A Study of On-line Monitoring and Evaluation Approach for Oil and Gas Pipelines Subsidence Deformation

Keqin DING¹, Guang Chen², Fangxiong TANG³, Li CHEN⁴, Yaying HE⁵, Li Qi YI⁶

¹,²,³,⁴,⁵,⁶ China Special Equipment Inspection and Research Institute (CSEI), Beijing, China
e-mail: kqding@sina.com, phone: 0086-13910579725

Key words: condition monitoring, pipeline, subsidence deformation, strain analysis, distribute monitoring method

Abstract

The long-distance pipeline would have subsidence deformation for the sake of nature disasters and artificial processes. Thus, monitoring the huge oil and gas transport pipeline system could discover abnormality instance without delay and prevent accidents to ensure the production and life. The distributed monitoring method of subsidence deformation of long-distance pipeline, presented in the paper, uses advanced distributed optical fiber sensing technology to monitor pipeline's strain in real-time. According to the relationship between strain and deflection on beam's large deformation theory, the deflection of pipeline could be calculation with numerical method. This paper provides technical supports for online monitoring and pre-warning of pipeline deformation oil and gas pipeline.

1 INTRODUCTION

As the bond of oil and gas resources and consumer markets, long-distance pipeline with the characteristics of efficiency, safety, environment, economy, occupies an important position in the national energy security strategy. Most of the geological disasters caused by complicated geographic types in China lead to the subsidence deformation of oil and gas long-distance pipelines, which will affect the normal production and life and cause serious pollution to the environment. What is more, the explosion of oil and gas will endanger human lives and cause great economic losses. Therefore, with the help of the real-time online monitoring of subsidence deformation of pipelines, the operating status can be timely grasped, which is essential to ensure the security of long-distance pipelines.

With characteristics of long distance, continuous and online monitoring on strain and temperature, the distributed optical fiber sensing technology will become a new method of pipeline health monitoring. Chunshu Zhang [1] used uniform distributed sensing optical fiber to monitor steel pipe simultaneously bears internal pressure, axial force and bending strain, and then predict the position of steel tube buckling. Brillouin sensor and strain gauge has been used to monitor the compression strain of the central and elongation near local wall-thinning of the pipe when buckling occurs by Fabien Ravet [2]. To monitor the displacement deformation of the pipeline by toroidal winding fiber in the line, R. BERNINI compared the experimental data with simulation results, and evaluated the health status of pipeline [3]. Based on distributed fiber optic monitoring technology, Glisic et al. used the experimental simulation influence of fault movement 13 meter long pipeline with joint to prove the optical fiber sensing technology can identify and locate pipeline damage and strata movement [4]. Hu Cheng et al. used distributed optical fibers to monitor the distribution of the pure bending
strain of polyethylene pipe surface, which provided some references of on-line monitoring of buried pipelines [5]. In view of pipeline of large deformation problems caused by frost-heaving and thawing in the permafrost environment, Zhou Zhi et al. used PVC pipes in water freezing and melting states for all distributed sensing monitoring simulation experiments [6]. Liqi Yi et al. proposed Quasi-distributed pipeline deformation monitoring method, which was used to do related simulation experiment on fiber Bragg grating sensing technology [7-8].

A distributed monitoring method for the subsidence deformation of long-distance pipelines is proposed in this paper on further study of the deformation failure modes of oil and gas pipelines. The single-mode fiber (a sensing element and a transport carrier) is used to obtain the temperature and strain information of pipelines by measuring the Brillouin optical frequency shift in the fiber. Firstly, pipeline is simplified as beam model, and a deformation distributed method on the strain analysis of the pipe is proposed on the large deflection beam theory. Secondly, the pipe axis displacement calculation formula is deduced combined with spline function. The feasibility of the distributed computing method is verified by simulation and experiment. The method is simple to calculate the deflection of the pipes by strain measured on the optical fiber instead of gathering a lot of information. The method is suitable for the analysis of the pipe deformation where the force status is unknown. This paper provides technical supports for online monitoring and pre-warning of pipeline deformation oil and gas pipeline.

2 OIL AND GAS PIPELINE DEFORMATION CALCULATION METHOD BASED ON STRAIN

Due to the section size of pipe is far less than the axial length, and the needs of calculation and analysis, the deformation of the Euler beam with large deflection is used as the mechanical model to study the pipeline of large elastic deformation.

Theory hypothesis of Euler beam is as follows:
(1) The vertical axis of the beam cross section is still a plane after the beam deformation;
(2) Before and after deformation cross section always vertical to the beam axle.

The diameter and length of pipe are $D$ and $L$, and both ends of the pipe are fixed. Along the axis, the pipeline is divided into $N$ uniformly, and the length of each segment is $h = L/N$. Assuming that the pipe deformation occurs in the x-y plane, and schematic diagram of the pipe axis bending shows in Fig.1.

\[
\frac{du}{dx} = \lambda \cos \theta - 1
\]  

(1)

As the pipe is bending, the point of the pipeline axis $p(x, 0)$ moves to $p'(x + u(x), w(x))$, and beam with large deflection deformation geometry relation is as follows
\[
\frac{dw}{dx} = \lambda \sin \theta \\
\frac{ds}{dx} = \lambda = \varepsilon + 1 \\
k_{ql} = \frac{d\theta}{\lambda dx}
\]  

In the formula, \( u(x) \) is the displacement of \( p \) on the x axis; \\
\( \lambda(x) \) is the elongation of beam axis; \\
\( \theta(x) \) is the angle of flexural tangent with the x axis; \\
\( w(x) \) is the displacement of \( p \) on the y axis, namely beam deflection value; \\
\( s(x) \) is coordinate of flexural arc length \\
\( \varepsilon(x) \) is the axis strain ; \\
k_{ql}(x) \) is curvature of deflection curve 

The value of elongation \( \lambda \) can be obtained by bring the axis strain \( \varepsilon_{ix} \) to the formula (1) – (4). \( \theta_i \) is the Angle of arbitrary cross section \( i \) relative to the y axis, named as absolute Angle. \( \theta_i^* \) is the Angle of arbitrary cross section \( i \) relative to its previous section, named as the relative angles. The calculation formula of \( \theta_i \) is as follows 

\[
\theta_i = \sum_{j=0}^{i} \theta_j^*
\]  

The calculation formula of \( \theta_i^* \) is as follows:

\[
\theta_i^* = \arctan \left( \frac{\varepsilon_{ix} - \varepsilon_{i0}}{h} \right)
\]  

The strain value at the lower busbar of the pipe section \( i \) is \( \varepsilon_{ix} \), while the strain value at the upper busbar of the pipe section \( i \) is \( \varepsilon_{i0} \). Expression of deflection after deformation can be written as:

\[
w_i' = \lambda_i \sin \theta_i = (\varepsilon_{ix} + 1) \sin \theta_i
\]  

The strain value at each node can be obtained by monitoring method, so the \( w'(x_i), (i = 0, 1, \ldots, N) \) is obtained. 

After inserting expression of B spline into the expression of deflection, follows can be obtained:
\[ w(x) = \sum_{j=3}^{N-1} b_j B_{j,4}(x) \]
\[ = b_3 B_{3,4}(x) + b_2 B_{2,4}(x) + b_1 B_{1,4}(x) + \sum_{j=0}^{N-4} b_j B_{j,4}(x) + b_{N-3} B_{N-3,4}(x) \]
\[ + b_{N-2} B_{N-2,4}(x) + b_{N-1} B_{N-1,4}(x) \]
\[ = b_3 \left( \frac{x_i - x_j}{h^3} \right) (x - x_0)_+^0 + b_2 \left[ \frac{(x_2 - x)^3}{4h^3} - \frac{2(x_i - x)^2}{h^3} \right] (x - x_0)_+^0 \]
\[ + b_1 \left[ \frac{(x_1 - x)^3}{6h^3} - \frac{3(x_2 - x)^3}{4h^3} + \frac{3(x_i - x)^3}{2h^3} \right] (x - x_0)_+^0 \]
\[ + \sum_{j=0}^{N-4} b_j \left[ \frac{(x - x_j)_+^3}{6h^3} - \frac{4(x - x_{j+1})_+^3}{6h^3} + \frac{(x - x_{j+2})_+^3}{h^3} - \frac{4(x - x_{j+3})_+^3}{6h^3} \right] (x_{j+4} - x)_+^0 \]
\[ + b_{N-3} \left[ \frac{(x - x_{N-3})_+^3}{6h^3} - \frac{3(x - x_{N-2})_+^3}{4h^3} + \frac{3(x - x_{N-1})_+^3}{2h^3} \right] (x_N - x)_+^0 \]
\[ + b_{N-2} \left[ \frac{(x - x_{N-2})_+^3}{4h^3} - \frac{2(x - x_{N-1})_+^3}{h^3} \right] (x_N - x)_+^0 + b_{N-1} \frac{(x - x_{N-1})_+^3}{h^3} (x_N - x)_+^0 \]
(8)

The derivative expression is as follows:
\[ w'(x) = 3b_3 \left( \frac{x_i - x_j}{h^3} \right) (x - x_0)_+^0 + b_2 \left[ \frac{3(x_2 - x)^2}{4h^3} - \frac{6(x_i - x)^2}{h^3} \right] (x - x_0)_+^0 \]
\[ + b_1 \left[ -\frac{(x_1 - x)^2}{2h^3} + \frac{9(x_2 - x)^2}{4h^3} - \frac{9(x_i - x)^2}{2h^3} \right] (x - x_0)_+^0 \]
\[ + \sum_{j=0}^{N-4} b_j \left[ \frac{(x - x_j)_+^2}{2h^3} - \frac{2(x - x_{j+1})_+^2}{h^3} + \frac{3(x - x_{j+2})_+^2}{h^3} - \frac{2(x - x_{j+3})_+^2}{h^3} \right] (x_{j+4} - x)_+^0 \]
\[ + b_{N-3} \left[ \frac{(x - x_{N-3})_+^2}{2h^3} - \frac{9(x - x_{N-2})_+^2}{4h^3} + \frac{9(x - x_{N-1})_+^2}{2h^3} \right] (x_N - x)_+^0 \]
\[ + b_{N-2} \left[ \frac{3(x - x_{N-2})_+^2}{4h^3} - \frac{6(x - x_{N-1})_+^2}{h^3} \right] (x_N - x)_+^0 + b_{N-1} \frac{3(x - x_{N-1})_+^2}{h^3} (x_N - x)_+^0 \]
(9)

\( N+1 \) equations can be obtained by the value of \((N+1)w'(x)\), which is calculated before, then coupled with the boundary conditions, a set of equations containing \(N+3\) equations can be obtained. The boundary conditions are:
By solving this equation set, \( b_j (j = 3, \ldots, N + 1) \) can be obtained, \( N+3 \) parameters in total. Then inserting \( b_j \) into the expression of deflection, i.e. the calculation of deflection is obtained, afterwards the deformation of the pipe axis can be calculated.

3 DISTRIBUTED STRAIN MONITORING METHOD FOR OIL AND GAS PIPELINE BASED ON BOTDA

3.1 Principle of BOTDA monitoring

When the temperature changes along the optical fiber or the axial strain exists, the frequency of the back Brillouin scattering light in the optical fiber will drift. The frequency drift is linearly related to the change of the optical fiber strain and temperature, and the temperature and strain distribution information can be obtained by measuring the frequency drift of the back Brillouin scattering in the optical fiber.

BOTDA is based on the Brillouin optical time domain analysis technique of Stimulated Brillouin Scattering. The basic principle is shown in Figure 2. The pulse light, which frequency is \( f \), and the continual light, which frequency is near \( \pm f_B \), are injected into both ends of the optical fiber. In the pulse position, pulse and continuous light are generated by Stimulated Brillouin Scattering, which makes continuous light in the position gain or attenuation, and the changes of power of continuous light are detected at different positions. The Brillouin gain spectrum along the whole fiber can be obtained by changing the frequency of the continuous light. And the distributed temperature and strain sensing can be realized by measuring the center frequency of the gain spectrum.

![Fig. 2 The basic principle of BOTDA](image)

According to the linear relationship between Brillouin shift, optical fiber temperature and axial strain, these relations can be expressed in the Eq.(12) under strain or temperature compensation:

\[
\Delta \nu_B = C_{vt} \Delta t + C_{ve} \Delta \varepsilon
\]  

(12)

where \( \Delta \nu_B \) is the Brillouin shift, \( C_{vt} \) is the temperature coefficient of Brillouin shift, \( C_{ve} \) is the strain coefficient of Brillouin shift, \( \Delta t \) is the temperature variations and \( \Delta \varepsilon \) is the strain variations.
3.2 Distributed strain monitoring test of oil and gas pipeline based on BOTDA

With long 6m, 45 steel pipe with section size of 68*4.5 as the experimental object, constraint is fixed in the form of simple supported beam. The distributed monitoring system of oil and gas pipeline is composed of STA-R BOTDA DIeSt system and bare fibers. The foil type resistance strain gauge with TDS303 static strain gauge and the resistance value of 120 is use for comparing and testing. The whole experimental device and arrangement are shown in Figure 3 and 4.

![Fig.3 Experiment field](image1)

![Fig.4 Arrangements of experiment layout](image2)

![Fig.5 Position of loads](image3)

Concentrated loads are exerted on the pipe. The half span is 3m, and the loading point of each concentrated load is 0.5m interval. As is shown in figure 5, heavy objects are hung 5times in 4 locations, including 3m, 3.5m, 4m, and 4.5m. Rotating the pipe after completing surface pressure measurements, the sensing fibers are placed in pipe side for the tension measurement.

4 RESULTS ANALYSIS OF THE EXPERIMENT

4.1 The Brillouin parameters under different load changes

![Figure 6 distributed optical fiber arrangement diagram](image4)

Figure 7 (a) is the Brillouin frequency variation under different load, and the red line is the concentrated load curve (load F=0). The figure shows that the instrument cabin jump line 0 to 2m do not accord with bare fiber sensing properties, when Brillouin frequency is 10.85GHz; 4m, 11m optical fiber fixed point under the influence of spatial resolution instruments appear step distribution; With the increasing of loads, spectrum between 4m to 11m appears a concave, fiber tensile compression deformation together with steel pipe, including 5-10m
fiber by about 1500µ of epsilon initial impact of strain Brillouin frequency of 10.84GHz. After 12m bare fiber evenly distributed, when Brillouin center frequency is 10.77 GHz.

(2) Brillouin gain spectrum and Brillouin width change
In Figure 7 (b) (c), when the fiber ends are in different states of strain, like in step 3.21m, 4.62m, 10.37m, the Brillouin gain appears a significant trough, while the Brillouin width of the corresponding appears obvious peaks.

![Fig. 7 Changes of Brillouin parameters by loads](image_url)

**4.2 Numerical Simulation and Experimental Data Processing & Analysis**

For the stability of experimental data, it is necessary to wait a few minutes and assure the stability of all data before the measure. Averaged values is obtained in 5 times measures for once load to do the last computational analysis.

The bending deflection of the pipe is obtained by the following three methods, and the comparison and analysis are carried out.

(1) The central position of the pipeline is repeatedly loaded and recorded for several times. The bending deflection of the pipe is solved by the deformation calculation method mentioned on the upper section.

(2) In the process of loading, the bending deflection of the pipeline is measured.

(3) The finite element model is established to calculate the strain of the pipe, and to solve the bending deflection of the pipe.
As shown in Fig. 8, the strain values are used to solve the pipe axis displacement value. It is shown from the trend line in figure that the overall trend is in accordance with the deformation. But uncertain numerical value leads to the deviation of the calculation result, which needs to be processed in order to reduce the error value. The comprehensive effect of algorithm restriction and error accumulation makes the deviation of either end appear, which needs to be eliminated. Considering that influence of multiple nodes is evident at both ends, the deviation of the first end has no effect on the terminal, and vice versa. The error at the end point is eliminated by the linear relation. The data is divided into 90 sections for the calculation, and the results after treatment is shown in Fig. 9.

Fig. 9 shows comparison of the calculated results and the simulated values after the error processing. Observing from the figure, the calculated results are already close to the true value. When not being processed, the error is 8.5% at the central location, and the error of the calculation result after processing is 3.7%. Thus the displacement values obtained by the simulation can be compared well.

By comparing the calculated results, the following conclusions can be obtained:

1. the distributed calculation method of pipeline deformation based on strain is feasible;
2. the calculation accuracy will increase by the more dense segments as much as possible in the actual measurement;
3. due to the limitation of the algorithm, the cumulative effect of error can be caused, which leads to the deviation of the data in the second half;
4. the experiment, unable to obtain the overall displacement, chose the central place of displacement measurement, when the error is 3.7%, it may be for the constraints of both ends of the pipeline experimental are unstable, and the experimental equipment also needs further optimization.
5. because the method of error processing is simple and effective, it can reduce the workload of data processing in the later period, and save the calculation time.
5 CONCLUSIONS

Long-distance oil-gas pipeline, as the main artery and lifeline of national economic development, plays an important role in modern industry and daily life. Oil and gas pipelines are being laid over long distances and serve in harsh environment; the security issue has been widely concerned, and excessive deformation is one of the main failure modes of oil and gas pipeline. In view of the pipe bending deformation, this paper has carried out the following work:

(1) A distributed computing method based on the analysis of the pipe strain deformation is proposed by simplifying pipeline to beam model based on the large deflection beam theory.

(2) By the means of simulation and experiment, the feasibility of the distributed computing method is verified.

(3) A distributed monitoring method for the subsidence deformation of long-distance pipelines is proposed in the article.

REFERENCES


