A Novel Fiber Grating Array Vibration Monitoring System for large area safety

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ABSTRACT

There are many vibration damages happen in the world, such as Pipeline broken, Historical Relics stolen, even for the board destroy. With conventional vibration detection methods there is a gap between what you believe is occurring along area and what is actually happening. This information gap can result a delay in your discovering and locating broken. Based on the non-linear optical scattering theory, we have developed a new fiber grating vibration-monitoring system. This new system overcomes the limitations of measurement technologies available today, thus closing the monitoring gap and improving system integrity and safety.

Key words：Vibration detection, Fiber grating vibration-monitoring system, OTDR(Optical Time – domain Reflectometry) OFDR(Optical Frequency-domain Reflectometry), Fiber Grating Array, Optical Fiber Grating Reflector.

1. INTRODUCTION

A few decades ago telecommunication had been revolutionized by fiber optic technology. This revolution became a route as mass production techniques coupled with technical improvements resulted in superior performance at low costs than those of alternative approaches. Next to this revolution emerged another one as result of combination of the fiber optic telecommunication product outgrowths with optoelectronic devices to create optic fiber sensors. These areas of opportunities include the potential of replacing the majority of environmental sensors in existence today as well as opening up entire markets where sensors with comparable capability do not exist.

The optic fiber sensors can be basically divided into two groups – extrinsic and intrinsic [1]. Many of the highest performance sensors are intrinsic. Fiber optic sensors of are passive, immune to electromagnetic interference, intrinsically safe, small size, lightweight, multiplexible and corrosion resist. The intrinsic optical fiber sensors also can be divided two groups – distributed sensors and quasi-distributed sensors. A crucial role in the distributed sensing play the backscattering method usually called Optical Time-Domain Reflectometry (OTDR). Based on the basic OTDR [2], distributed optical fiber sensors has been developed a number variant techniques including Optical Frequency-Domain Reflectometry (OFDR)[3].

In this paper we have developed a novel fiber grating array vibration monitoring system for large area safety based on the traditional OFDR-FS technology. The conventional OFDR has high space resolution; the resolution can be down to 20μm, has high sensitive; the sensitivity.It is an excellent temperature test sensor system. The conventional OFDR-FS numerical measurement value is the average data of m-times measurement. The system has to spend more measurement time to get the numerical measurement value Therefore; the conventional OFDR-FS system is not suitable for vibration. To solve this problem, we design a Fiber Grating Array OFDR-FS for fast movement system, such as vibration damage monitoring.

There are many vibration damages happen in the world, such as Pipeline broken, Historical Relics stolen, even for the board destroy. With conventional vibration detection methods there is a gap between what you believe is occurring along area and what is actually happening. This information gap can result a delay in your discovering and locating broken.

Fiber Grating Array OFDR-FS monitoring system is very sensitive to the vibration near the fiber sensor. So it can be used in monitoring the vibration damage.

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The next chapter is the Theoretical background of Fiber Grating Array OFDR-FS. Following is the structure of the Fiber Grating Array OFDR-FS system and its applications. The last chapter is the conclusion.

2. THEORETICAL BACKGROUND OF FIBER GRATING ARRAY OFDR-FS

Fiber Grating Array OFDR-FS consist three parts: The highly coherent laser diode which linearly swept around its central wavelength $f_{s;}$ Fiber Grating Array; Signal receive and process unit as shown in Fig. 1

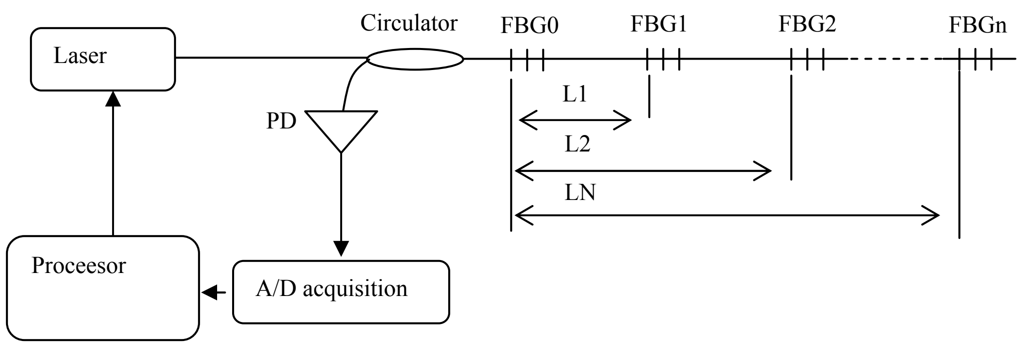

Fig .1 the schematic of Fiber Grating Array OFDR-FS system

As the Fig.1 shown, the input light passes through the optical circulator and enters to the Fiber Grating Array sensing fiber. This input light will be partial reflected by each fiber grating which is distributed in the fiber as a reflector. The reflected light will return to the optical circulator again and enters to the photodiode(PD) detector.

Fiber grating sensing cable is both the sensor and communication path. Fiber gratings are evenly distributed in one single fiber as the reflectors. The function of each fiber grating is to reflect part of input light. The signal processing unit includes photodiode detector, Analog-to-Digital(A/D) acquisition device, and Digital Signal Processor(DSP). The photodiode detector's function is to convert light signal to analog electrical signal. The A/D acquisition device's function is to transform the analog signal to digital signal for DSP processor to use.

The first fiber grating FBG0 has higher reflectivity than the other fiber gratings. In our present experiment, the reflectivity for the FBG0 is 20 times large than the other fiber grating. We set the distance between FBG0 and PD as zero.

The Laser light source optical field can represent as:

$$E_s(t) = E_s e^{j2\pi f_s(t)} \quad (1)$$

Here E_s is the amplitude of the Laser, $f_s(t)$ is the frequency of the Laser at time t.

$$f_s(t) = f_s + \alpha t \quad (2)$$

Where f_s is the initial output frequency of the Laser. α is the sweeping slope.

At time t, the reflected light signal to photodiode detector from the ith fiber grating FBGi is:

$$E_i(t) = r_i E_s(t + \Delta t_i) \qquad \text{i=0,1,2…N} \quad (3)$$

$$= r_i E_s e^{j2\pi f_s (t+\Delta t_i)+\varphi_i}$$

Where the r_i is the reflectivity of ith fiber grating, Δt_i is the time delay due to the optical path difference, φ_i is the phase difference due to the optical path difference. We set the distance between FBG0 and PD is equal to zero. Therefore, the time delay and the phase differences for FBG0 is 0 ($\Delta t_0 = 0, \varphi_0 = 0$). Then we have:

$$\Delta t_i = \frac{2nL_i}{C} \qquad \text{i=1,2…N;}$$

$$\varphi_i = 2\pi \frac{2nL_i}{\lambda} \qquad \text{i=1,2…N.} \tag{4}$$

Here n is the index of refraction of the optical fiber, C is the velocity of the light in air and λ is the wavelength of the light source.

The photodiode detector current I(t) is proportional to the square magnitude of the light field. We set the FBG0 is the reference fiber grating. We get that the photodiode detector current from the ith fiber grating is:

$$I(t) = \eta \sum_{i=0}^{N} E_i(t) \sum_{i=0}^{N} \overset{*}{E_i}(t) \tag{5}$$

$$= \eta \sum_{i,j=0}^{N} E_i(t) \overset{*}{E_j}(t)$$

$$= \eta \sum_{i,j=0}^{N} r_i E_s e^{j2\pi f_s (t+\frac{2nL_i}{C})+\varphi_i} r_j E_s e^{-j2\pi f_s (t+\frac{2nL_j}{C})-\varphi_j}$$

$$= \eta \{ \sum_{i,j=0(i=j)}^{N} r_i^2 E_s^2 + \sum_{i,j=0(i\neq j)}^{N} r_i r_j E_s^2 e^{j2\pi (f_s (t+\frac{2nL_i}{C}) - f_s (t+\frac{2nL_j}{C})) + \varphi_i - \varphi_j} \}$$

Here η is the transformation rate constant of the photodiode detector.

The dc part of the photodiode detector current is:

$$I_{-} = \eta \sum_{i=0}^{N} r_i^2 E_s^2 \tag{6}$$

The ac part of the photodiode detector is:

$$I_{\sim} = \eta \sum_{i,j=0(i\neq j)}^{N} r_i r_j E_s^2 e^{j2\pi (f_s (t+\frac{2nL_i}{C}) - f_s (t+\frac{2nL_j}{C})) + \varphi_i - \varphi_j} \tag{7}$$

The FBG0's reflectivity is much higher than others. The frequency different mainly comes from ith fiber grating with FBG0. The frequencies different, which the ith fiber grating reflects with other fiber gratings, are very small. We can neglect these frequency differences. Therefore, the frequency difference between FBG0 and ith Fiber Grating is:

$$I_{0\sim}=\eta\sum_{j=1}^{N}r_0 r_j E_s^2\,(e^{j2\pi(f_s(t+\frac{2nL_j}{C})-f_s(t+\frac{2nL_0}{C}))+\varphi_j-\varphi_0\ ]}+e^{-j2\pi(f_s(t+\frac{2nL_j}{C})-f_s(t+\frac{2nL_0}{C}))+\varphi_j-\varphi_0\ ]}) \quad (8)$$

$$=\eta\sum_{j=1}^{N}\frac{1}{2}r_0 r_j E_s^2\cos(2\pi f_s(t+\frac{2nL_j}{C})+\varphi_j)$$

There are N different frequency and phase in $I_{0\sim}$ each frequency and phase only dependent the distance between the ith fiber grating and the FBG0.

From equations 6 and 7, if the reflectivity of each fiber grating doesn't change; the amplitude Es of the light source, the sweep slope α and the distance between each fiber grating and PD doesn't change, we can get that the current of PD will not be changed.

If we keep all above parameters are constant except for the distance Li between ith fiber grating and PD, then we get the change of PD current only dependents on the distance Li. Therefore, we measure the PD current we can get the change of Li. If the vibration happens between kth fiber grating and (k+1)th fiber grating, This vibration doesn't change the distance between ith fiber grating and PD when th i<k and changes the distance between ith fiber grating and PD when i>k. Let the change be $\Delta L\sin(\beta t)$, we have

$$I_{0\sim}=\eta\{\ \sum_{i=1}^{k}\frac{1}{2}r_0 r_i E_s^2\cos(2\pi f_s(t+\frac{2nL_i}{C})+\varphi_i)$$

$$+\sum_{j=k+1}^{N}\frac{1}{2}r_0 r_j E_s^2\cos(2\pi f_s(t+\frac{2nL_j+\Delta L\sin(\beta t)}{C})+2\pi\frac{2nL_j+\Delta L\sin(\beta t)}{\lambda})\ \} \quad (9)$$

Monitoring the begin position kth fiber grating and analyzing the character of this charged frequency, we can get the position of the vibration and know what kind vibration happened.

This Fiber Grating Array OFDR-FS system is very sensitive to all physical parameters, such as temperature, pressure, vibration et al. It keeps all advantages of the traditional OFDR-FS and overcomes the traditional OFDR-FS's lack. It is an excellent monitoring system for the vibration damage.

3. THE FIBER GRATING ARRAY OFDR-FS SYSTEM AND ITS APPLICATIONS

There are three units in the Fiber Grating Array OFDR-FS system. They are: Highly coherent laser diode which linearly swept around its central wavelength $f_{s;}$ Fiber Grating Array; Signal receive and process unit as shown in Fig. 1.

A crucial element in the Fiber Grating Array OFDR-FS system is the light source, which strongly influences the achievable spatial resolution and measurement range [1]. High spatial resolution requires the highly coherent light source having a broad, phase continuous and simultaneously linear tuning range. Recently, the use of laser diode with external fiber grating resonators allows enhancing the coherence length and to increase the measurement range.

The second crucial element in the Fiber Grating Array OFDR-FS system is the Fiber Grating Array cable. The space resolution is dependent on the distance between two closest fiber gratings. The longer distance between two closest fiber gratings is, the larger space resolution will be. Beside the light source, the measurement range also dependents on the reflectivity of each fiber grating. The lower reflectivity of each fiber grating, the longer range can be monitored, but this will lower the Signal-noise ratio. We have to consider all requirement of the special application and decide each parameter. The parameters are: The coherent length of the Laser source, the distance between two closest Fiber Gratings, The reflectivity of the first Fiber Grating FBG0, the reflectivity of other Fiber Gratings.

Our Fiber Grating Array OFDR-FS instrument based on the use of a tunable fiber laser with very narrow line-width (about 1 kHz) tuned mechanically by piezo-electric transducer. The reflectivity of the first fiber grating in the fiber grating sensor cable is 20 times larger than other fiber gratings. The reflectivity of the other fiber gratings is almost same value [4]. The distance between two closest fiber-gratings is about 250m. The reason for the distance between two closest fiber gratings is dependent on the application. This Fiber Grating Array OFDR-FS is applied to monitor the damage of the pipeline by the people who try to steal the oil or gas illegally. This Fiber Grating Array OFDR-FS system can monitor the begin of this illegal activity happening. If the people want to steal oil or gas from the pipeline, the first thing is to break the pipeline. The vibration will take place at the pipeline broken point. The 250m distance between two closest fiber-gratings is good enough to monitor the illegal activity. In above condition, our Fiber Grating Array OFDR-FS monitoring system makes possible to measure to 60 km.

Fig. 2 is the reflective spectrum of the Fiber Grating Array Cable.

Fig. 2 The spectrum of the Fiber Grating Array cable

This Fiber Grating Array monitoring system [5] is extremely sensitive the vibration and able to detect the vibration damager with minute, therefore, in the event that the illegal activity does occur, it can be found immediately. It is a permanent monitoring solution and continually monitors at all place along the pipeline at all times. This system provides benefits at all levels of organizations: Including protecting the state property, low risk of environmental damager, improvement of safety of infrastructure and for personnel. According the report from the pipeline company in China, the largest lost property in the pipeline industry is pipeline oil is stolen. After the illegal people broke the pipeline and stole the oil, they never try to repair the broken pipeline. The oil or gas will overflow to the environment around the pipeline. The oil pollution reached a level pernicious to the health of the population. It also destroys the environment. The environment costs are very difficult to predict and in some case, damages the operator has had to pay as a result of product spillage from a pipeline have been as high as $4.5 million [6].

The Fiber Grating Array Cable contains no moving parts is immune to the EMC interference, making it ideal for use in industrial sensing applications, especially in oil industry, high power electric industry, chemical industry and nuclear industry. In 2007 we used this Fiber Grating Array OFDR-FS system [5] to monitor the pipeline damage from DaGang to Zaozhuang in China. The Fiber Grating Array Cable is installed with the communication optical fiber cable. It reduces the pipeline cost. The cable is buried under the ground about one meter and above the pipe line 20 cm. The figure 3 is the pipeline station. We installed the monitoring system inside of this station. Each side of this station we installed 30km Fiber Grating Array Cable. The engineers are installing the cable as shown in the figure 4. In the figure 5, the engineer is testing the Fiber Grating Array Cable.

Fig. 3 the pipeline station.

Fig. 4 The engineers are installing the Fiber Grating Array cable

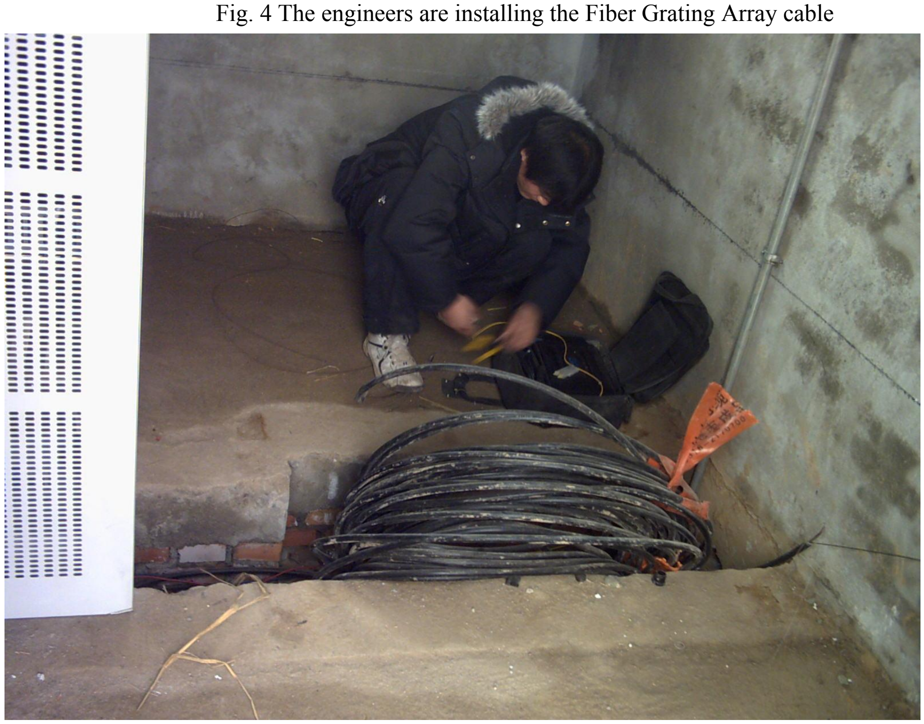

Fig. 5 The engineer is testing the Fiber Grating Array cable

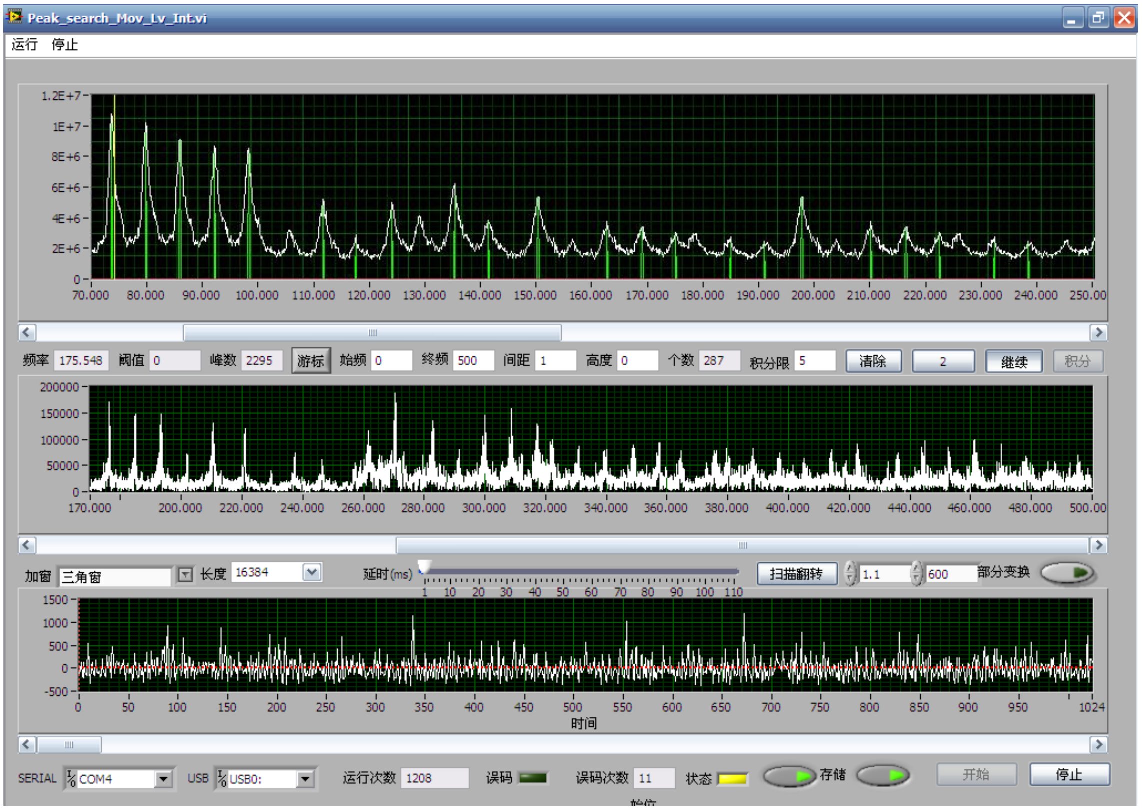

Fig.6 The computer interface of the monitor system

4. CONCLUSION

This system is based on vibration measurement using quasi-distributed Fiber Grating Array sensing technology and can be used to detect the vibration damage. There are lots of vibration damages in the real world. For example, in developing countries, some people want to steal the pipeline oil. They have to break the pipeline first. The vibration will happen. Using this system, we can measure the vibration damage happening point and know what kind vibration take place in moment. This system can be applied to all vibration damage area.

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REFERENCE

Book

[1] Jozef Jasenek, Assoc. Prof. FEI STU Bratislava, Slovakia, The theory and application of fiber optic sensors with spread parameters.

Journal

[2] PatM. Nazarathy, S. A. Newton, R. P. Giffard, D. S. Moberly, F. Sischka, W. R. Trutna and S. Foster, "Real-Time Long Range Complementary Correlation Optical Time Domain Reflectometer", J. Lightwave Tech., vol. 7, no. 1, pp. 23 -i38 (1989)

[3] U. Glombitza and E. Brinkmeyer, "Coherent Frequency-Domain Reflectometry for Characterization of Single-Mode Integrated Optical waveguides", J. Lightwave Technol., vol. 11, no. 8, pp. 1377 - 1384(1993)

Other

[4] AT Photonics, Inc. patent in China. CN2938163,2007-8-22

[5] AT Photonics, Inc. patent in China: CN200979076,2007-11-21

[6] Colonial pipeline November 1997- United States