Pipeline Leakage Test Based on FBG Pressure Sensor

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Abstract. Because of the problem of oil and gas pipeline leakage, a pipeline leakage detection platform based on FBG pressure sensor has been build, which experiments on measurement of negative pressure wave and localization of pipeline leak. And this platform analysis the detection model, as well as denoised and singularly solved to the pressure signal which have been measured through wavelet transform motion. The test results show that the average error of leakage location is 14.17%. This proves that FBG pressure sensor can be fully used in the field of pipeline leak detection.

1. Introduction

With the rapid development of economy, the demand for oil and gas is experiencing growth in our country, which has greatly facilitated the development of the pipeline transportation industry. However, with the increase of running time of pipeline, these result to construction defects, erosion corrosion and human destruction, pipeline leakage accidents occur frequently [1]. The leakage of transportation medium as pipeline for oil and gas not only results in the waste of resources, environmental pollution, but also may even threaten the lives and property of surrounding residents [2]. Therefore, it is significant for long-term and effective real-time monitoring of oil and gas pipelines.

At present, pipeline leak detection methods are divided into two broad categories: hardware-based method and software-based method [3]. The hardware-based method detect pipeline leakage and positioning by using temperature sensors, ultrasonic sensors, carbon and oxygen detection and other detections; software-based detection method real-time collects pipeline media flow, pressure, temperature, velocity and other pipeline dynamic model parameters, then leak detection and positioning achieve by calculation [4]. These methods are inefficient due to long term real-time monitoring, large cost, slow response, poor anti-interference ability and low detection precision. and other issues. In recent years, FBG sensing technology has been developing rapidly in engineering monitoring [5, 6]. As a new sensing element, FBG not only has the advantages of small volume, good stability, corrosion resistance, anti-electromagnetic interference [7], high precision [8], no electricity [9], and also has the advantage of wavelength division multiplexing [10], it is very suitable for oil and gas pipeline monitoring.

Based on the FBG pressure sensing model and the negative pressure wave model, this paper designs and sets up the experimental model of pipeline leak detection. The FBG pressure sensor instead of the traditional electromagnetic sensors, which has played a good stability in the field of oil and gas pipe monitoring, corrosion-resistant, no electricity, intrinsically safe advantages. The experiment proves that FBG pressure sensor can be effectively applied to pipeline leak detection.
2. Pipeline leakage detection theory based on FBG pressure sensor

2.1. Negative pressure wave pipeline leak detection theory

When a leak occurs in the pipe, the fluid in the leak point is rapidly lost and the pressure drops. The fluid on both sides of the leak point is replenished to the leak point due to the pressure difference. This process is transmitted upstream and downstream to the leak point, which is equivalent to the negative pressure wave propagating at a certain speed at the leak point [11]. The pressure wave is measured with two FBG pressure sensors mounted on the pipe and the time difference required for the pressure wave to reach the sensor is used to determine the position of the leak. Figure 1 illustrates how the method works. As shown in the figure below, the negative pressure wave velocity is \( v \). The velocity of fluid in the pipeline is \( \mu \), and the distance between the pressure gauge 2 and the pressure gauge 1 is \( L \). The distance between the pressure gauge 1 and the leak point 1 is \( L_1 \). The distance between the pressure gauge 2 and the leakage point 1 is \( L_2 \).

\[
\text{Figure 1. Pipeline leakage monitoring principle diagram.}
\]

When a leak occurs at leak point 1, the time of the negative pressure wave reaches pressure gauge 1 and pressure gauge 2 from leak point 1 respectively are \( t_{11} \) and \( t_{12} \). Order \( \Delta t_1 = t_{11} - t_{12} \), then:

\[
\Delta t_1 = \frac{L_1 - L}{v - \mu} - \frac{L_1 - L_2}{v + \mu}
\]

After the transformation formula can be obtained:

\[
L_1 = \frac{1}{2v} \left[ \frac{L(v - \mu) + \Delta t_1 (v^2 - \mu^2)}{v^2 - \mu^2} \right]
\]

Where: this experiment pipe liquid does not flow, the value of \( \mu \) is 0 m/s. So the above equation can be simplified as:

\[
L_1 = \frac{L + \Delta t_1 \cdot v}{2}
\]

It is known from formula (3) that if the position of the leak point 1 is required, the value of \( \Delta t_1 \) and \( v \) must be known at the same time.

In the experiment, the value of \( v \) obtained by the actual measurement. The specific method is to make leakage point 2 leak, the time of the negative pressure wave reaches pressure gauge 1 and pressure gauge 2 from leak point 2 respectively are \( t_{21} \) and \( t_{22} \). Order \( \Delta t_2 = t_{21} - t_{22} \), then:

\[
v = \frac{L}{\Delta t_2} - \mu = \frac{L}{\Delta t_2}
\]

Substitute formula (4) into formula (3):

\[
L_1 = \frac{L (\Delta t_1 + \Delta t_2)}{2 \Delta t_2}
\]
2.2. FBG sensor perception principle

Fiber grating sensors are a new class of passive components that reflect light of a particular wavelength when broad-band incident light passes through the fiber grating. The wavelength of reflection is sensitive to strain and temperature. In the actual measurement, the influence of temperature on the wavelength shift must be eliminated and the separate strain should be obtained.

Figure 2. FBG pressure sensor structure diagram.

The structure of the FBG pressure sensor used in this paper is shown in Figure 2. The sensor is mainly composed of case, flat diaphragm, force transmission rod, L-shaped cantilever, capillary tube and two FBG. In the actual measurement, the diaphragm deflects under the pressure and transmits it to the L-shaped cantilever. The L-shaped cantilever drives two FBGs to expand and contract, resulting in the change of the center wavelength of the FBGs. The structure of the pressure sensor wavelength drift and pressure relationship:

\[ \Delta \lambda_{2} - \Delta \lambda_{1} = \frac{K_{T2} - K_{T1}}{K_{T}} \left( \Delta \lambda_{2} + \Delta \lambda_{1} \right) = K_{P}P \]  

(6)

Where \( \Delta \lambda_{1} \) and \( \Delta \lambda_{2} \) are the FBG1 and FBG2 wavelength drift respectively. \( K_{T1}, K_{T2} \) and \( K_{T} \) are FBG1, FBG2, and sensor temperature sensitivity respectively. \( K_{P} \) is sensor pressure sensitivity.

After selecting the material and size of the pressure sensor, \( K_{P}, K_{T}, K_{T1}, K_{T2} \) are constant, two FBG center wavelength shifts can be linearly correlated with the measured pressure, thus the influence of temperature on the measurement results can be eliminated.

The sensor output wavelength offset signal is converted to pressure signals by formula (6), and using wavelet transform to denoise and singularity of the pressure signal, then finding the leak location by formula (5).

3. Text Pipeline leak detection test based on FBG pressure sensor

In order to study the feasibility of FBG pressure sensor used in the field of oil pipeline leakage detection, a static oil pipeline leakage model was built. The material of the pipe model was selected as 20 steel. The length of the test straight pipe is 3.92 m and the pipe diameter is 257 mm. Select water as the medium, the system design maximum pressure of 2 MPa.

Figure 3. Experiment system schematic.
Figure 3 is the experimental system schematic. Test system consists of manual pressure test pump, pipeline, pressure gauge, manual ball valve, mechanical pressure gauge, pressure gauge (FBG pressure sensor), demodulator, host computer. The manual pressure test pump is used to pressurize the piping system. The FBG pressure sensors are installed at both ends of the pipeline. Leak point 1 is used for leak test. Leak point 2 is used to measure the negative pressure wave speed in the test. The distance between the pressure gauge 1 and the leakage point 1 is 1050 mm. And the distance between the pressure gauge 2 and the leakage point 1 is 2000 mm. The two FBG pressure sensors are connected end to end and connected to a fiber grating demodulator. The demodulator transmits the demodulated wavelength values to the host computer. Table 1 is FBG pressure sensor sensitivity parameters.

| Numbering | \( K_p \) (pm / MPa) | \( K_T \) (pm / °C) | \( K_T1 \) (pm / °C) | \( K_T2 \) (pm / °C) |
|-----------|----------------------|----------------------|----------------------|----------------------|
| pressure gauge 1 | 1185.621 | 53.920 | 36.189 | 17.667 |
| pressure gauge 2 | 1230.476 | 53.384 | 35.896 | 17.408 |

4. Experiment and data analysis

The purpose of the experiment is to verify the feasibility of FBG pressure sensor in the field of oil pipeline leak detection. For each test, pipe system pressure is loaded as 1 Map and manual ball valve is selected as 50%. At the beginning of the experiment, the leakage point 2 is controlled to be leaked. When the pressure indication is 0.4 Map, the manual ball valve is closed, and then the initial pressure is restored. Then the leakage point 1 is controlled to leak. When the pressure indication is 0.4 Map, the manual ball valve is closed. The whole process is one cycle. The test repeated a total of three cycles. During the whole test, setting the demodulator's acquisition rate to 8000 Hz and recording the data in real time.

![Figure 4](image-url)

**Figure 4.** Pressure gauge 2 wavelength drift curve.

Figure 4 is the pressure gauge 2 wavelength drift curve for the first cycle when leakage point 2 leak. It can be seen that the wavelengths of FBG1 and FBG2 increase and decrease respectively. The wavelength tends to a constant value after the leakage stops, and there is a significant inflection point at the beginning and end of the leakage curve, indicating that the response of the pressure gauge good degree.

Figure 5 is the curve of the pressure varying with time by using formula (6) to calculate the wavelength drift value of the pressure gauge during leak point 2 leaking of the first cycle. It can be seen, after the leak, the pressure drops, and there is a clear inflection point, the pressure tends to be a constant value after the leak. Comparing the two pressure gauge curves ,it is found that the change trend is consistent, but the inflection point of the pressure gauge 1 curve lags behind the pressure gauge 2 inflection point, which is consistent with the negative pressure wave theory.
During the actual test, the pressure signal will be affected by the noise. As shown in the upper right corner of Figure 5, the signal glitch is serious. In this paper, wavelet transform is used to denoise the signal, and the sym8 wavelet base is selected to denoise the pressure signal. The result is shown in Figure 6. It can be seen that the burr of the pressure signal is significantly reduced compared to Figure 5. Figure 7 is shown that using wavelet transform to calculate the singularity of the pressure signal of pressure gauge 2 in Figure 6, the original signal is decomposed by wavelet and then the signal is reconstructed at a given level. Among all the reconstructed signals, the reconstructed signal at level d3 can be compared good response to the original signal mutation. From the figure you can find the point where the inflection point stops to leak, and the abscissa of the inflection point begins to leak is $t_{22} = \frac{45140}{8000} = 5.6425$ s.
The data which obtained according to the above steps to calculate the final results is shown in Table 2. The average positioning error available from the table is 14.17%. The positioning error is much larger compared to the mature system at this stage, the main reasons are: the test pipe is too short, the demodulator acquisition rate is limited.

Table 2. Experimental results obtained by wavelet transform.

| cycle | \( t_{21} \) (s) | \( t_{22} \) (s) | \( \Delta t \) (s) | \( t_{11} \) (s) | \( t_{12} \) (s) | \( \Delta t \) (s) | \( L_r \) (mm) | error |
|-------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-------|
| 1     | 5.645375        | 5.6425          | 0.002875        | 5.73425         | 4.733           | -0.00125        | 862.0           | 17.9% |
| 2     | 5.17225         | 5.1695          | 0.00275         | 4.195125        | 4.19625         | -0.001125       | 901.1           | 14.2% |
| 3     | 6.94925         | 6.946125        | 0.003125        | 5.945125        | 5.946125        | -0.001          | 1159            | 10.4% |

5. Conclusion

In this paper, the feasibility of FBG pressure sensor in the field of oil pipeline leak detection is studied. First of all, the principle of pipeline leak detection based on FBG pressure sensor is revealed through theory. Second, set up a static oil pipeline leakage model. Finally, the oil pipeline leak test was carried out. The test results show that the average value of the model leak location error is 14.17%. The test proves that FBG pressure sensor can be effectively applied to pipeline leak detection. In the farther research, optimizing the test system to reduce the leakage positioning error should be noticed.

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References

[1] XIA H B, ZHANG L B, WANG C H. Development actualities of pipeline leak-detection technologies at home and abroad[J]. Oil and Gas Storage and Transportation,2001,20(1):1-5.
[2] ZHOU Y, QU Z. Study on the distributed optical fiber sensing technology for pipeline leakage protection[J]. Journal of Optoelectronics Laser,2005,16(8):935-938.
[3] ZHANG J. Designing a cost-effective and reliable pipeline leak-detection system. Pipe Pipelines Int, Jan-Feb:20-25[J]. Pipes & Pipelines International,1997,42(1):20-26.
[4] LI W, ZHU Y. Analysis on leakage detection and location technologies for long transmission pipeline[J].Natural Gas Industry,2005,25(6):105-109.
[5] JIANG D S, HE W. Review of applications for fiber Bragg grating sensor [J]. Journal of Optoelectronics-Laser,2002,13(4):420-430.
[6] LIANG L, CAO S, FENG K,et al. Research of FBG sensor with temperature self-compensation based on lozenge structure[J]. Instrument Technique and Sensor,2017(12):1-3+24.
[7] ZHU P Y, LI Y J, SHEN H W,et al. Development of a “Wang” shaped temperature compensated FBG strain sensors[J]. Instrument Technique and Sensor,2017(08):15-18.
[8] LI H N, LI D S, SONG G B. Recent applications of fiber optic sensors to health monitoring in civil engineering[J]. Steel Construction,2008,26(11):1647-1657.
[9] HUANG Y H, GAO X R, DU L Q. Application of fiber bragg grating sensor in bridge defect detection and structural health monitoring[J].Railway Quality Control,2007,35(11):17-20.
[10] WANG Y B, LAN H J. Study of fiber bragg grating sensor system based on wavelength-division multiplexing / time-division multiplexing[J]. Acta Optica Sinica,2010,30(08):2196-2201.
[11] CHENG J M, ZHANG H G. Leakage principle and realization of negative pressure wave method in oil pipeline[J]. China Petroleum Machinery,2002(09):28-30+1.