ISSN : 0974 - 7435 Volume 10 Issue 15

2014

BioTechnology

An Indian Journal

FULL PAPER

BTAIJ, 10(15), 2014 [8379-8384]

The fiber optic sensor-based online monitoring technology for oil well down-hole casting strain and pressure

Peng Liu
College of Computer Science, Yangtze University, Jingzhou Hubei, 434023, (CHINA)
Email : liupengjz@126.com

ABSTRACT

Oilfield casing not only bring economic losses, but also oil field development program and the application of enhanced oil recovery measures adversely affect, directly affecting the development of oil fields, well casing damage has become the hard problem of oil fields. In recent years, domestic and foreign scholars have been conducting research damaged well casing, casing damage mechanism in a certain degree of understanding achieved, but there is no effective way to prevent and mitigate the damage cased hole, therefore, to grasp the casing deformation and stress and strain, early prevention and treatment has become an urgent problem. In accordance with the special circumstances of oil well and characteristics of oil field casing, made using fiber-optic sensors monitoring strain and pressure oil well casing, making the analysis of fiber grating sensor and fiber-optic Brillouin sensors external pressure during oil well casing pipe and casing deformation when the strain monitoring of the working process. Through the real-time monitoring experiment, it shows that the casing real-time monitoring system based on the fiber-optic sensors can reflect the axial and circumferential casing stress real-timely and accurately. It is significant to forecast the casing damage accurately and reduce economic losses.

KEYWORDS

Fiber optic sensor; Oil well; Hole casting strain and pressure; Online monitoring.

INTRODUCTION

Casting outside pressure monitoring is of great importance in oil-gas exploration and development. It can not only help us better know about the production capacity and performance of the underground oil and gas reservoir, but also have guiding significance for researches about the distribution of residual oil saturation as well as the adjustment of development programs, such as the water injection well pattern deployment, etc. Setting a reasonable limit of water injection pressure based on the casting outside pressure monitoring can effectively slow down the speed of casting damage. However, the conventional methods for casting outside pressure monitoring are all single point measurements through which the pressure distribution in oil reservoir cannot be obtained.

Many researches concerning casting damage have been conducted by oil field related research institutions both at home and abroad. Since it is difficult to use ordinary sensors that are often incompetent to perform the monitoring task for direct measurement of the strain and pressure of underground casting, most of the researches cannot be verified through experiment, nor can their results be supported by data, and thus the impending casting damage prediction becomes almost impossible. Therefore, a sensor which is capable of down-hole monitoring task, as well as corresponding measurement method, is urgently needed.

The fiber optic sensing technology is gradually generated with the development of optical fiber and optical communication technique. Optical fiber is the medium for the long distance transmission of light wave signal in optical communication system. But in actual light transmission, it is prone to be influenced by environmental factors, including temperature, pressure, magnetic field and electric field, etc., the changes of which will result in the changes of the amount of light, such as intensity, phase, frequency, polarization state of the light. Therefore it has been found that the physical quantity, such as temperature, pressure, magnetic field, etc. leading to light amount changes, can be determined, if the amount of change is measured out. As a result, the fiber optic sensing technology comes into being, and based on which external environment factors such as temperature, stress, etc. are monitored making it possible for casting damage monitoring with this technology.

THE MECHANISM OF FIBER OPTIC SENSOR-BASED ONLINE MONITORING TECHNOLOGY FOR CASTING

The fiber optic sensing technology can be used to monitor external environment factors such as temperature, stress, etc., and the light weight, small volume, strong anti-interference capacity and high-accuracy measurement of the fiber optic sensor further make it possible for casting damage monitoring.

FBG sensing technology applicable for casting outside pressure monitoring

Fiber Bragg Grating (FBG, for short) is to form space phase grating in the core of mono-mode optical fiber based on the photosensitivity of optical fiber (the interaction between incident photon and the fiber core resulting in the permanent refractive index changes of the later) using UV-laser direct-writing method, that is to generate a narrowband filter or reflector in the fiber core. FBG (Fiber Bragg Grating) sensing technology realizes the absolute measurement of measurand’s stress, strain and temperature via detecting the reflection and transmission FBG wavelength spectrum inscribed into the fiber core.

FBG is the simplest and most common type of fiber grating. It is constructed in a short segment of optical fiber with periodically varying refractive index; the modulation depth of refractive index and the grating period are always constant. When a beam of wideband spectrum light λ goes through the FBG structure acting as selective narrowband reflector, the monochromatic light λ_B will be reflected by it. The central wavelength λ_B of the reflected light is related to period variation Λ of the fiber core reflective index and the effective refractive index n_{eff} of FBG. Changes of temperature and strain will lead to period as well as reflective index changes of FBG, thereby causing reflection spectrum and transmission spectrum changes of FBG, and through the examination of which the corresponding temperature and strain information can be obtained. This is the fundamentals of using FBG for temperature and strain measurement.

According to coupled-mode theory, uniform FBG can couple a guided mode to the other guided mode transmitted along the opposite direction forming narrowband reflection, and the reflection-peak wavelength (FBG wavelength) λ_B is

$$\lambda_B = 2n_{eff}\Lambda \quad \mathbf{(1)}$$

From equation (1), we yield

$$\frac{\Delta\lambda_B}{\lambda_B} = \frac{\Delta\Lambda}{\Lambda} + \frac{\Delta n_{eff}}{n_{eff}} \quad \mathbf{(2)}$$

From equation (2), we know the wavelength of FBG varies with the changes of n_{eff} and Λ, and therefore is extremely sensitive to external force as well as thermal load. Strain causes Bragg wavelength changes due to period changes and the Elasto-optical effect of FBG, while temperature changes Bragg wavelength due to thermal expansion and thermo-optic effect of FBG.

Suppose that the external temperature is constant; the optical fiber produces axial strain $\Delta\varepsilon$ under axial (z-direction) stress; the strains in the other two directions perpendicular to the fiber axis are $-\mu\Delta\varepsilon$ (μ is the Poisson's ratio); the shear stress is zero; therefore the period changes of FBG is

$$\Delta\Lambda = \Delta\varepsilon \bullet \Lambda \tag{3}$$

The corresponding changes of effective refractive index of the fiber core is

$$\Delta n_{eff} = \frac{{n_{eff}}^3 \Delta\varepsilon}{2}[\mu p_{11} - (1-\mu) p_{12}] \tag{4}$$

Form the above equation, we yield,

$$\frac{\Delta\lambda_B}{\lambda_B} = \frac{\Delta\Lambda}{\Lambda} + \frac{\Delta n_{eff}}{n_{eff}} = (1 - p_e)\Delta\varepsilon \tag{5}$$

And it can be simplified as

$$\Delta\lambda_B = k_e \Delta\varepsilon \tag{6}$$

Where k_e is the sensitivity coefficient of strain causing wavelength variation, and k_e =1.2pm holds in mono-mode optical fiber.

From equation (6), we know a good linear relationship exists between FBG wavelength drift and strain. Meanwhile, light wavelength is the smallest unit of measurement in FBG strain sensor. Since the resolution for wavelength drift detection reaches pm order of magnitude at present, strain measurement with FBG sensor can be accurate down to one micro-strain. The strain value of the FBG sensor is calculated based on wavelength offset value to indicate the stress and strain of the monitored segment, thereby obtaining the deformation, stress and strain values of the structure.

BOTDR sensing technology applicable for casting strain monitoring

In BOTDR optical fiber sensor, a light-wave frequency shift exists between scattered light and pump light, and it is called BOTDR frequency shift. BOTDR frequency shift in BOTDA scattering spectrum is represented as the following equation:

$$v_B = 2nv_\alpha / \lambda_0 \tag{7}$$

Where v_B is BOTDR frequency shift, n is reflective index of the fiber core, v_α is phonon velocity, λ_0 is incident light wavelength in a vacuum.

BOTDR frequency shift is related to sound velocity in the fiber optic materials. Because the photoelasticity and thermo-optic property of the material will influence sound velocity in it, both strain and temperature changes in the fiber will cause variations of BOTDR frequency shift. In the following equation, E is Young's modulus; κ is Poisson's ratio; ρ is density.

Sound velocity in the fiber is represented as

$$v_\alpha = \sqrt{\frac{(1-\kappa)E}{(1+\kappa)(1-2\kappa)\rho}} \tag{8}$$

Therefore, substituting (7) into (8), we have

$$v_B = \frac{2n}{\lambda_0}\sqrt{\frac{(1-\kappa)E}{(1+\kappa)(1-2\kappa)\rho}} \tag{9}$$

Because n, E, κ, ρ are functions of temperature and strain, and BOTDR frequency shift varies with the changes of temperature and strain of the sensing fiber making it possible for optic fiber measurement of temperature and strain.

The reflective index, the Young's modulus, the Poisson ratio and density of the optical fiber can all be expressed as the functions of temperature T and stain ε, which are referred to as $n(T,\varepsilon)$, $E(T,\varepsilon)$, $\kappa(T,\varepsilon)$ and $\rho(T,\varepsilon)$, respectively. With $\theta=\pi$, substituting them into equation (9), we have

$$\nu_B(T,\varepsilon)=\frac{2\nu_0}{C}n(T,\varepsilon)\sqrt{\frac{(1-\kappa(T,\varepsilon))E(T,\varepsilon)}{(1+\kappa(T,\varepsilon))(1-2\kappa(T,\varepsilon))\rho(T,\varepsilon)}} \quad \textbf{(10)}$$

From equation (10), we know BOTDR frequency shift becomes a function of temperature and strain. The properties of the fiber optic material are apparently related to BOTDR frequency shift, which is sensitive to both temperature and strain. Supposing the external temperature being constant indoor temperature (T =20°C), we have

$$\nu_B(T_0,\varepsilon)=\frac{2\nu_0}{C}n(T_0,\varepsilon)\sqrt{\frac{(1-\kappa(T_0,\varepsilon))E(T_0,\varepsilon)}{(1+\kappa(T_0,\varepsilon))(1-2\kappa(T_0,\varepsilon))\rho(T_0,\varepsilon)}} \quad \textbf{(11)}$$

Since optic fiber is a kind of brittle material, its tensile strain ε is small. So we can make Taylor expansion of all ε related terms on the right-hand side of the equation at the point ε =0, and let them be accurate to a monomial of ε,

$$\nu_B(\varepsilon)=\nu_B(0)[1+(\Delta n+\Delta E+\Delta\kappa+\Delta\rho)\varepsilon] \quad \textbf{(12)}$$

Equation (12) can be simplified as

$$\nu_B(\varepsilon)=\nu_B(0)(1+\alpha\varepsilon) \quad \textbf{(13)}$$

Where $\nu_B(\varepsilon)$ is frequency shift with strain ε, $\nu_B(0)$ is frequency shift without strain, α is fiber attenuation coefficient.

Equation (13) can be further rewritten as

$$\Delta\nu_B=\alpha\nu_B(0)\Delta\varepsilon=k_e\Delta\varepsilon \quad \textbf{(14)}$$

From equation (14), we know that with the temperature being constant, BOTDR frequency shift variation is in a good linear relationship with strain. The main task of BOTDR sensor is to accurately measure the BOTDR frequency shift variation, based on which the strain of the senor can be calculated, thereby obtaining the stress and strain of monitored part of the structure. Then values of deformation, stress and strain of the structure can be obtained.

Online monitoring technology for casting strain and outside pressure

The principle of outside casting deformation monitoring is originated from the fact that frequency shift of the wavelength changes with the occurrence of axial strain in BOTOR optical fiber. The casting outside pressure monitoring mechanism is similar with BOTDR monitoring technology, which is based on the principle that wavelength changes with the occurrence of axial strain in FBG. To better monitor casting deformation and casting outside pressure, BODTR fiber and FBG are wrapped together in a FRP tendon.

When deformation of down-hole casting occurs, there will be coordination deformation of the BOTDR fiber optic sensor that is cemented together with the casting; then the fiber strain will cause frequency shift variation of BOTDR scattered light compared with pump light, which is often referred to as BOTDR frequency shift. In BOTDR scattering along the fiber, BOTDR frequency shift is represented by the equation (11).

Because n, αv are functions of temperature and strain, with the temperature being constant indoor temperature (T0=20°C), the above equation can be further simplified as

$$\Delta\nu_B=\alpha\nu_B(0)\Delta\varepsilon=k_e\Delta\varepsilon \quad \textbf{(15)}$$

From equation (15), we know that with the temperature being constant, BOTDR frequency shift is in a good linear relationship with the strain. The casting deformation data can be obtained based on the BPTDR frequency shift variation accurately measured by the BOTDR fiber optic sensor.

Pressure outside forced upon the casting will accelerate its breakdown. So outside pressure monitoring not only can help to determinate the limit of water injection, but also plays a certain role in casting damage pre-warning. Based on four-point bending in mechanics of materials, the down-hole casting outside pressure is transmitted via a high sensitivity sensor, in which the FBG packaged FRP tendon is sealed with clamped-clamped beam in the shell of pressure sensitive element, and in the center there are two points of pressure contacts which transmits outside pressure to FRP tendon. With the FBG between the pressure contacts free from acting force of other directions, the outside pressure can be converted completely into axial strain of FBG. The mechanics principles of four-point bending is as follows; and with a clamped-clamped beam as well as a single point under pressure, the maximum deflection is

$$f=-\frac{pb(3l^2-4b^2)}{48EI} \tag{16}$$

Where p is the single-point pressure; b is the distance between the force bearing point and the nearest fulcrum; l is the length of the beam; E is elasticity modulus of FRP tendon; I is section modulus. The four-point bending in the above equation can be superposed on three-point bending, thereby yielding the equation of FRP tendon deflection under compressing pressure contact

$$f=-\frac{pb(3l^2-4b^2)}{24EI} \tag{17}$$

Based on the deflection from equation (18), the axial strain of FRG can be determined, as shown below:

$$\varepsilon=\frac{2(\sqrt{b^2+f^2}-b}{l-2b} \tag{18}$$

Where ε is axial strain of FBG; $\sqrt{b^2+f^2}$ is fiber elongation with the beam under single point force; b is the distance between force bearing point and the fixed fulcrum; $l-2b$ is the length of FBG.

FIELD EXPERIMENT OF OIL WELL CASTING DEFORMATION MONITORING BASED ON FIBER OPTIC SENSOR

The Establishment of Fiber Optic Sensor Network for Casting Deformation Monitoring

The depth of the II section marker bed of the 2-88 well is 1100.5m; the depth of the FBG sensor running is 1174.2; the depth of locating slot is 1175.1m; and the BOTDR sensor end is deployed in the depth of 1172.7m. Place FBG sensor at the designated location of the casting the day before casting running; with the casting running into the purposed bed, fix the end of the senor at the designated place of the casting. Via its own transmission cable, the sensor sends optical signals back to the surface going through FBG interrogator and the BOTDR optical time domain reflectometer. The transmission cable of FBG sensor and BOTDR sensor will be wielded outside the wellhead and protected by the terminal box for the convenience of follow-up monitoring.

Casting Strain Data Collection and Analysis

Real-time data are collected in the process of senor running into the well. Part of the casting axial strain data obtained from the sensor is shown in TABLE 1.

TABLE 1 : Casting axial strain aata collected in well cementing process

Depth	88-1	88-2	88-3	88-4	88-5
800	858.362	464.132	633.675	475.213	468.284
801	869.532	452.311	627.432	459.981	455.381
802	876.587	443.546	618.491	457.785	454.512
803	867.972	436.342	605.213	468.583	457.872
804	873.104	431.423	588.701	471.109	455.439
805	865.478	429.213	558.786	453.903	454.893

Several days later after the well completion, recollect strain data from the sensor; and part of the data from the interrogator are shown in TABLE 2.

TABLE 2 : Casting Axial Strain Data in Production Phase

Depth	88-1	88-2	88-3	88-4	88-5
800	857.762	668.950	385.911	464.712	425.638
801	852.332	673.137	383.323	447.753	408.879
802	838.527	673.538	380.968	453.012	409.771
803	854.586	669.983	379.177	468.480	390.433
804	846.622	662.462	378.271	478.793	377.542
805	844.778	651.211	378.550	439.126	383.798

Data in the leftmost column are the distances between the monitored points and the earth surface; data in the second column are the strain initial values at each BOTDR point. Data in the rest columns are strain values monitored at intervals at each point after the well completion, and the numerical difference between the strain value in these columns and the corresponding one in the second column is the actual strain value at that point. From the table, we know strain is small at every point and varies little over time, indicating down-hole casting is under stable stress condition.

Since the BOTDR sensors assume the shapes of smart tendons intertwined together before running down the well, the real time data cannot be obtained in the down running process. After the well completion, BOTDR sensor connectors outside of the well is linked to the optical time domain reflectometer, thereby monitoring the axial strain of the whole casting string. In production phase, the casting and smart tendon are consolidated together with cement, and there will be down-hole coordination deformation of the two; the axial tension decreases with the consolidation of cement.

CONCLUSIONS

In this paper, the stress and strain sensing principles of fiber optic sensor are analyzed from a theoretical point of view. It is concluded that:

(1) The analysis shows BOTDR frequency shift is in a good linear relationship with strain of the BOTDR sensor. It theoretically verifies the feasibility of the application of BOTDR senor in casting strain monitoring, and based on which the security pre-warning of casting deformation can be achieved.

(2) Based on the actual loading of the casting and the two-force members bending principles in mechanics of materials, outside pressure effected on the casting is converted to FBG axial tensile strain verifying the practicability of monitoring casting outside pressure with FBG strain sensor.

REFERENCES

[1] Yang Zhao; Journal of Engineering Science and Technology Review, **7(1)**, 45-51 **(2014)**.
[2] Yang Zhao; International Journal of Control and Automation, **7(7)**, 371-382 **(2014)**.