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Design and performance of the FBG hoop-strain sensor for corrosion detection of pipeline

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ABSTRACT

Monitoring pipeline is one of the indispensable parts for the economical and safety operation, and circumferential strain is of significant in pipeline integrity monitoring. This paper presents a new methodology of pipe to monitor hoop strain using fiber Bragg grating (FBG) as the sensing element. A FBG hoop-strain sensor is proposed for transforming circumferential strain of pipe into an axial strain on fiber. In order to demonstrate the characteristic of FBG hoop-strain sensor, basic formula is deduced, numerical analysis is carried out by using SAP2000 experimental results are discussed and parametric study of the sensor is also conducted. The results show that the reflected Bragg wavelength shift has a linear relation with the thickness and pressure in pipe. Therefore, thickness variation of pipe induced by corrosion can be detected by this sensor.

KEYWORDS

FBG hoop-strain sensor, fiber Bragg grating, pipeline corrosion

1. INTRODUCTION

Pipeline corrosion is seen as the main reason causing leak and rupture. As evident, the pipeline rupture will cause not only product loss, but also serious environmental damage (Ren L 2013).

Pipeline monitoring is an important issue nowadays (Abdelmalek Bouazza 2008) (Wang Zou 2012). As corrosion is the main reason leading to leakage (R.C. Tennyson 2006), more and more experts are devoted to pipeline monitoring, trying to find a way to detect corrosion and protect pipeline from pipeline corrosion. Described below is a brief discussion on advantages and disadvantages of the existing monitoring methods. In the conventional method of pipeline monitoring, direct observation is the easiest one to be realized, but it had many disadvantages, like time-consuming, labor consuming, low resolution and long period. Detecting robot detection, which has been used in some

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areas, has advantages like, high precision and low error, but the disadvantages like, long period and high cost, are also unavoidable. Tracer detecting can't overcome the disadvantages like, high cost and no real-time monitoring, neither. There are many other methods to detect the leakage of pipeline, which based on hardware methods and software methods (Bernahard 2001) (Mendoza 1998) (X. J. Wang 2007) (A. L. H. Costa 2002). Considering the significant advantages of FBG (Hong-Nan Li 2009) (Ren Liang 2009) (Ren Liang 2006) such as easy to be integrated into structures, immunity to electromagnetic interference, and especially the excellent multiplexing capabilities, a new method is proposed which is based on FBG strain sensor. In this paper our initial work on the development of pipeline monitoring method based on FBG hoop-stain sensor is presented.

Nature Gas and oil pipeline corrosion have been occurred due to a variety of unexpected natural or man-made factors. In service environment, corrosion initiate on weakness area of the pipeline, such as stainless steel welt, then the thickness of the area decrease. In this article, FBG hoop-strain sensor is used to measure the hoop stain variation of the pipeline caused by corrosion. The performance of the FBG hoop-strain sensor is tested and the sensitivity of the sensor is discussed firstly. In the following part, corrosion simulation test was presented.

2. Principle of FBG hoop-strain sensor

2.1 The basic theory

There is a big pressure in the pipeline. With the increasing of pressure, the circle deformation will be extended. So the hoop strain of the pipeline changes accordingly. As shown in Eq. (1)

$$\varepsilon_y = \frac{\sigma_y - \upsilon\sigma_z}{E} \tag{1}$$

Where, εy is the pipeline hoop strain variation; υ is the pipeline Poisson's ratio; σy is the pipeline hoop stress; σz is the pipeline axial stress; E is pipeline elasticity modulus.

We assume the pipeline is infinitely long, therefore axial stress can be neglected, that is σz=0; we can get the relationship between the pipe wall thickness and pipeline hoop strain by substituting σ_y=PR/h and σ_z=0 into Eq. (1). That is Eq. (2)

$$\varepsilon_y = \frac{pR}{hE} \tag{2}$$

where, p is the pressure in the pipeline; R is the pipeline internal radius; h is the pipe wall thickness. From Eq. (2) we find that when the pressure in the pipeline changes, the pipeline hoop strain also changes proportionally. The pressure is in proportion to the hoop strain and the wall thickness of pipeline is in inverse proportion to the hoop strain. The FBG sensor which is wrapped around the pipeline is sensitive to strain. Fig. 1 and Fig. 2 are schematic diagram and physical diagram of FBG hoop-strain sensor. Based on this principle, the measured hoop strain can be used to estimate the wall thickness deduction caused by pipeline internal corrosion.

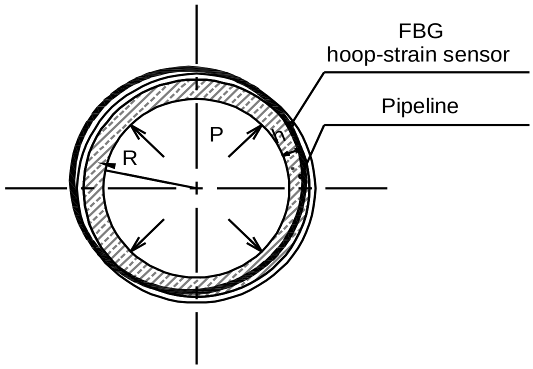

Fig. 1 Schematic diagram

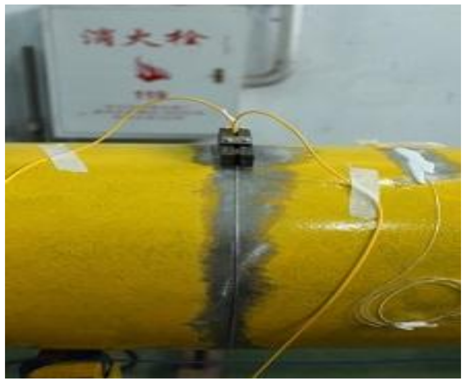

Fig. 2 Physical diagram

2.2 Case of local corrosion

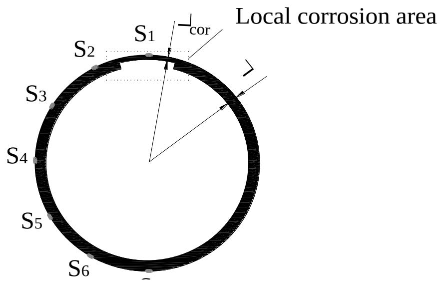

Fig. 3 Diagram of local corrosion and strain measuring point

In most cases of pipeline long-term service without being subjected to accidental damage, where the wall thickness deduction induced by gradual corrosion is circumferentially homogenous at the same pipe cross-section, any measuring point with strain sensor at the same section can be used to reflect the wall thickness variation. However, if a local corrosion happens or the pipeline is partially damaged, the single-point measurement functions ambiguously supposing that the sensor is located relatively far away from the corrosion area. Here an example of partial corrosion analysis based on finite element method is illustrated to explain the above mentioned phenomenon.

In this finite element pipeline model, the corrosion happens partially on the pipe internal wall, shown in Figure 2, where δ_{cor} denotes the reduced wall thickness caused by the local corrosion. Seven dummy single-point strain sensors are used to represent the circumferential strain variation respectively, in which S1 is the measure point exactly located at the corrosion part while S7 has the longest distance from the corrosion area.

It can be seen from Table 1 that the strain variation ratio η of S3~ S7 is rather small, which means the circumferential strain at these points is insensitive to local corrosion. Furthermore, in the actual pipeline monitoring, if strain sensors are installed at these insensitive points, the local corrosion may be undetected. On the other hand, it's also uneconomic to set quantity of strain sensors at same pipeline cross-section.

Table 1 The strain variation ratio η of S1~ S7

Circumferential strain (×10^-4)	S1	S3	S4	S5	S7
Intact(ε_{int})			1.96		
Local corrosion(ε_{cor})	3.63	1.98	1.90	1.94	1.98
Strain variation ratio(η)	0.85	0.01	0.03	0.01	0.01

Generally, the pipeline corrosion is considered to be a gradual altering process, for which the circumferential strain variation can be used to estimate the slow decreasing of pipeline wall thickness during long-term operating. However, the significance of circumferential strain measurement lies not only in the steady change monitoring. The dynamic circumferential strain response induced by some emergency events functions as an indicator of pressure sudden reduction.

For instance, when a leakage happens, a negative pressure wave (NPW) is always formed from the leaky point and spreads out along the pipeline in a definite velocity. Since that the inner pressure decreases when the NPW arrives, the circumferential strain ε will decrease, according to Eq. (2). Based on this principle, the dynamic signal of circumferential strain can be used to detect the NPW occurrence.

Taking into consideration of the above aspects, a circumferential strain measuring device is attempted to design, which must meet the following requirement. Firstly, the measured circumferential strain of this sensor can reflect the overall circumferential deformation on the same cross-section, in order to estimate the pipeline corrosion even local corrosion. Secondly, the sensor can monitor the dynamic response and the data acquisition system has an enough sampling rate. Thirdly, the sensor needs to be attached on the pipeline surface firmly and reliably to satisfy long-term monitoring.

2.3 The working principle of the FBG hoop-strain sensor

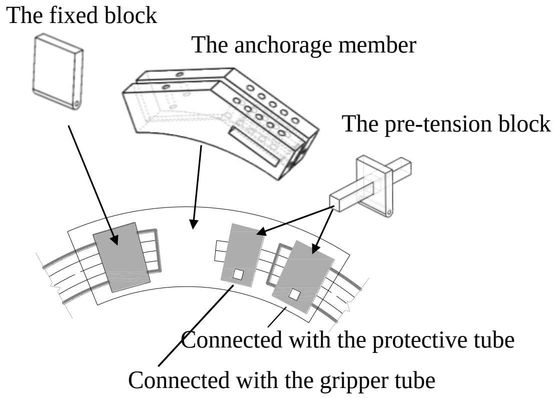

Fig. 4 Detailed diagram of the FBG hoop-strain sensor

As shown in Fig. 4, the anchorage member is adhered on the pipeline external surface by super glue. The fixed block bonded with the protective tube is installed into it, becoming a fixed end. Then the pre-tension block bonded with the protective tube by Epoxy resin is stretched along the pipeline circumference to make the protective tube seamlessly contact and firmly adhered onto the pipeline surface. It should be noted that the pre-tension block used in the above process can't be connected to the anchorage member, so the protective tube only functions as an "obit" for the inner fiber rather than bear the pipe circumferential deformation. Then the pre-tension block with the gripper tube is stretched as well, in turn tensioning the fiber along the protective tube to avoid the bending condition which will affect the final results. The advantage of this approach is that errors of strain measurement induced by the fiber deflection may be eliminated.

3. Experimental study on the FBG hoop-strain sensor

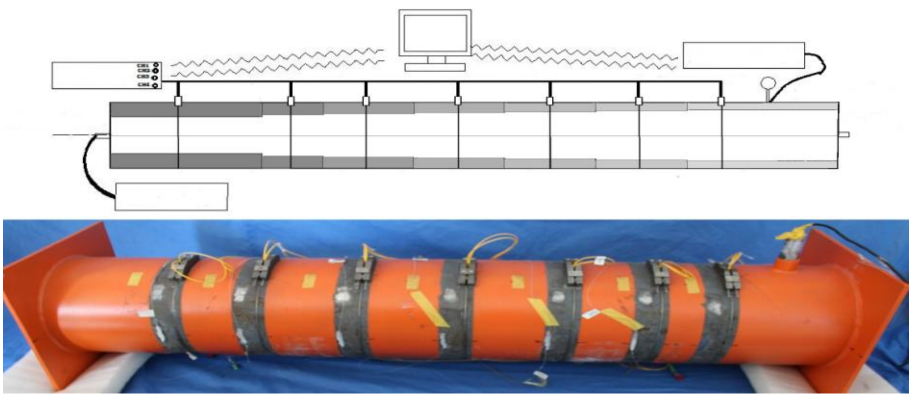

Fig. 5 Device physical figure

3.1 Introduction of experiment platform

Test-design contains a steel pipeline divided seven part with different wall thickness representing different corrosion degree, as shown in Fig. 5. In order to control the pressure in the pipeline, a pressure sensor was used. And air pump with 0.4Mpa maximum pumping pressure was used to provide pipeline working environment. Seven FBG hoop-strain sensors were mounted on the pipeline by super glue. SM-130 and C-RIO were used as demodulation instruments with rates of 10Hz for data acquiring. For there is noise, which mainly comes from power source and machine, existed in actual practice, it is hard to read an exact figure from computer. Testing data won't be taken until figure on computer is stable, than take the mean value as final result. In general, an average error of 0.0005nm was observed for wavelength shift and an average error of 0.1 Kpa was observed for pressure. The tests were conducted at a temperature of 26℃. FBG is sensitive to temperature as well, however, the experimental result of this sensor was carried out except effect of temperature by using temperature sensor, so in the analytical model, the effect of temperature was neglected.

3.2 Calibration of FBG hoop-strain sensors

Calibration tests were implemented in this part, in order to verify the effectiveness of this sensor. As stated in the analytical model in section 2, wavelength shift increases as the pressure increases. Here, pressure sensor was used for monitoring pressure change in pipe and the results measured by FBG hoop strain sensors were calibrated with pressure sensors', and then parameter study was conducted. Typical calibration results on PVC and steel model pipe were shown in Figure 6 and Figure 7 respectively. Sensor along PVC pipe with thickness intensity t=3.8mm, was tested with pressure of 0-50Kpa in step of 5Kpa and sensor along steel pipe with thickness intensity t=3.0mm was tested from pressure 0kpa to 200kpa by 20kpa for each load step.

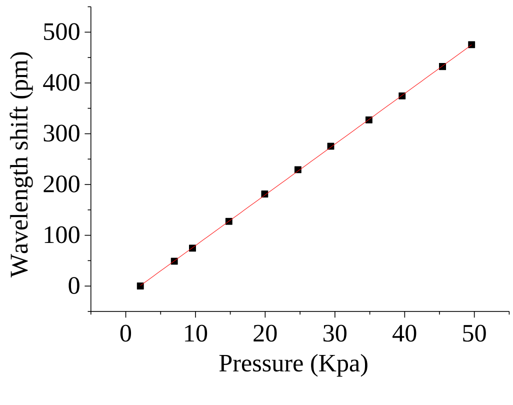

Fig. 6 Calibration of PVC

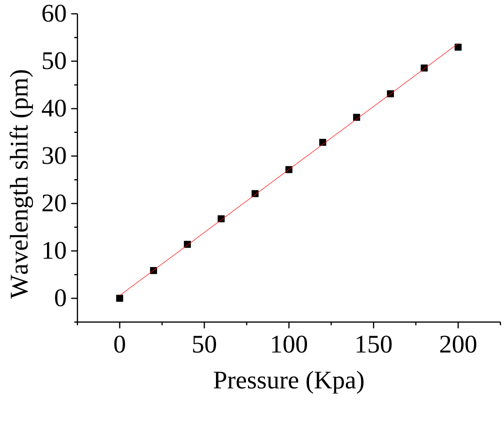

Fig. 7 Calibration of steel

All data were collected as previously described above. Fig. 6 and Fig. 7 show the response of the sensors with the applied pressure. Linear variations reach to 0.9999, which shows an increase in the hoop strain with an increase in the pressure which is in good agreement with the theoretical analysis.

3.3 Corrosion simulation test

For the relationship between the hoop strain and corrosion has been discovered, corrosion simulation test was conducted on steel pipeline to verify the theoretical conclusion. With pressure 50Kpa, five sensors around the different thickness areas of the PVC pipeline, like 5.1mm, 4.4mm, 4.2mm, 3.8mm and 3.4mm, were tested. Similar test method was carried out on steel pipe, five sensors around the different thickness area like, 5mm, 4.6mm, 4.2mm, 3.8mm and 3.0mm, were tested. That linear variations value achieves to 0.99 (see from Fig.7 and Fig. 8) are in good agreement with the theoretical conclusion that wall thickness of pipeline is in inverse proportion to the hoop strain. Therefor the FBG hoop-strain sensor is sensitive to the hoop strain variation caused by corrosion, and the measured results reflect the corrosion degree directly.

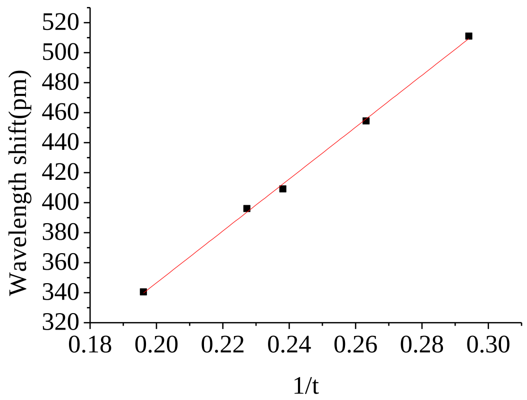

Fig. 8 PVC pipeline

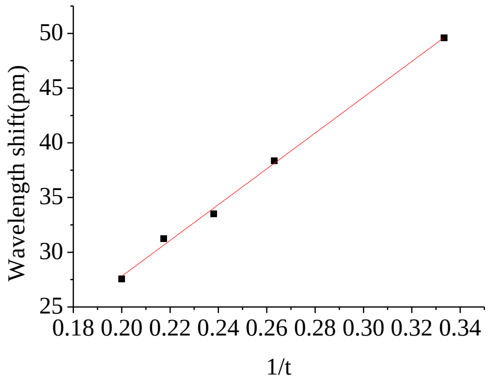

Fig. 9 steel pipeline

4. CONLUSION

A new method for long pipeline corrosion monitoring based on the FBG hoop-strain was developed. The results of experiment showed that the FBG hoop-strain sensor is sensitive to the hoop strain variation and reflect the corrosion degree directly. With the outstanding features, the FBG hoop-strain sensor is appropriate to applying to pipeline monitoring. As a kind of Nondestructive Testing, the FBG hoop-strain sensor has a broad future. Further study is still need to be done, like development of sensor precision and establishing of smart net-work. Local corrosion simulation test is undertaking now.

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