Research of Fiber Bragg Grating geophone based on cantilever beam

WANG Liang[*a], CHEN Shao-hua[a], TAO Guo[b], LU Gui-wu[a], ZHAO Kun[a]

([a]Department of Mathematics and Physics, China University of Petroleum, Beijing 102249, P.R.China
[b]Faculty of Natural Resource and Information Technology, China University of Petroleum, Beijing 102249, P.R.China)

ABSTRACT

Along with the development of seismic exploration, the demand of frequency, dynamic range, precision and resolution ration is increased. However, the traditional geophone has disadvantages of narrower bandwidth, lower dynamic range and resolution, and cannot meet the new needs of seismic exploration. Geophone technology is a choke point, which constrains the development of petroleum prospecting in recent years. Fiber Bragg Grating seism demodulation technology is the newest kind of seism demodulation technology. The sensing probe of the Fiber Bragg Grating geophone is made up of Fiber Bragg Gating. The information which it collects is embodied by wavelength. The modulation-demodulation is accomplished by Fiber Bragg Gating geophone directly. In this paper, we design different size Fiber Bragg Grating geophones based on the transmission properties of Fiber Bragg Grating and cantilever beam method. Beryllium bronze and stainless steel are chosen as the elastic beam and shell materials, respectively. The parameters such as response function and sensitivity are given theoretically. In addition, we have simulated the transmission characteristics of Fiber Bragg Grating geophone by virtue of finite element analysis. The influences of wavelength, mass block, fiber length on the characteristics of geophones are discussed in detail, and finally the appropriate structural parameters are presented.

Keywords**:** Fiber Bragg Gating geophone, cantilever beam, Ansys

1. INTRODUCTION

Seismic exploration technology has been widely employed for exploration of oil and other mineral resources, detection of geological hazards, hydrographic surveys, and engineering quality inspection. During seismic surveys, the seismic signals received by a geophone at the surface may come from either shallow or deep geological structures and can contain different frequency components. These signals arriving at the geophone are thus different in amplitude or energy level due to the frequency dependant wave attenuation and absorption of the subsurface formations. During a survey, the geophone with wide dynamic range is indispensible to record the seismic signals during a survey. To record the reflected seismic waves, especially describing subsurface structure deeper than 4000 m, it often requires a geophone

*wlknow@163.com; phone 86-010-89731037; fax 86-010-89731037

International Symposium on Photoelectronic Detection and Imaging 2009: Material and Device Technology for Sensors, edited by Xu-yuan Chen, Yue-lin Wang, Zhi-ping Zhou, Qing-kang Wang, Proc. of SPIE Vol. 7381, 738116 · © 2009 SPIE
CCC code: 0277-786X/09/$18 · doi: 10.1117/12.835522

of greater than a 100 dB dynamic range. A dramatic increase in the capabilities of the seismic recording equipment has been realized in the last decades. Very high channel-count recording equipment with a dynamic range of 130 dB is common in a modern seismic data acquisition system. However, the dynamic ranges of traditional geophones still widely used are below 60 dB [1] and becoming a choke point of the system. Therefore, the development of a new type geophone with higher performance is one of the keys to improving the detection capabilities of seismic surveys. Among all the dynamic characteristics of the traditional geophones, the most difficult to be enhanced is the distortions due to the inherent limitations of their moving coil structure. It is particularly the case in land seismic surveys that the moving coil geophones have been the dominant data acquisition sensors so far. This type of geophone has had almost no essential changes except only a little improvement in the manufacturing process in the last decades. In recent years, researches on new types of geophones have focused on two kinds of sensors[2]. One is so called the MEMS (micro-electro-mechanical-system) geophone, which is based on high precision micro electro-mechanical capacitance and ASIC (application specific integrated circuit) [3].Another is fiber optical sensor (FOS) technology based accelerometer geophones [4]. The FOS-based geophones can be divided into two types: Michelson and Mach-Zehnder interferometers based geophones and fiber Bragg grating (FBG) sensor based ones. A geophone is essentially a special vibration sensor. For low-cost, electric immunity, multiplexing suitability, high sensitivity and stability [5], FBG vibration sensors are potentially solutions in engineering applications, and can be an element candidate to improve the geophone dynamic range. At the same time, a FBG geophone can be a highly accurate and sensitive point receiver with digital output. The output signals can be easily manipulated by the computer. These advantages are just right for high resolution seismic surveys.

There have been many papers published abroad that briefly introduced some studies on high performance FOS accelerometer geophones with unbalanced interferometer fabrications. Most of them are for military applications and we can seldom find the necessary details as references. There had only preliminary work in this field in China. Zhang presented a study on FBG geophones and their field experiments in Shengli Oilfield in China [6]. Among others, Liang and Zhou reported that the natural frequency and the frequency bandwidth were 152 Hz and 0–1000 Hz, respectively. They also worked out the relationship between the change of grating period of the FBG and the corresponding change of accelerate to be measured [7].

In this paper, a prototype of a new type FBG geophone is presented. Then its amplitude- and phase curves are given by analyzing the sensing process. A new kind of FBG geophone is designed according to the above stimulation. In the geophone, the FBG sensor head is stick on a beryllium bronze cantilever beam. To sensing the vibration, a mass block is fixed in the cylinder shell through the beam. The parameters such as response function and sensitivity are given theoretically. In addition, we also stimulated the transmission characteristics of FBG geophone by virtue of finite element analysis. The influences of FBG length, mass block, and the beam dimension are all discussed in detail, and the appropriate parameters are presented finally.

2. PRINCIPLES OF THE FBG SENSOR

The basic principle of operation commonly used in a FBG-based sensor system is to monitor the shift in wavelength of the reflected “Bragg” signal with the changes in the measurand (e.g., strain, temperature). The Bragg wavelength or resonance condition of a grating, is given by the expression [8]

$$\lambda_B = 2n\Lambda \tag{1}$$

Where Λ is the grating pitch and n is the effective index of the core. With such a device, injecting spectrally broadband source of light into the fiber, a narrowband spectral component at the Bragg wavelength is reflected by the grating. In the transmitted light, this spectral component is missing, as depicted in Fig. 1. The bandwidth of the reflected signal depends on several parameters, particularly the grating length, but typically is 0.05 to 0.3 nm in most sensor applications. Perturbation of the grating results in a shift in the Bragg wavelength of the device which can be detected in either the reflected or transmitted spectrum, as shown.

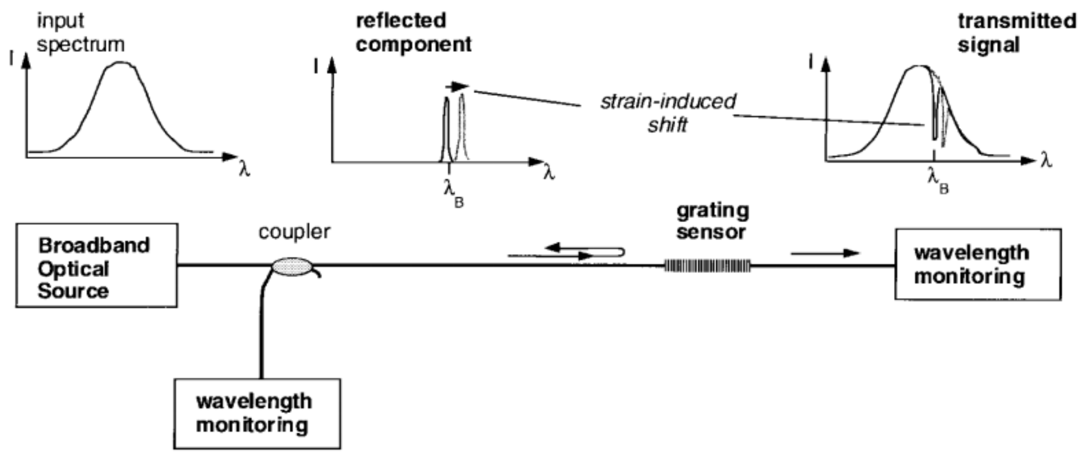
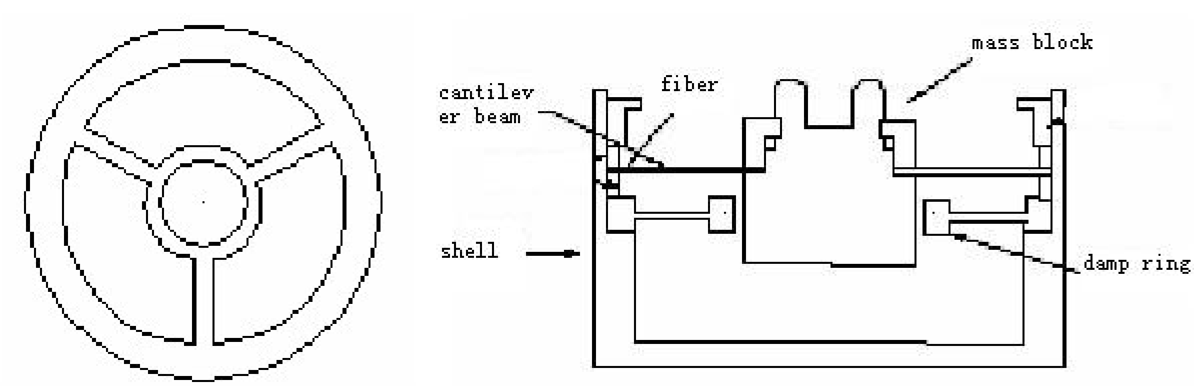


Fig. 1. Principles of the FBG sensor.

3. FBG GEOPHONE ANALYSES

The FBG geophone system consists of a sensing head, demodulate system, and signal processing, and output units. The sensing head is designed in detailed in this paper. Here the head of the geophone is made up of a cylinder shell. The frame for maintaining the optical fiber was fixed on the shell. A 3-arm metal piece for restricting lateral displacement is employed to connect the mass to the shell of the head. The FBG fiber is threaded through the mass tail and its adjustable nut. Then the mass is bonded to the beam with epoxy resin. At the same time, a damp ring is applied below the beam to introducing a feasible damp, as shown in Fig.2 (b).

Based on the mechanics theory, the structure model of the sensor head is presented in Figure 3a, and the forces imposing on the moving mass are analyzed in Figure 3b.



(a) (b)

Fig.2 cantilever beam and shell

Now we suppose that the ground movement equation is $x = x_0 \sin(\omega t)$, where x_0 is the maximum ground displacement in microns(μm), x is the ground displacement with time, and ω is the angle frequency of the ground excitation. When the ground is moving downwards to a displacement of x, the acceleration of the movement is $\frac{d^2x}{dt^2}$. The mass is thus also moving down with a displacement of y relative to the geophone case, with a velocity of $-\frac{dy}{dt}$ and an acceleration of $\frac{d^2y}{dt^2}$.

We assume in the following analyses that, m denotes the mass of the suspending mass in kilograms (kg), y denotes the displacement of the mass in microns, ε denotes strain, k denotes the stiffness coefficient of the spring, and c denotes the damping factor. The counter force from the spring and FBG is –ky in the direction opposite to the ground acceleration. The force due to the movement of mass, friction, and damping is $c\frac{dy}{dt}$. The analyses of the forces acting on the mass are illustrated in Figure 3b.

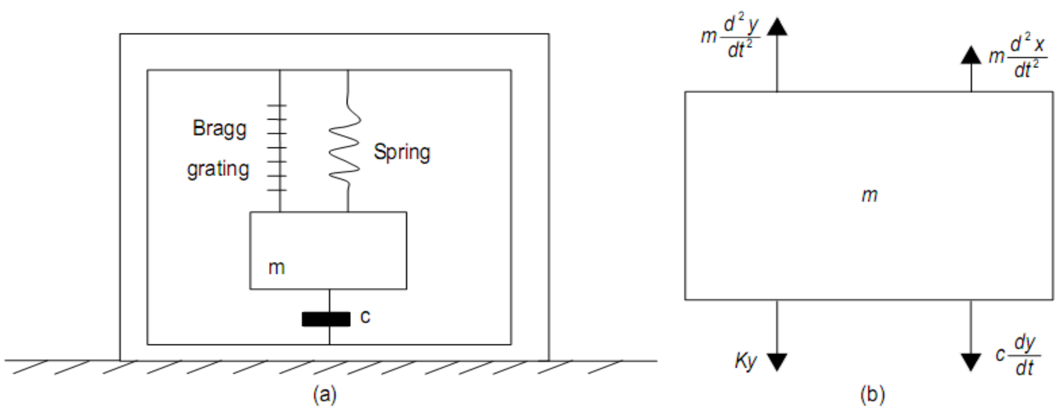


Fig. 3 Physical model of the FBG geophone (a) and the exerting force analyses (b).

Based on Newton's law we have

$$m\frac{d^2y}{dt^2} + m\frac{d^2x}{dt^2} = -(c\frac{dy}{dt} + ky) \quad (2)$$

After some manipulations of equation we arrive at

$$M\frac{d^2y}{dt^2} + d\frac{dy}{dt} + ky = Ma_0 \sin(2\pi ft) \quad (3)$$

In these equations, $\xi = \frac{d}{d_0}$, $d_0 = 2\sqrt{Mk}$, and The angle frequency $\omega_0 = \sqrt{\frac{k}{M}}$, $\gamma = \frac{\omega}{\omega_0}$,we have

$$\frac{d^2y}{dt} + 2\xi\omega_0\frac{dy}{dt} + \omega_0^2 x = a_0 \sin(2\pi ft) \quad (4)$$

$$H(s) = \frac{X(s)}{A(s)} = \frac{1}{s^2+2\xi\omega_0+\omega_0^2} \quad (5)$$

The amplitude-frequency and the phase-frequency characteristics

$$\begin{cases} H_A(\omega) = |H_A(\omega)| = \frac{1}{\omega_0^2}\frac{1}{\sqrt{(1-r^2)^2+(2\xi r)^2}} \\ \phi = -\tan^{-1}\frac{2\xi r}{1-r^2} \end{cases} \tag{6}$$

So we can obtain the amplitude- and the phase-frequency characteristics, which are depicted in Fig.4

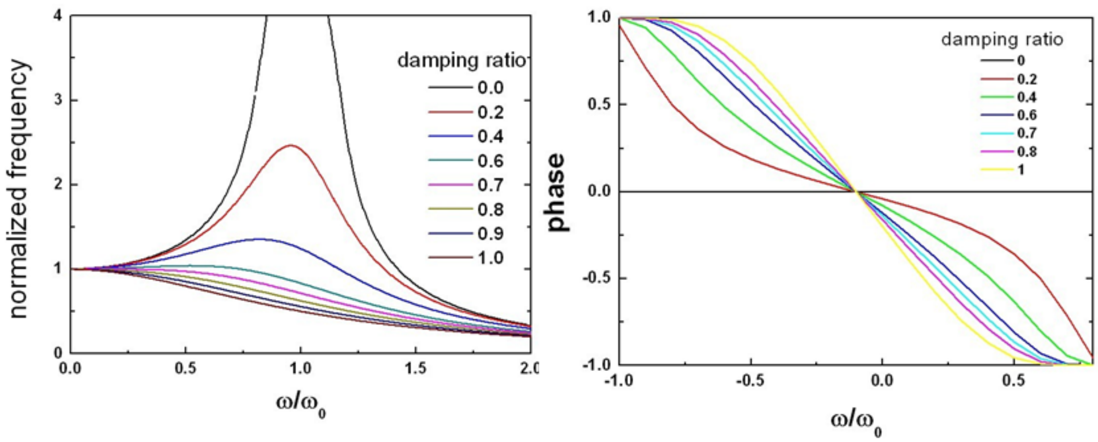


Fig. 4 amplitude-frequency and the phase-frequency characteristics

In this paper, we design different size Fiber Bragg Grating geophones based on the transmission properties of FBG and cantilever beam method, as shown in figure 2(a). Beryllium bronze and stainless steel are chosen as the elastic beam and shell materials, respectively, as shown in figure 2(b).

The earth is a low pass filter and the seismic wave frequency range is from several Hertz to a few hundred Hertz. In the case of this study, f_0 is calculated as:

$$f_0 = \frac{1}{2\pi}\omega_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{7}$$

$$k = \frac{Ebh^3}{2L^3} \tag{8}$$

The mass of mass block is selected as 8.45g, then $f_0 = 220.82\text{Hz}$.

In application, the geophone sensitivity and natural frequency can be modified by adjusting the mass weight and the parameters of cantilever beam. For example, the frequency can be enhanced by either increasing the spring stiffness or reducing the weight of the mass.

It is understood that the FBG wavelength shift is induced by the ground movement. Therefore, the sensitivity of the wavelength shift is defined as the shift length under a unit exciting acceleration. It can be calculated as:

$$S = \frac{\Delta\lambda}{a} = \frac{0.78\lambda_B\varepsilon}{a} \approx \frac{0.78\lambda_B}{\omega_0^2 L} \tag{9}$$

Where S represents the sensitivity of wavelength shift versus the acceleration $\Delta\lambda$ is the wavelength shift, λ_B is the central wavelength, ε is the strain of the FBG [9].

We Suppose the L is 10 mm and the Young's modulus of the optic fiber E is 7.3×10^{10} N/m^2, and the S should be

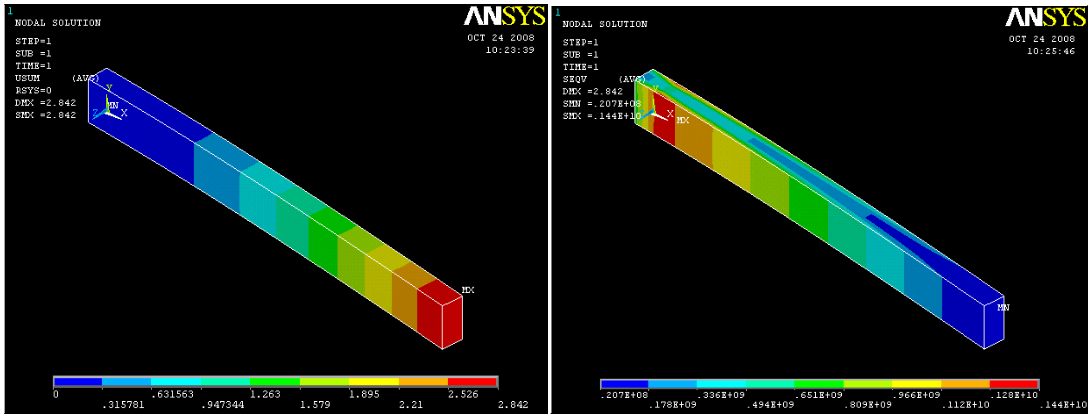
$$S=31.2\text{pm/m/s}^2=305.8\text{pm/g}$$

This is four times larger than that of Ref. [9].

In addition, we simulate the geophone displacement and stress in virtue of finite element analysis, as shown is Fig.5.

Both of the curves accord with the theory well.

Based on our analyses and inheriting previous work on the FBG sensor-based geophone, a prototype of a new FBG geophone has been developed and designed. The principles and fabrication of this kind of FBG geophone have been presented in this paper. The important parameters such as response functions, dynamic range, and sensitivities are calculated theoretically.



(a) (b)

Fig5 Simulation of displacement and stress

ACKNOWLEDGEMENTS

This work is sponsored by the National 863 Program (No. 2006AA06Z207 & 2006AA06Z213), the Youth Foundation of China National Petroleum Corporation (No.07E1003).

REFERENCES

[1] Fu, X. N., The problems with seismic geophone: Petroleum Instrument (in Chinese), 15(2), 11 – 2(2001).

[2] Liu, G. L., Liu, T. H., Gao, Z. L., Li G., and Yao, G. K., On the development trends of seismic geophone: Progress for Exploration Geophysics (in Chinese), 26(3), 178 – 185(2003).

[3] Zhang, H. L., An accelerometer geophone MEMS for geophysical prospecting: Petroleum Instrument (in Chinese), 16(6), 1 – 3(2002).

[4] Liu, Z. F., Research on all fiber optic acceleration seismic geophone based on compliant cylinders: MS Thesis, Tianjin University (2002).

[5] Lei, L., and Zhou, X. F., Research on the new type of fiber Bragg grating geophone: China Cement, 6, 52 – 53(2003).

[6] Zhang, Y., Yin, Z. F., Chen, B. Q., and Cui, H. L., A novel fiber Bragg grating based seismic geophone for oil/gas prospecting: Proc. of SPIE, 5765, 1112 – 1120(2005).

[7] Liang, L., and Zhou, X. F., Research on the new type of fiber Bragg grating geophone: Journal of Chengdu Petroleum College (in Chinese), 5(1), 4 – 7(2003).

[8] Meltz, G., et al., Formation of Bragg gratings in optical fiber by a transverse holographic method: Opt. Lett., 14(15), 823 – 825(1988).

[9] Tao, G., and Zhang, X, L., A new type of fiber Bragg grating based seismic geophone, APPLIED GEOPHYSICS, Vol.6, No.1 (2009).