modes and the fiber's strain response have been studied theoretically and numerically. Experimental results further demonstrate sensitivity improvement across a broad ultrasonic frequency range. The proposed structure exhibits significant potential for ultrasonic sensing.

Keywords: PS-FBG,thin plate,sensitivity improvement,ultrasonic hydrophone,bending vibration

Introduction

Fiber optic acoustic sensors have shown broad application prospects in many fields such as oil exploration[1], structural health monitoring[2, 3] and medical diagnosis[4, 5] due to their unique advantages of anti-electromagnetic interference, small size, light weight and long-distance transmission. As a typical fiber optic sensing element, phase-shifted fiber Bragg grating (PS-FBG) has become the core component because of its narrow-band reflection spectrum characteristics and extremely high strain sensitivity. However, in practical applications, due to the rigid material and small size of the optical fiber, when the acoustic pressure acts directly on the bare optical fiber, the resulting strain response is extremely weak, which leads to insufficient acoustic pressure sensitivity, especially in high-frequency band.

To solve the above problems, this study innovatively designs a FBG-plate coupled structure, aiming to improve the sensor's sensitivity through the mechanical amplification effect of the structure. In this paper, the vibration theoretical model of the thin plate under the action of sound waves was established, especially for sound waves in the high frequency band. Numerical method was also used to analyze the improvement effect of the structure on the acoustic pressure reception sensitivity. Experimental results also proved that the structure can improve the sensitivity. This research work provides a theoretical and technical basis for the design of high-sensitivity fiber optic acoustic sensors.

Sensor Structure and Theoretical Analysis

The schematic diagram of the FBG-plate coupled structure proposed in this study is shown in Fig. 1. The planar circular thin plate is fixed on the support substrate, and the PS-FBG area is axially pasted on the surface of the thin plate with optical UV glue to sense the wavelength drift caused by ultrasonic waves. The fiber tail is fixed in the groove at the center of the support substrate and protected by a fiber sheath. When ultrasonic waves act on the planar circular thin plate, the plate will undergo bending vibration, so that the incident acoustic energy is efficiently converted into in-plane strain, and the strain is directionally transferred to the axial sensitive direction of the fiber through the high-stiffness adhesive layer, resulting in the drift of the central wavelength of the fiber Bragg grating, thus realizing the significant improvement of the acoustic pressure-strain conversion efficiency. This is the working principle of the structure.

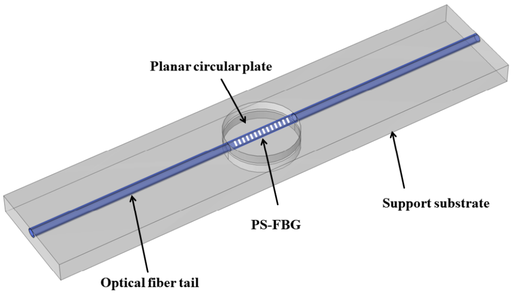

Fig. 1: Schematic diagram of the FBG-plate coupled structure.

Fig. 2 shows the deformation schematic diagram of a planar circular thin plate structure fixed around under uniform acoustic pressure P. The bending vi-

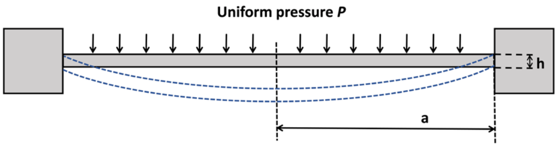

Fig. 2: Deflection of a clamped plate under uniform pressure.

bration of the thin plate under the incidence of plane sound waves belongs to small deflection vibration, which can be analyzed by Kirchhoff-Love plate theory[6]. It is assumed that the radius of the thin plate is a, the thickness is h, and the density is ρ; the thin plate is caused forced vibration by a plane sound wave with pressure amplitude P_0 and frequency of ω_0, and the corresponding equation can be expressed as

$$D\nabla^4 w + \rho h \frac{\partial^2 w}{\partial t^2} = P_0 e^{i\omega_0 t} \tag{1}$$

where $D = \frac{Eh^3}{12(1-\nu^2)}$ is the bending stiffness of thin plate, E is the Young's modulus of the plate, ν is the Poisson's ratio of the plate, $w = w(r,\theta,t)$ is the plate deflection.

For a circular plate fixed around, its deformation and rotation angle are both 0 at the boundary, so the boundary conditions are as follows:

$$\begin{cases} w|_{r=a} = 0 \\ \left.\dfrac{\partial w}{\partial r}\right|_{r=a} = 0 \end{cases} \tag{2}$$

The homogeneous solution of Eq. (1) can be expressed as follows

$$w_{nm}(r,\theta,t) = G_{nm} \cdot \mathcal{F}(r) \cdot \cos(n\theta) e^{i\omega_{nm} t} \tag{3}$$

where $\mathcal{F}(r) = J_n(k_{nm}\, r) - \frac{J_n(k_{nm}\, a)}{I_n(k_{nm}\, a)}\, I_n(k_{nm}\, r)$, $k_{nm}^4 = \frac{\omega^2 \rho h}{D}$ and ω represents the natural frequency of the free vibration of the thin plate. G_{nm} is the dimensionless maximum amplitude at any point in the thin plate and n,m represents that the circular thin plate is in the (n,m) order vibration mode. When considering the incidence of a plane ultrasound wave, the thin plate vibrates in the axisymmetric mode, that is $n = 0$.

Next, on the basis of the solution of the above free vibration, the analytical solution of the vibration response of the thin plate under the action of plane sound waves can be obtained

$$w(r,t) = \frac{P_0 e^{i\omega_0 t}}{\rho h} \sum_m \frac{F_m(r) W_m(r)}{\omega_m^2 - \omega_0^2} \tag{4}$$

where $F_m = \left(\int_0^a W_m(r)\, r\, dr\right) / \left(\int_0^a W_m^2(r)\, r\, dr\right)$.

When the optical fiber is axially pasted on the surface of the thin plate, the radial strain of the thin plate in the state of ultrasonic wave-induced bending vibration will be converted into the axial strain of the optical fiber. At the same time, since the central π phase shift of the PS-FBG is the most sensitive to the response of the sound wave when the ultrasonic wave is vertically incident on the PS-FBG[7], the axial strain at the center of the thin plate determines the sensitivity of the acoustic pressure of the PS-FBG. Under the action of acoustic pressure, the axial strain at the center of the thin plate can be expressed as

$$\begin{aligned} \varepsilon_r(r,t)|_{r=0} &= -z \left.\frac{\partial^2 w(r,t)}{\partial r^2}\right|_{r=0} \\ &= \frac{P_0 e^{i\omega t}}{4\rho} \sum_{m=1}^{\infty} \frac{F_m(0) k_m^2 G_m \left(1 + \frac{\mathrm{J}_0(k_m a)}{\mathrm{I}_0(k_m a)}\right)}{\omega_m^2 - \omega^2} \end{aligned} \tag{5}$$

The above theoretical analysis ignores the influence of damping. While a thin plate vibrates in water, the damping effect of water to the vibration system cannot be ignored. Then a damping factor ζ_m is introduced, the axial strain at the center of the thin plate can be expressed as

$$\varepsilon_r(r,t)|_{r=0} = \frac{P_0 e^{i\omega_0 t}}{4\rho} \sum_{m=1}^{\infty} \frac{F_m(0) k_m^2 G_m \left[1 + \frac{\mathrm{J}_0(k_m a)}{\mathrm{I}_0(k_m a)}\right]}{\omega_m^2 - \omega_0^2 + i\, 2\zeta_m \omega_m \omega_0} \tag{6}$$

When the ultrasonic wave is vertically applied to the PS-FBG, the optical fiber can be regarded as a cylindrical elastic body. It is assumed that both ends of the optical fiber are free, and the axial strain caused by the ultrasonic wave is

$$\varepsilon_z = -\nu_0 \frac{p}{E_0} \tag{7}$$

where $\nu_0 = 0.17$ is the Poisson's ratio of the fiber and $E_0 = 70\,\text{GPa}$ is the Young's modulus of the fiber.

By comparing the central axial strain of the thin-plate structure ε_z with the axial strain ε_r generated by the bare optical fiber directly under the action of ultrasonic waves, the improvement effect of the structure on ultrasonic wave sensing can be analyzed.

Numerical Analysis

On the basis of the theoretical analysis of the coupled structure, the strain amplification characteristics can be further revealed through numerical calculation method. According to the derived analytical solution of the axial strain of the planar circular thin plate under the action of sound waves, the amplification factor of the axial strain of the coupled structure relative to the axial strain of the bare fiber directly under the action of sound waves can be quantitatively

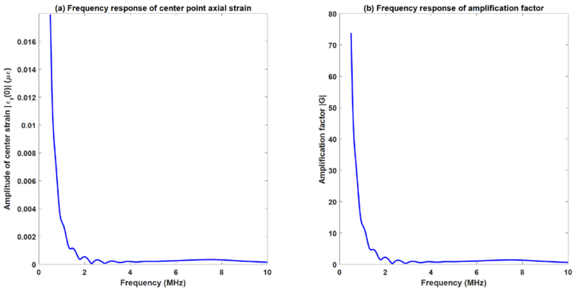

Fig. 3: (a)Frequency response of center point axial strain and (b)Frequency response of amplification factor.

obtained through numerical calculation, so as to intuitively evaluate the sensitivity improvement effect of the structure.

The material of the thin plate is resin. Its Poisson's ratio is 0.3, Young's modulus is 1.25GPa , the radius of the circular plate is 3.75mm, and the thickness is 0.25mm. Considering the material internal consumption and fluid radiation damping effect, the damping ratio ζ_m of the thin plate in water is taken as 0.2, and the optimal damping ratio will be subsequently determined by inversion of the experimental results. The numerical method is applied to simulate the dynamic response of the circular thin plate under the excitation of ultrasonic wave. In order to calculate the frequency response of the axial strain at the center point, the acoustic pressure P_0 is selected as 100 Pa, and the sound wave with a frequency range of 0.5-10 MHz are calculated. The calculation results are shown in Fig. 3. It can be seen from Fig. 3 that in the low-frequency 0.5-0.8 MHz frequency band, the amplification factor exceeds 1000 times at the highest, and the amplification effect is remarkable; in the high-frequency 1-10 MHz frequency band, the frequency response of the amplification factor is relatively gentle, and the amplification effect is stable.

The response to 1 MHz sound-wave excitation is calculated. The strain response of the bare fiber is $2.429\times10^{-4}\mu\varepsilon$, and the axial strain at the center point of the thin plate is $0.003\mu\varepsilon$, with an amplification factor of 12.4 times, which verifies the improvement effect of the thin plate structure on the acoustic pressure sensing of the fiber.

Experiment and Result

The structure of the sensor system established in this study is shown in Fig. 4. During the experiment, the fiber ultrasonic sensor is placed in a water tank, and the signal generator is used to apply excitation to the ultrasonic transducer in the water tank to generate an acoustic signal, which propagates through the water to the PS-FBG. After the wavelength shift is generated, it is converted into a phase change by a Mach-Zehnder interferometer (MZI), and finally three cosine signals with a phase difference 120° are output after passing through a coupler and a photodetector. The three signals collected in the experiment are demodulated by the arc tangent demodulation algorithm to obtain the phase signal. According to the linear relationship between the phase and wavelength of the MZI, the obtained phase signal can represent the response of the sensor.

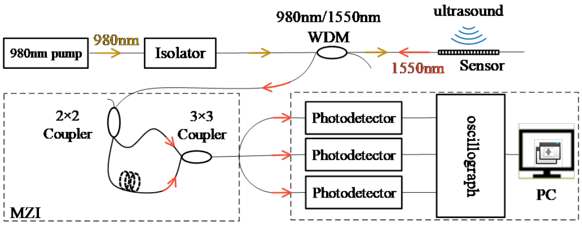

Fig. 4: The schematic diagram of the sensor system.

In the experiment, the position of the transducer was kept unchanged, and the bare fiber and the fiber packaged with the sensitivity improvement structure were placed at the same position in the water tank to ensure that the two received the same sound field. The experimental device is shown in Fig. 5.

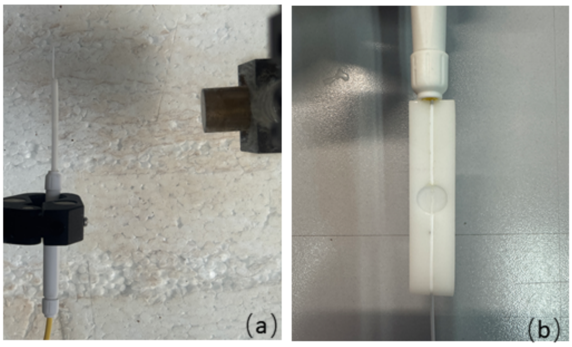

Fig. 5: (a) Experimental diagram of a sound wave incident vertically on PS-FBG and (b) Physical diagram of the sensitized structure package.

The amplification effect of the sensitivity improvement structure can be known by comparing the signal responses of the two. An ultrasonic transducer with central frequency 1 MHz was applied in the experiments to generate an ultrasonic pulse train with 20 cycles. The experimental results are shown in Fig. 6. It can be found that the responses of both to the sound wave show a process from oscillation down to stability, which is consistent with the sensing characteristics of PS-FBG to the non-uniform strain field caused by

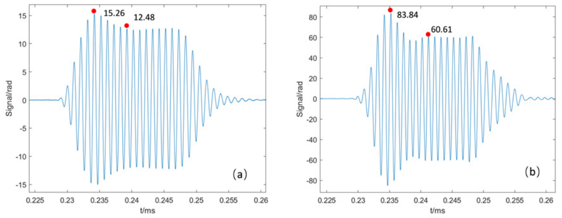

Fig. 6: Acoustic signal obtained by demodulation of (a) bare fiber and (b) sensitized structure.

ultrasonic waves. The maximum value of the oscillatory response and the amplitude of the response after stabilization are marked in the results. It can be found that the maximum value of the sensitivity improvement structure is 5.49 times that of the bare fiber, and the stable value of the sensitivity improvement structure is 4.86 times.

This result fully verifies that the structure can improve the acoustic pressure reception sensitivity of PS-FBG. There is an error between this result and the theoretical calculation value. The main reason is that in the packaging process, the optical fiber is pasted on the surface of the thin plate with UV glue, and the adhesive layer has a great influence on the strain transfer between the thin plate and the optical fiber, so there is a difference from the theoretical value. In the future, the strain transfer efficiency between the thin plate and the optical fiber needs to be inversed through experiments.

Fig. 7 amplifies the stable part of the demodulated signal, and it can be further observed that both structures can accurately measure the acoustic signal without waveform distortion, which indicates that the sensitivity enhancement structure can stably improve the acoustic pressure reception sensitivity.

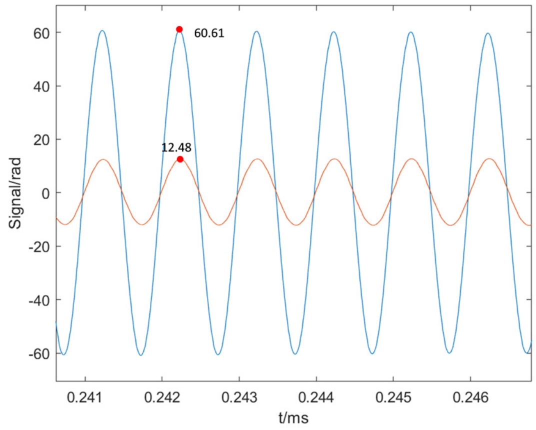

Fig. 7: Enlarged view of acoustic stabilization section.

Conslusion

In order to address the problem of insufficient sensitivity in the high-frequency band of the bare fiber ultrasonic hydrophone, this study designs and tests a coupled sensitivity improvement sensor. In this paper, the vibration theoretical model of the thin plate under the action of ultrasound is established. Based on this model, numerical calculation shows that under the excitation of 1 MHz ultrasound, the axial strain at the center of the thin plate is increased by about 12.4 times compared with that of the bare fiber,and the sensitivity improvement effect was further verified experimentally. However, there are still optimization directions, such as exploring the multi-objective optimization of thin plate materials. The next step will continue to carry out in-depth research.

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