Optical fiber pressure sensor based on F-P cavity in the oil and gas well

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Abstract. To meet the need of the measurement in high temperature and high pressure in oil and gas well, an optical fiber pressure sensor based on extrinsic Fabry Perot (F-P) cavity is developed. The sensor is fabricated by hydrogen and oxygen flame thermal bonding in high temperature technique, and the change of the senor’s cavity length is compensated in temperature changing with cascading fiber bragg grating, and the sensor has characteristics of large dynamic range, high resolution, high repeatability, long term operation stability and high temperature resistance. The pressure measuring range is 0~69MPa, the repeatability is 0.01% F-S, the hysteresis is less than 0.01% F-S, the long term stability is less than 0.02MPa/y, and the sensor can satisfy the requirement of the measurement in the oil and gas well. Practical application proved that the relative deviation of the pressure measurement value is less than 0.01% compared with the traditional electronic pressure sensor.

1. Introduction

In the process of oil and gas exploitation, it is one of the important measures to understand the physical condition of oil and gas wells, optimize the oil recovery technology scheme and improve the oil and gas recovery and production [1, 2]. But the oil and gas environment is extremely poor underground, the most is high temperature, high pressure and strong corrosion, etc. The traditional electronic sensors cannot run in this harsh environment stably in long-term. Fiber optic sensor with its small size, high precision, high temperature resistance, corrosion resistance and other advantages [3], has a wide range of applications in the mining process of the oil and gas field.

In recent years, the use of optical fiber sensors to monitor the pressure parameters in the oil and gas well are mainly based on fiber bragg gratings and optical extrinsic Fabry Perot (F-P) cavity [4-6], because the temperature and pressure cross-sensitivity of fiber bragg grating is very large, it cannot operate reliably in oil and gas well; And for the fiber F-P cavity, in current the fiber and quartz capillary is adhesived by epoxy glue, because the expansion coefficient of different material in the bonding point is different, which can lead to thermal mismatch phenomenon, resulting in cavity length the occurrence of temperature crosstalk of the cavity length, and because the epoxy glue can creep at high temperatures[7], the accuracy, repeatability and long-term stability of the sensors are affected, and the sensors cannot operate reliably in the oil and gas wells.
This paper has developed a kind of fiber-optic F-P cavity pressure sensor which can be applied to the harsh environment in the oil and gas wells. The sensor has characteristics of large dynamic range, high resolution, high repeatability, long term operation stability and high temperature resistance, and it has been successfully applied and achieved good results.

2. Design of fiber optic F-P cavity pressure sensor

2.1 Working principle of the sensor
Fiber-optic F-P cavity pressure sensor is based on Fabry-Perot (F-P) interferometer, and its structural diagram is shown in Figure 1, mainly consist of the incident fiber, the reflective fiber and the quartz capillary in total of three parts, two parallel end faces of the incident fiber and the reflective fiber form an optical fiber FP interferometer (also referred to as a F-P cavity) inside the capillary. When a bunch of monochromatic light (wavelength $\lambda$, intensity $I_0$) transmit the incident fiber to the fiber F-P cavity, the incident beam will be reflected several times in the two parallel ends of the fiber, and it will occur interference effect when the beam was reflected several times\(^8\), the spectral information was shown in Figure 2.

![Figure 1. The structure diagram of optical fiber F-P cavity.](image1)

When the static pressure is applied to the F-P cavity structure, the quartz capillary is crushed to produce deformation, which causes the change of the length of the F-P cavity. The change of the $d$ will cause the reflection spectrum to change, and the spectral signal is measured by the signal demodulation system, which calculated the length $d$ changes of F-P cavity, and we can get the pressure change information.

2.2 The design of fibre optic F-P cavity pressure sensor
In this paper, the sensor is fabricated by hydrogen and oxygen flame thermal bonding in high temperature, the thermal expansion coefficient of each material is basically the same at the connection point, which avoids the occurrence of thermal mismatch at the connection point, completely solves the problem of temperature crosstalk at the connection point. At the same time, the connection point
material is quartz, which solves the high temperature creep problem which exists in the gelatinized package, and greatly improves the precision, repeatability and long term stability of the sensor.

![Figure 3. The structure diagram of temperature compensation](image)

In this paper, a fiber grating is connected with fiber F-P cavity in series, which is shown in Figure 3, is used to monitor the temperature and compensate the influence of temperature change on the cavity length of the fiber optic F-P cavity, and greatly reduces the temperature and pressure cross sensitivity of the fiber optic F-P cavity pressure sensor.

As shown in Figure 1, the inner diameter of the quartz capillary which constitute the F-P cavity is \( r_i \), the outer diameter is \( r_o \), and the sensor cavity length change \( \Delta d \) caused by the external application of the pressure \( P \) is \([9]\):

\[
\Delta d = \frac{L_g r_0^2}{E (r_o^2 - r_i^2) (1 - 2\mu)} \cdot P
\]

In the formula, \( \mu \) is the Poisson's ratio of quartz glass, \( E \) is the Young's modulus, and the change of the external pressure can be measured by measuring the cavity length. In addition, it can be seen from the above formula we can adjust the pressure sensor measurement sensitivity and dynamic range within a certain range by adjusting the capillary diameter \( r_i \), outer diameter \( r_o \) and gauge \( L_g \) of the three geometric parameters.

3. The performance test of the fibre optic F-P cavity pressure sensor

The performance test system of fiber optic F-P cavity pressure sensor which is designed in this paper is shown in Figure 4, mainly including pressure gauges, thermostats, pressure pipes, pressure devices, demodulators, and computers and so on. We use the GE 3100 piston pressure gauge of United States which can provide high precision and stable pressure, whose range is 0 ~ 110MPa and the accuracy is one ten thousandth. We use the FM841-3 oven of Wujiang fei ma company whose temperature range is room temperature ~ 250 ℃ and the accuracy is ± 2 ℃. We use the high-pressure pipe of Shanghai Dayton Electrical and Mechanical Technology Co., Ltd. The pressure device is designed by ourselves whose maximum pressure is 150MPa and which is use to place the sensors.
3.1 Test of the linearity
For the quartz material: $E = 74\text{GPa}$, $\mu = 0.17$, and $L_{eq}$, $r_1$ and $r_o$ whose change is very small in the monitoring process which can be considered constant, so from the formula (1) we can see that the change of the cavity length $\Delta d$ is proportional to the pressure $P$ applied, and we can obtain the relationship between the cavity length $d$ and the pressure $P$ by calibrating the cavity length of the sensor.

During the test, the sensor was pressurized by positive stroke (from 0 MPa to 62 MPa) or reverse stroke (from 62 MPa to 0 MPa), and the F-P cavity length was recorded and then was linear fitted. The figure show that the linearity of the test of the fiber optic F-P cavity pressure sensor, for linear fit degree $R^2 > 0.999999$, the relationship between cavity length and pressure is $y = -216.000000x + 122327.000000$, the sensitivity is 216nm/MPa, and the resolution is greater than 0.005MPa.
3.2 Test of the repeatability

Repeatability is defined as the inconsistency (volatility) of the resulting characteristic curve which is got by the continuously repeated measurements under the same operating conditions within the full range of input within the forward or reverse stroke.

![Figure 6](image)

**Figure 6.** The repeatability of the optical fiber sensor based on F-P cavity

Figure 6 shows the repeatability test results for the fiber optic F-P cavity sensor. Keep the temperature constant in the process of testing and calibrate it three times from 0 MPa to 62 MPa and in reverse stroke (from 62 MPa to 0 MPa) to measure its repeatability. The results show that the maximum deviation of F-P cavity length is 1nm and the repeatability is less than 0.01% F.S (Full scale) in three measurements, and the repeatability is very good.

3.3 Test of the hysteresis

The hysteresis is defined as the degree of inconsistency between the forward and reverse travel outputs when the sensor is tested over the full range under the same measurement conditions.

![Figure 7](image)

**Figure 7.** The hysteresis of the optical fiber sensor based on F-P cavity
Figure 7 shows the hysteresis test results for the fiber optic F-P cavity sensor. Keep the temperature constant of 100 \(^\circ\)C in the process of testing. Do the step-up and step-down pressure test whose forward stroke is from 0MPa to 62MPa and reverse stroke is from 62MPa to 0MPa. The results show that the hysteresis is very small and the maximum deviation of F-P cavity length is 1.2nm and the hysteresis is less than 0.01% F.S (Full scale).

3.4 Test of the long-term stability
The long-term stability is defined as the ability of the sensor to maintain its performance parameters over a long period of time. In this paper, the length of the fiber optic F-P cavity is 115um ~ 125um. Place the fiber optic F-P cavity in the test system, keep the pressure constant of 21MPa and the temperature constant of 100 \(^\circ\)C, and then observe the long-term stability of the sensor, and the test results is shown in Figure 8.

![Figure 8. The long term stability of the optical fiber sensor based on F-P cavity](image)

Figure 8 show that the change of the cavity length of the fiber optic F-P cavity pressure sensor in this paper is only 4nm and about 0.02MPa in 12 months, and the long-term stability is very good under high temperature and high pressure.

4. Application test
In order to test the performance of fiber-optic F-P cavity pressure sensor under the condition of actual field conditions, a test experiment was carried out in a test well of CNOOC Shanghai Branch, and the monitoring date was compared with the synchronous data obtained with the more mature electronic pressure sensor. The depth of the test well is 2000 meters and the bottomhole temperature is about 75 \(^\circ\)C. The fiber F-P chamber pressure sensor and the electronic pressure sensor are simultaneously placed into the bottom of the well and the well is continuously monitored for about 42 days.

![Figure 9. Optical fiber pressure sensor based on F-P cavity prepared to installed in the well](image)
Figure 10. Test results of the optical fiber pressure sensor and electronic pressure sensor

Figure 10 shows the temperature and pressure monitoring results of the electronic pressure sensor and the fiber pressure sensor on the bottom of the well. The results show that the bottomhole pressure value monitored by the fiber F-P cavity pressure sensor is 18.45MPa during the 42-day monitoring process, the pressure value monitored by electronic pressure sensor is 18.67MPa, the deviation is about 0.01%, the temperature deviation does not exceed 1.0 °C, the measurement accuracy is high; and the wellhead operation causes the pressure to change three times, which can be measured by the fiber optic F-P cavity pressure sensor.

5. Conclusion
A kind of pressure sensor based on fiber FP cavity was developed for the harsh environment of high temperature, high pressure and corrosive of oil and gas wells. The sensor is fabricated by hydrogen and oxygen flame thermal bonding in high temperature technique, and the change of the sensor’s cavity length is compensated in temperature changing with cascading fiber bragg grating. The designed sensor’s pressure range is 0 ~ 69MPa, resolution is greater than 0.005MPa, linear fit is greater than 0.999999, repeatability is 0.01% FS, hysteresis is less than 0.01% FS, the fluctuation of the cavity length is within 4nm (pressure is less than 0.02MPa); and it showed a good stability in 100 °C and 21MPa environment. In the field application, it can accurately measure the pressure in the 2000m deep well. Compared with the mature electronic pressure sensor, the monitoring pressure deviation is about 0.01% and the temperature deviation is less than 1°C.

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