

Fiber Grating-Based Strain Sensor Array for Health Monitoring of Pipelines

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Abstract: Pipelines are one of the most important modern energy transportation methods, used especially for the transportation of certain dangerous energy media materials such as crude oil, natural gas, and chemical raw materials. New requirements have been put forward for the health monitoring and early security warning of pipelines because of the large-scale and complicated development trend of the pipe network system. To achieve an accurate assessment of the health conditions of pipeline infrastructure, obtaining as many precise operating parameters as possible, particularly at some critical parts of the pipeline, is necessary. Therefore, a novel type of fiber grating strain sensor array is proposed herein to monitor the pipeline hoop strain. The sensor utilizes fiber grating characteristics such as light weight, corrosion resistance, remote transmission, and strong environmental adaptability. The fiber containing the grating measurement points is implanted into the composite material to complete the sensitization encapsulation and protection of the bare fiber grating. The design of the sensor array fulfills the requirements for monitoring pipeline mass data, making it easy to form a pipeline health monitoring sensor network. The sensor sensitivity is researched by using a combination of theoretical and experimental analysis. A sensitivity test, as well as linearity and stability tests, are performed on the sensor. The experimental results show that the average sensitivity of the sensor is $14.86 \text{ pm}/\mu\epsilon$, and the error from the theoretical calculation analysis value is 8.75%. Due to its high reliability, good linear response and long-term stability, and the ability to reflect the exact strain change of the outer wall of the pipeline, the designed sensor can support long-term online pipeline monitoring. The fiber grating sensor array network has successfully realized the monitoring of the pipeline's internal operation by using external strain changes. In addition to the performance benefits, there are other merits associated with the applicability of the sensor namely simple structure, compact size, manufacturing ease, and exterior installation ease.

Keywords: Strain sensor array; fiber grating; composite material; monitoring pipeline

1 Introduction

Since K. O. Hill developed the first fiber grating in the 1970s [1], there has been growing prominence of the application advantages of fiber grating sensing technology [2, 3]. Due to its features such as easy long-distance transmission [4], strong anti-interference ability [5], intrinsic security [6], high measurement accuracy and distributed survey [7], fiber grating has a wide range of applications in aerospace, civil engineering, petrochemicals, transportation, and military fields [8-11].

Sensing systems based on fiber gratings have proven promising for long-term online pipeline health monitoring. Considerable work has been conducted by several researchers on pipeline health monitoring [12, 13]. Fiber grating technology-based pipeline health monitoring has been rapidly developed since it came into being [14, 15]. Ren L proposed a new type of fiber grating strain hoop sensor based on ring-shaped strain measurement of the reflective function in corroded pipes [16, 17]. The sensor has the merit of measuring the average strain in the circumferential direction without damaging pipelines. Lim K utilized a distributed optical fiber sensor based on Brillouin optical time-domain (BOTD) analyses to monitor external pressure and stiffness changes in initially non-circular pipes under internal pressure [18]. A BOTD sensor can detect the stiffness irregularity of a non-circular pipe. Wang Q studied the dynamic strain measurement of a pinhole metal tube in view of a fiber Bragg grating sensor [19]. The sensor has a great potential for the quasi-distributed measurement of dynamic strain, and it can be exploited for the dynamic characteristics of research and health monitoring in hydraulic system pipelines. Morshed AH compared two different types of optical fiber sensors that can be used for monitoring the hoop strain on a pressurized pipe; the well-developed fiber Bragg grating (FBG) sensor, and a proposed simple fiber sensor based on multimode interference (MMI). The FBG sensor shows a better strain measurement linearity [20]. An all-fiber vector acoustic sensor based on crossed microfiber Bragg gratings (micro-FBGs) has been proposed by Gao R and it has been experimentally demonstrated that it enables two-dimensional sound source localization with a size less than 1.5 mm [21]. Wang Z proposed an enhanced damage indicator based on the fiber Bragg grating to detect cracks in pipelines [22]. Jia Z used a distributed FBG strain sensor set along the pipeline to extract multiple hoop strain signals to reflect the leakage process [23]. The parameters of different kernel functions are optimized through a five-fold cross validation process to obtain the highest leakage localization accuracy. FBG-based pipeline monitoring has multiple sensing measures such as strain, stress [24], vibration [25] and temperature [26], but the sensors in the above monitoring methods are difficult to manufacture and install; they are also expensive and prone to damage.

The annular strain on the outer surface of the pipeline is taken as the research object. Combined with the characteristics of distributed sensing fiber gratings and the adopted fiber with multi-points sensing array, the paper proposes an online fiber grating sensing array monitoring method for the circumferential strain on the outer surface of a pipeline. The basic idea of the method is to embed a fiber grating into certain composite materials, that is, the forth-putting of composite materials to complete the bare fiber grating package. The strain sensor array can not only reflect the internal stress state of the pipeline accurately but also has other strengths including simple structure, compact volume, fabrication ease and installation convenience. The fiber grating sensor array designed in this paper can form a fiber grating sensor network to monitor pipeline corrosion in real time, and the network has successfully achieved the use of external strain changes to monitor the internal operating state of the pipeline. By monitoring the axial and circumferential strains on the outer wall of the pipeline, long-term online monitoring of the corroded pipeline is realized, and the corrosion trend and service life of the pipeline can be estimated.

2 Design Theory of Fiber Grating Strain Sensor Array

Although bare fiber grating has many sensing characteristic strengths, it cannot withstand the harsh-complex environmental factors and extensive construction methods in practical pipeline engineering. Therefore, designing a bare fiber grating package is indispensable. When designing sensors from basic

mechanical analysis and the sensing characteristics of the sensor and measured pipe, the characteristic pipeline stability monitoring and maintenance should consider the strain transmission reliability throughout the monitoring process. The sensor should closely adhere to the outer wall surface and thus be able to gauge the hoop strain at a certain point on the outer wall of the pipeline. Due to the advantages of fiber grating distributed sensing, a single sensor with multi-points monitoring system is used to monitor external strain changes, as shown in Fig. 1.

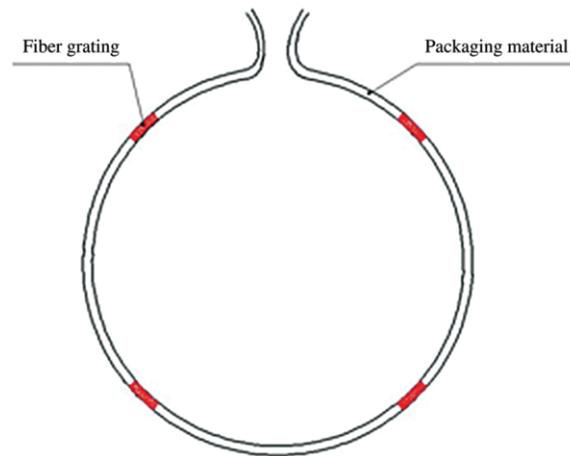


Figure 1: Fiber grating strain sensor array

The internal force through the sensor, M , is due to a certain change in the pipe interior. The total length of the annular composite material fixed on the pipe is $L_S = L_{S1} + L_{S2}$, as shown in Fig. 2. According to the basic theory of material mechanics, the total deformation of the fiber grating and the ring composite can be written as ΔL ,

$$\Delta L = \frac{ML_s}{E_s A_s} + \frac{ML_B}{E_B A_B} \quad (1)$$

To determine the sensitivity of the proposed sensor, that is, the relationship between the fiber grating strain and the circumferential pipe strain, the following assumptions are made: 1) The circumferential deformations of the sensor and pipe structures are the same and the influence of the entire sensor stiffness

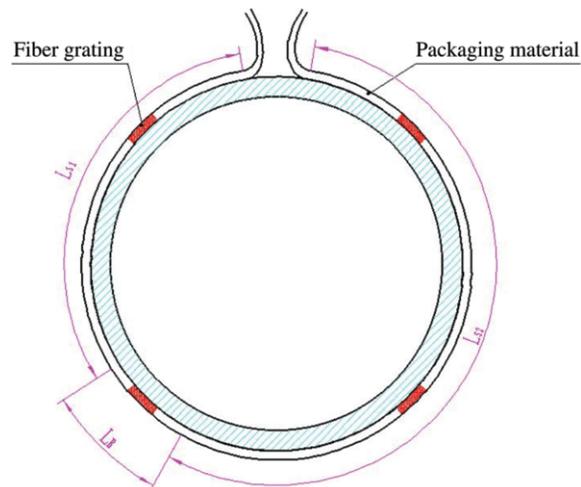


Figure 2: Strain sensor array calculation

on the original pipe should be neglected; and 2) some strain transfer loss due to the gluing and clamping methods, and the effect of the pipe self-weight should also be ignored. Thus, ε_B the strain of fiber grating and ε_p pipe hoop strain can be expressed as follows

$$\varepsilon_B = \frac{\Delta L_B}{L_B} = \frac{M}{E_B A_B} \quad (2)$$

$$\varepsilon_p = \frac{\Delta L}{L} = \frac{\frac{M L_s}{E_s A_s} + \frac{M L_B}{E_B L_B}}{L} \quad (3)$$

The strain relationship between the fiber grating and the pipe can therefore be written as

$$\frac{\varepsilon_B}{\varepsilon_p} = \frac{L}{\frac{E_B A_B}{E_s A_s} L_s + L_B} \quad (4)$$

Type, order

$$\beta = \frac{E_B A_B}{E_s A_s}, \gamma = \frac{L_B}{L} \quad (5)$$

K_P is the strain sensitivity coefficient of the FBG strain sensor array. The relative parameters of the packaging material and the fiber are selected as shown in Tab. 1, and the data in the table are substituted into the formula (5). As the elastic modulus of the fiber material is much smaller than that of the packaging material, the value of β can be approximated as 0. The expression for the sensor strain sensitivity coefficient is given as

$$K_P = \frac{1}{\gamma} = \frac{L}{L_B} \quad (6)$$

Table 1: Optical fiber and composite material parameters

Parameter	Optical fiber	Composite material
Elastic Modulus/MPa	$E_B = 70$	$E_s = 71500$
Diameter/mm	0.125	2
Area/mm ²	$A_B = 0.01227$	$A_s = 3.14159$
Length/mm	L_B	L_s

As L is always greater than L_B , it can be concluded that K_P is always greater than 1, the fiber grating strain sensor array has a strain-sensitizing property. In this paper, a grating of 1550 band is adopted. Morey defines the strain sensitivity coefficient as $1.2 \text{ pm}/\mu\varepsilon$ [27]. The relationship between the strain and the wavelength of the grating in this band can be approximated as

$$\varepsilon_B = \frac{\Delta \lambda_B}{1.2} \quad (7)$$

Therefore, the connection between the strain of pipe and the center wavelength of the grating is expressed by formulae (6) and (7):

$$\varepsilon_p = \frac{\Delta \lambda_B}{1.2 K_P} \quad (8)$$

Compared with the ordinary linear sensor that is directly installed in the structure of the test location for monitoring the research object, the ability of the sensor array to maintain the raster site closely with the pipe wall fit is the most important factor. To solve the problem, a new particular pre-tensioning device has been designed for pre-tensioning during sensor installation. The clamping support is the most critical factor in the pre-tensioning device design, where an arcing part exists in its lower surface. The diameter of the arcing part should be consistent with that of the pipeline being monitored.

3 Strain Sensor Array Fabrication

Different numbers of fiber gratings and different pitches can be set in each sensor. That is, each strain sensor includes one or several gratings on an optical fiber, and it can form a sensing array. As we all know, it is necessary to take a reasonable and effective package for the bare grating in order to meet the actual needs of various projects. It is similarly essential to promote sensitization of the bare grating package to meet certain practical engineering application conditions. Composites have a high status in practical engineering because of their high specific strength, specific modulus and convenience of molding [28-30]. At present, composite materials have been widely used in various engineering fields and daily lives. A strong health monitoring capability can be realized by combining fiber gratings with a composite material to form a certain intelligent structure. The idea of using a composite material to encapsulate (embed) a fiber grating has also been studied in depth, and related research results have been obtained [31]. The fiber material itself has a high degree of integration with composite materials [32]. In this paper, the main reason for choosing fiber-reinforced composite materials is that the long-fiber form material is stronger than the bulk form material. Packaged sensors comprising of composite materials ought to consist of a polymer encapsulated material, fiber grating, fiber optic connectors and other components. The main process of the composite packaged fiber Bragg grating sensor is to implant the fiber grating into the composite material by special equipment. The formed structure has good strain transmission performance, high shear strength and durability. The critical role of polymer composites is to promote good transfer of measured physical quantities of gratings and for the protection of the grating. Fig. 3 shows the material object photograph.

During the installation of the FBG strain sensor array, the pre-stretching operation needs to be carried out in two steps. First, the end of the sensor containing the clamp block is passed through the reserved space of

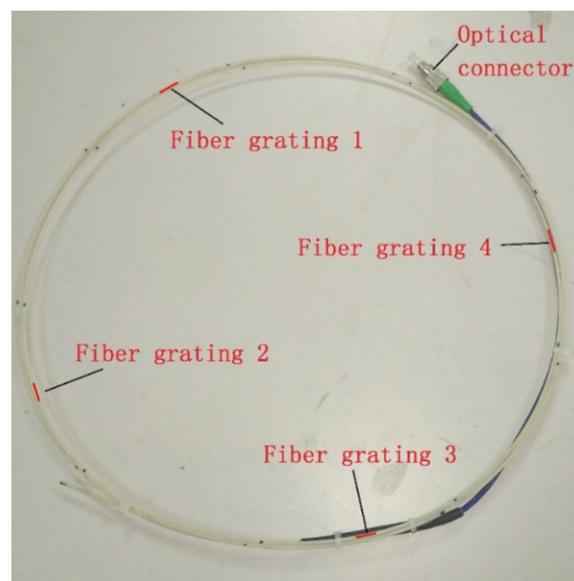


Figure 3: Pictorial diagram of the sensor

the pre-stretching device and made to move back and forth in the groove reserved in the holder. The movement is meant to make the sensor and the pipe wall to fit closely into the site, then the block is bolted to the clamping support. Specific glue is then used to attach the sensor to the surface and left to dry. This pre-stretch refers to the grating pre-pull; and it should be noted that it is necessary to control the wavelength change during the stretching process. The connection of the support to the pipe wall can be welded or detachable. The pre-stretch is carried out on the entire annular composite material. On the one hand, it ensures that the fiber grating strain sensor array is closely attached to the outer wall of the pipe, so the sensor can have the same amount of circumferential deformation as the measured pipe. On the other hand, the pre-stretching provides the pre-tightening force needed for the optical fiber pre-tensioning to reduce the inaccuracy caused by the abnormal bending of the optical fiber. Fig. 4 shows the installed packaged fiber grating strain sensor array and preload device.

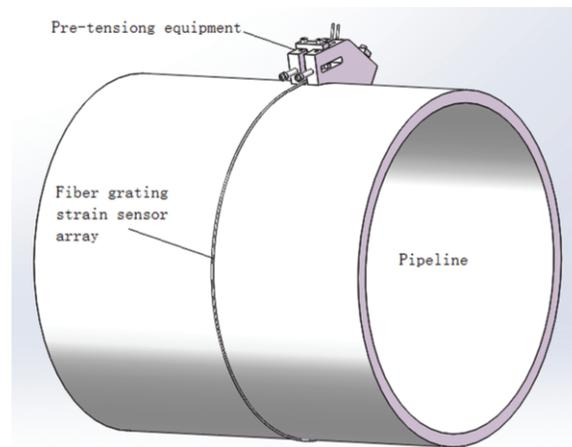


Figure 4: Sensors installed in the pipeline

4 Sensor Performance Experiments

The primary purpose of performance testing on the sensitivity, stability and linearity of the FBG sensor is to test the influence of the sensor's packaging mechanism (including material and method) on the strain measurement, by comparing the strain values in bare fiber grating with those in the FBG sensor. The second purpose is to explore the practicality of the FBG sensor through the sensitivity coefficient, stability and linearity test. In the experiment, the bare grating is bonded at the corresponding position of the FBG sensor array, and the strain gage is close to the bare grating position. The strain gage is calibrated as the standard value of strain. The measured values of the strain sensor array and the bare grating are compared.

Experimental device schematic diagram is as shown in Fig. 5, and the experiment is carried out at room temperature. The experiment exploits the variation value of the bare grating as a contrast to evaluate the sensitivity, stability and other properties of the fiber grating strain sensor array.

4.1 Strain Sensor Sensitivity Experiment

First, the strain sensor array is installed on a cross section of the pipe before the experiment, and the sensor's pre-tensioning device is fixed. The strain sensor is fixed to the outer surface of the pipeline by pre-drawing and stretching, which ensures the close cooperation between the array sensor and the pipeline. The pressure in the pre-tightening process should not be too large to damage the fiber grating. In

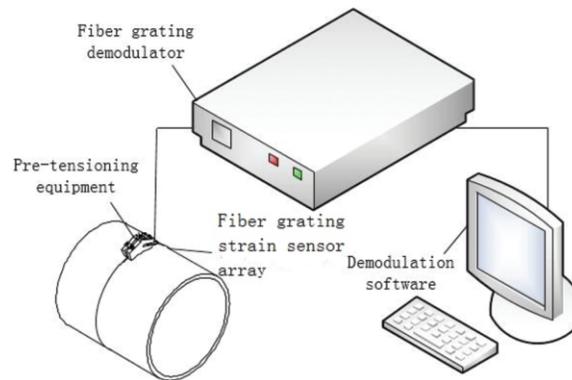


Figure 5: Experimental setup

order to facilitate the installation of the bare grating, clearly pasting the position of the sensor pipe is necessary. The naked grating is glued directly to the surface of the pipe with some special glue. Before pasting the grating onto the surface of the pipe, the attached rust and oxide must be removed from the wall of the pipe. Epoxy binders are used for bonding. Since the actual strain on the pipe cannot be predicted in the experiment, the corresponding strain gauge should be used as the calibration value. The array sensor installation in the test is shown in Fig. 6.

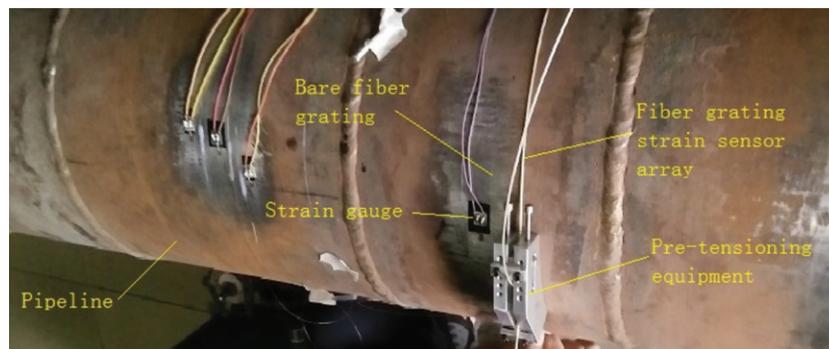


Figure 6: Experimental installation

The experimental pipeline uses 0.2 KPa as a change unit and gradually pressurizes from 0 KPa to 1.0 KPa. After the compression data is stable, the wavelength values of the fiber grating and fiber grating strain sensor arrays are stored by the fiber grating high-speed demodulator and the corresponding computer software. Several pressurization experiments were carried out, the results of which are shown in Fig. 7.

The wavelength change of the fiber grating strain sensor array is greater than that of the bare grating, that is, the fiber strain sensor array has higher strain sensitivity than the bare grating. An average sensitivity of $14.86 \text{ pm}/\mu\epsilon$ is obtained. The sensitization mechanism of materials and structures used in the packaging of strain sensors is the critical factor here. Fig. 7 also shows that the linear coefficient of the strain sensor reaches 0.9984, which is not much different from the naked grating. The strain sensor encapsulation mechanism does not adversely affect the linear properties of the bare grating. In addition, unlike other linear FBG sensors, strain sensors need to be fixed to the outer wall of the pipeline after deformation. The

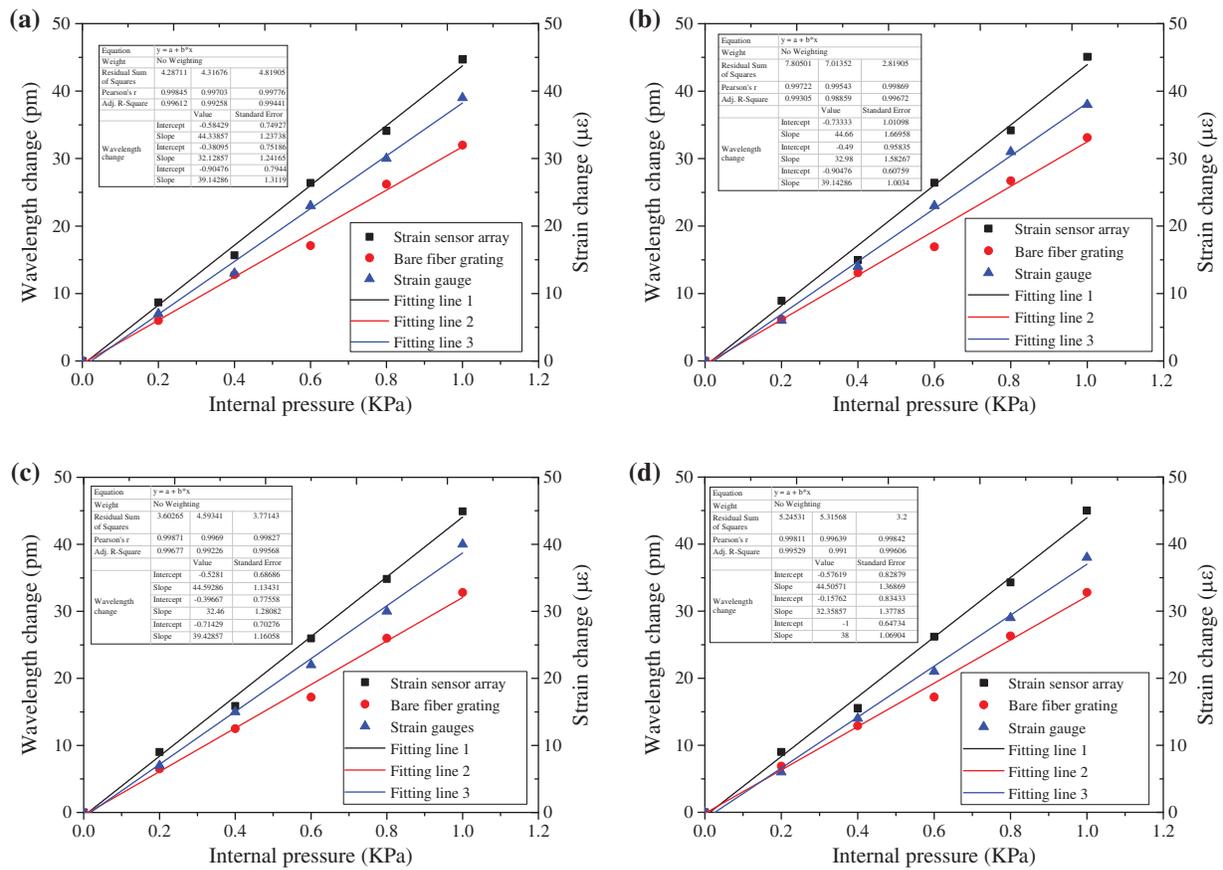


Figure 7: Fiber grating experimental test results: (a) grating 1; (b) grating 2; (c) grating 3; (d) grating 4

grating chirps may appear in the deformation processes of some sensors, which have high requirements for the production process.

4.2 Strain Sensor Stability Experiment

To investigate the long-term stability of the fiber grating sensor array strain measurement, there is need to perform a cyclic compression test on the sensor. Cyclic loading and unloading experiments are carried out to verify the stability and accuracy of the pipeline's circumferential strain. The main equipment used in the experiment is the strain sensor array, manual pressure test pump, fiber grating demodulator, resistance strain meter, and a computer. Two stability tests are performed one week apart.

Because of the degree of risk associated with the pressure test, this paper used the hydraulic test. Before the strain sensor array is installed and the bare gate is pasted, the pipe is filled with water to eliminate the impact of water gravity on the test results. The pressure gauge reading before the experiment was 0 MPa. During the experiment, the pipe was reloaded to between 0.2 KPa and 1.2 KPa. The experimental scene is shown in Fig. 8. The maximum and minimum wavelengths of the strain sensor arrays are recorded in each cyclic load and the difference between the maximum and minimum values of each reciprocating load is calculated. The experimental results are shown in Fig. 9.

As can be seen from Fig. 9, the difference between the maximum and minimum wavelengths during the entire reciprocating loading process is very small. Based on the above test results, the FBG strain sensor array

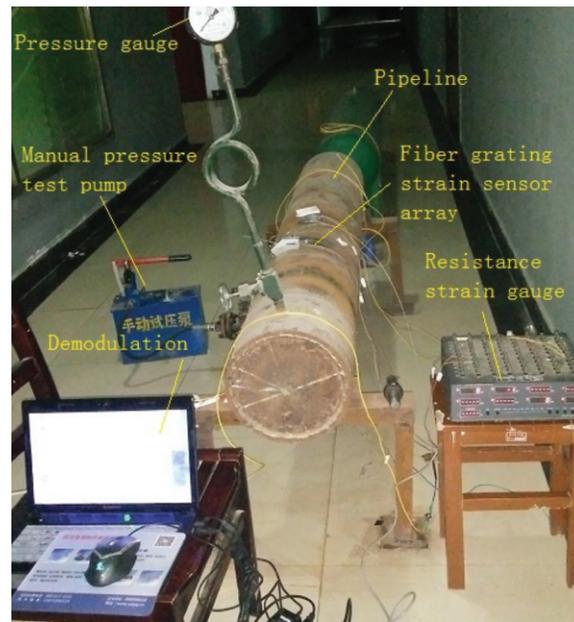


Figure 8: Stability experiment test site

can guarantee stable strain data under cyclic loading. Pre-tensioning equipment and strain sensor arrays are devised with long-term stability.

4.3 Dynamic Sensor Performance Test

According to the practical dynamic performance of the fiber Bragg grating strain sensor array, the uniform corrosion experimental model of the pipeline is designed and built to determine whether the strain sensor array could be effectively applied to pipeline dynamic strain monitoring. A pipeline corrosion monitoring experimental model is built as shown in Fig. 10. The experimental equipment includes a manual pressure test pump, the test pipe, a pressure gauge, an FBG strain sensor array (1, 2), FBG demodulator and a computer. The pipe model used was 3920 mm in length, 257 mm in diameter, and 8 mm in wall thickness. Selecting water as the medium, the system design maximum pressure is 2 Mpa. The wall thickness of the pipeline as measured by FBG strain sensor array 2 is 6 mm.

In order to avoid the influence of gravity on the experimental results, the pipe is filled with water before the sensor is installed. The pressure of the pipeline system is set to 1 Mpa. The pressure relief valve of the manual pressure test pump is opened by opening the manual ball valve by 50%, the waiting pressure drops to 0.1 Kpa, then the manual ball valve is closed, and the initial pressure is restored. The initial data of the central wavelength of the FBG is stored once before the compression, and then the loading experiments of 0.2–1.2 Kpa are carried out. The experiments are carried out in three runs. The acquisition rate of the FBG demodulator is set at 2000 Hz in each experiment, and the experimental data is saved in real time. The experimental data are processed and the average test results of the three sets of experimental data are shown in Fig. 11. As can be seen from Fig. 11, the wavelength change of Sensor 2 is more obvious than that of Sensor 1, because the wall thickness of Sensor 2 is smaller than that of Sensor 1. The strain sensor array can monitor the dynamic strain of the pipeline and reflect the stress state of the pipeline structure, thus realizing the long-term health monitoring of the pipeline.

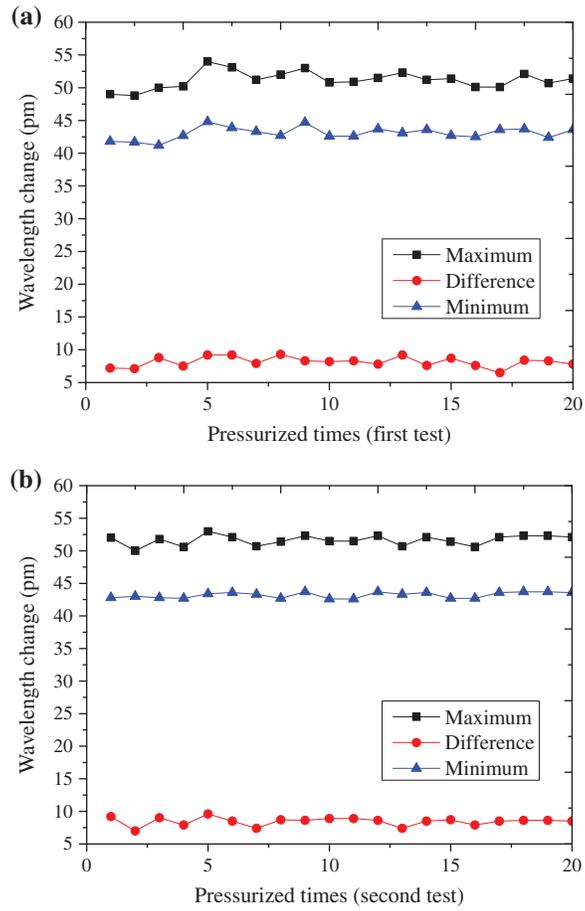


Figure 9: The stability test: (a) first; (b) second

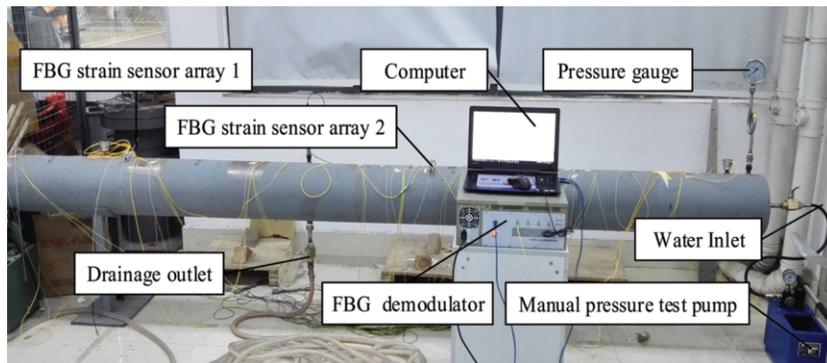


Figure 10: Dynamic performance test site

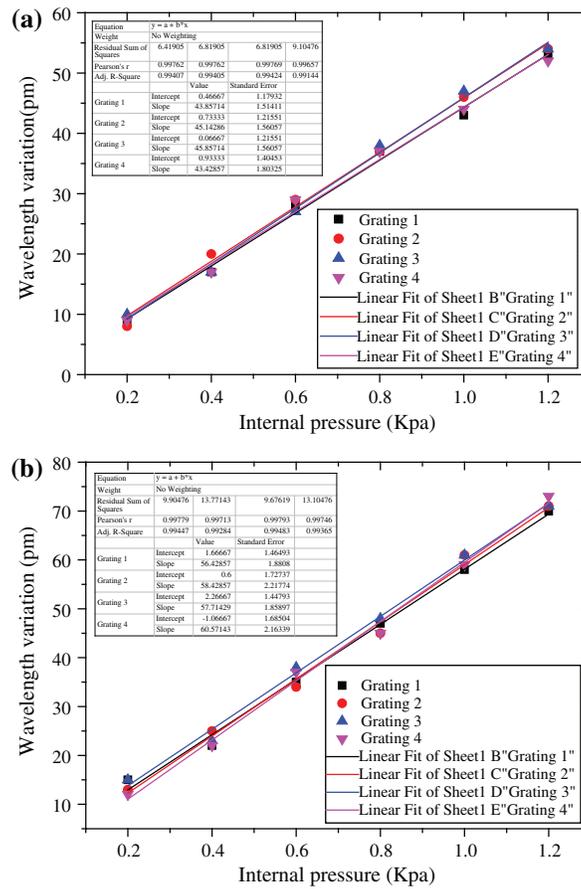


Figure 11: The dynamic performance test: (a) fiber grating strain sensor array 1; (b) fiber grating strain sensor array 2

5 Conclusions

In summary, this paper designs the fiber grating strain sensor array for circumferential strain measurement on the outer wall of a pipeline. The paper presents a theoretical analysis of the sensor design process is performed as well as the design of the pre-tensioning equipment aimed to keep the sensor and pipe wall close-fitting. The packaged strain sensor array is installed on the outer wall of the pipeline and compared with the bare grating in terms of sensitivity, stability and linearity. The results show that the novel sensing array has stable performance and is suitable for long-term pipeline monitoring. It has an average sensitivity of $14.86 \text{ pm}/\mu\epsilon$. The fiber grating strain sensor array can not only monitor the strain changes, but also reflect the stress state of the internal structure of the pipeline. This type of fiber grating array sensor network solves the problem of long-term real-time online monitoring of pipeline corrosion and has successfully realized the monitoring of internal operation of pipelines by using external strain changes. Through the axial and circumferential strain monitoring of the outer surface of a pipeline, the long-term online monitoring of pipeline corrosion is successfully realized. It is possible to estimate the corrosion trend and the remaining life of a monitored pipeline from its running state. Therefore, the strain sensor array successfully realizes accurate judgment of the pipe's running state; and it has wide ranging applications in industries such as aerospace, civil engineering, petrochemicals, transportation and the military because of its advantages of simple structure, compact volume, manufacturing ease, convenient installation, among others.

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