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Research on Strain and Displacement ILI Technology for Oil & Gas Pipeline

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ABSTRACT

The safe and rapid transportation of oil and natural gas, as strategic resources for national energy and power, is one of the important factors restricting the development of national economy. The pipeline often passes some areas vulnerable to geological hazards, placing pipes under the bending stress caused by bending strain apart from normal internal pressure load. Hence, the existence of bending strain on pipeline severely affects the structural integrity and operational safety of pipeline. Especially when any severe defect exists at the position with flexural strain, it may cause the failure of pipeline more easily. This paper proposes an In-line inspection method for pipeline displacement and strain which based on inertial navigation technology. The measurement of pipeline centerline and algorithm of pipeline strain are presented. The method has been verified by pull through and field test. It offers an effective method for safe operation of long-distance oil & gas transportation pipeline in seismic area.

INTRODUCTION

Long-distance oil & gas pipeline is the most economical and feasible way of oil & gas transportation, and laid on land and under the sea around the world. China started the long-distance pipeline industry very late, but the industry has achieved great development for decades starting from the 1950s. Considering its features of

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long-distance transportation, oil & gas pipeline is inevitably exposed to displacement and deformation in the areas where geological hazards may easily occur, such as microseism and seism. This situation leads to significant flexural strain on local pipes, and even causes the instability of pipeline or damage to materials in serious cases, which results in severe losses of national economy. For this reason, displacement and deformation detection of pipeline in seismic area should be carried out periodically to evaluate the integrity of pipeline structure and identify the points where the risk of pipeline deformation is high, so as to take preventive measures against accident of pipeline failure.

Considering the displacement and strain detection of long-distance oil & gas pipeline in geological disaster area, the traditional method is to survey the geological information and identify the areas where earthquake or other disaster such as frost heave may often happen, so as to install strain gauge or displacement monitoring device on the pipeline when it passes through these areas for monitoring the displacement and strain of pipeline[4,5]. However, this method requires the excavation of pipeline and is able to monitor local areas of pipeline only. Due to such limitation, operator is unable to completely understand the status of pipeline[10].

To deal with these problems, this paper puts forward the in-line detection of pipeline based on high-precision inertial measurement unit (IMU) to place IMU on the internal detector[2,6], which can survey and plot the pipeline, but is unable to accurately locate the points where pipeline features exist. Also, the surveying and plotting information can be used to further judge whether pipeline suffers from flexural deformation and displacement due to external geological hazards. In this way, the flexural strain on pipeline can be calculated to provide the important basis for integrity evaluation and safe operation of pipeline in seismic area.

SYSTEM FORMATION AND CENTERLINE ALGORITHM

System Formation

The in-line detection system of pipeline centerline and strain consists of internal detector, calibration ground box, and transmitter, etc. Internal detector can move forward along the transportation direction of pipeline through leather cup under the drive of oil or gas as shown in Fig. 1. IMU is the core unit of internal detector. Due to limited space and demand for detection, strap-down inertial navigation system is employed to realize independent surveying and plotting as well as system control. IMU is mainly composed of three-axis gyroscope and three-axis accelerometer, which are installed orthogonally. It can collect the acceleration and angular velocity of internal detector and the data of odometer at a certain frequency, and store them in the system memory. Since the error of inertial navigation system and displacement error of odometer accumulate as time goes by, low-frequency signal transmitter is also added apart from odometer in the detector, and cooperates with the GPS ground tracking device to help modify the position error of detector, so as to achieve the high-precision centerline coordinates of pipeline[1,7,8].

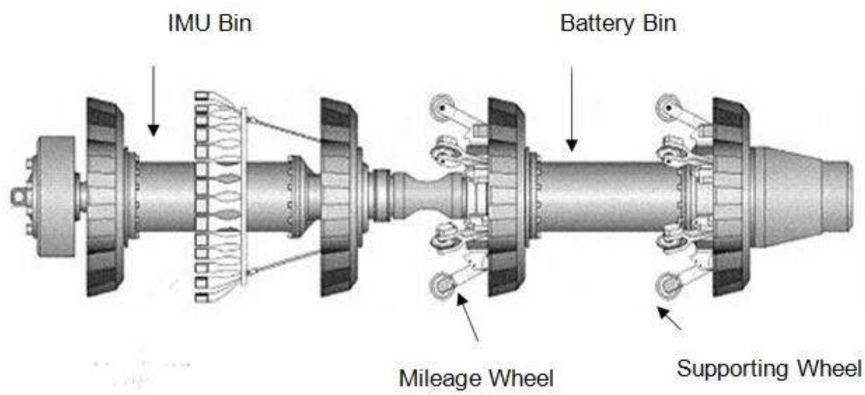

Figure 1. Formation of IMU detector.

Centerline Data Fusion Algorithm

As shown in Fig. 2, the system can perform dead reckoning based on the speed measurement of odometer and the information on attitude provided by inertial navigation system. By building a Kalman filtering model of integrated navigation system based on inertial navigation and dead reckoning, forward Kalman filter is utilized for optimal filtering. Then backward filter is employed for smoothing, so as to obtain the movement track of inertial measurement unit inside pipeline. Eventually, the navigation error of system can be rectified by using the known high-precision position information at calibration ground points as well as the results of dead reckoning by odometer, so as to further improve the accuracy of positioning and complete the accurate measurement of pipeline track[9].

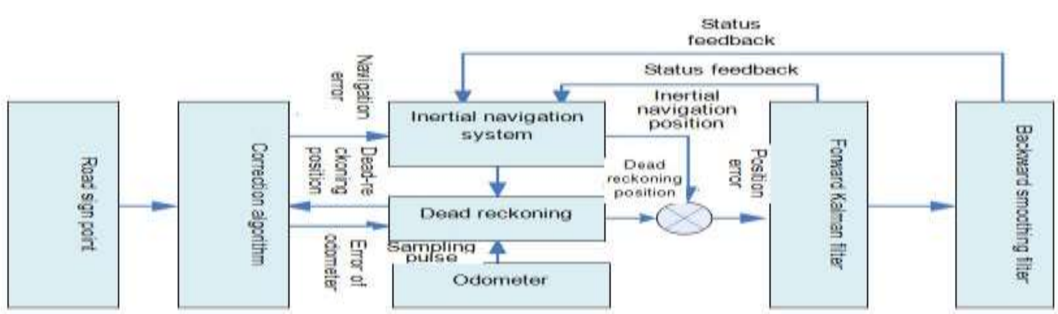

Figure 2. Block diagram of pipeline centerline data processing principles.

The dynamic equations for speed and position of strap-down inertial navigation system and internal detector are as follows:

$$\dot{V}_e^n = C_b^n f^b - (2\omega_{ie}^n + \omega_{en}^n) \times V_e^n + g_l^n \tag{1}$$

$$\dot{q} = \frac{1}{2} q \cdot \omega_{nb}^b \tag{2}$$

$$\dot{L} = \frac{v_N}{(R_N + h)} \tag{3}$$

$$\dot{l} = \frac{v_E}{(R_E + h)\cos L} \tag{4}$$

$$\dot{h} = -v_D \tag{5}$$

In which, $V_e^n = [v_N \ v_E \ v_D]^T$ is speed vector of internal detector, g_l^n is gravity acceleration, $q = [q_0 \ q_1 \ q_2 \ q_3]^T$ is quaternion, f^b is percentage of collection, L and l stand for latitude and longitude respectively, and h is elevation. R_E and R_N indicate the radius of the earth as defined in the WG84 system. The matrix C_b^n converts the carrier coordinate system into local navigation coordinate system, and can be obtained through four-element calculation as follows:

$$C_b^n = \begin{bmatrix} q_0^2 + q_1^2 + q_2^2 + q_3^2 & 2(q_1q_2 - q_0q_3) & 2(q_1q_3 - q_0q_2) \\ 2(q_1q_2 + q_0q_3) & q_0^2 - q_1^2 + q_2^2 - q_3^2 & 2(q_2q_3 - q_0q_1) \\ 2(q_1q_3 - q_0q_2) & 2(q_2q_3 + q_0q_1) & q_0^2 - q_1^2 - q_2^2 + q_3^2 \end{bmatrix} \tag{6}$$

ω_{ie}^n is the rotational angular velocity of the earth in navigation reference, ω_{en}^n is the rotational angular velocity relative to the earth in navigation reference, and ω_{nb}^b is the rotational angular velocity of platform in the navigation system. The expressions of these rotational angular velocities are given as follows:

$$\omega_{ie}^n = [\Omega \cos L \quad 0 \quad -\Omega \sin L]^T \tag{7}$$

$$\omega_{en}^n = [\frac{v_N}{R_E + h} \quad -\frac{v_N}{R_N + h} \quad -\frac{v_N}{R_E + h} \tan L \ ]^T \tag{8}$$

$$\omega_{nb}^b = \omega_{ib}^b - C_n^b (\omega_{ie}^n + \omega_{en}^n) \tag{9}$$

Among them, Ω stands for the rotational angular velocity of the earth—that is, $7.292115\times10^{-5} rad/s$. The vector $\omega_{nb}^{b}=[\omega_{nbx}^{b} \quad \omega_{nby}^{b} \quad \omega_{nbz}^{b}]^{T}$ is the annular velocity from carrier coordinate system to geographic coordinate system to update the attitude angle of system. With Equations (1)-(9), the centerline position coordinates of pipeline can be calculated. The accumulated error of inertial device and odometer increases the error of centerline position as the detection of system lasts, so it is necessary to rectify the position of system for integrated navigation based on the known GPS information from the ground. The real-time state of system is obtained through calculation based on a series of nonlinear formulas, so Kalman filter can be employed to estimate and compensate attitude, heading angle error, and odometer scale factor error, and the information on GPS position from the ground can be used to rectify the position errors of inertial navigation and dead reckoning.

State equation and output equation:

$$x_{k+1}=f(x_k,u_k,k)+w_k \tag{10}$$

$$z_k=h(x_k,k)+v_k \tag{11}$$

Partial derivative matrix of estimated filter state after every time interval of calculation (t = kT):

$$A_k=\frac{\partial f(x_k,u_k,k)}{\partial x_k}\Big|_{x=\hat{x}_k} \quad H_k=\frac{\partial h(x_k,k)}{\partial x_k}\Big|_{x=\hat{x}_k} \tag{12}$$

Filter update equation:

$$K_k=P_kH_k^T(H_kP_kH_k^T+R)^{-1} \tag{13}$$

$$\hat{x}_{k+1}=f(\hat{x}_k,u_k,k)+K_k(z_k-h(\hat{x}_k,k)) \tag{14}$$

$$P_{k+1}=A_k(I-K_kH_k)P_kA_k^T+Q \tag{15}$$

In which, v_k is measurement error vector, while z_k is measurement vector. Through Equations (10)-(15), the equation of system state is obtained from the error model of system to determine the relations among system velocity, position error and other errors. Kalman filter can be used to estimate the errors of system and obtain the estimated values at various states.

CALCULATION OF FLEXURAL STRAIN ON PIPELINE

As geological instability easily causes landslide and other hazards in seismic area, strong external forces place additional stress on pipeline to generate deformation and displacement and severely affect the safety of pipeline proper. Hence, pipeline strain should be monitored periodically[3]. The additional stress caused by external forces increases the longitudinal strain, resulting in the flexure and extension of pipeline. Generally, the flexural strain of pipeline is directly related to its curvature. By calculating the centerline of pipeline, the coordinates of pipeline are obtained together with the corresponding information on attitude of internal detector, including pitch, yaw and roll. In this way, the curvature of pipeline is calculated first. Any change to the pitch of detector can be presented in the fixed observation of pipeline, while the angle of inclination of pipeline varies relative to the plane. The yaw stands for the angle formed by the direction of pipeline along the line and the northern direction. There are the following relations among the variations of pitch and yaw ΔP and ΔA, pipeline centerline length Δs, total curvature of pipeline k, and its vertical component k_v and horizontal component k_h:

$$k = \sqrt{k_v^{\ 2} + k_h^{\ 2}}$$

$$k_v = \frac{\Delta P}{\Delta s} \tag{16}$$

$$k_h = -\frac{\Delta A}{\Delta s}\cos(P)$$

If it is assumed that the centerline of pipeline is neutral axis, there is the following relationship between flexural strain and centerline curvature of pipeline:

$$\varepsilon = \frac{D}{2}k$$

$$\varepsilon_v = \frac{D}{2}k_v \tag{17}$$

$$\varepsilon_h = \frac{D}{2}k_h$$

In which, D is nominal diameter of pipeline, ε is total flexural strain of pipeline, ε_v and ε_h are vertical and horizontal strain components.

Total flexural strain ε stands for the maximum flexural strain caused by flexure at the place where pipeline passes through. Vertical strain component ε_v is corresponding to the longitudinal strain at the bottom of pipeline (the flexural strain at its top is equal to the longitudinal strain at its top, but they use opposite symbols). Horizontal strain component ε_h indicates the longitudinal strain at the right outermost side of pipeline (along the direction of medium flow), which is equal to the flexural strain on the left, but has an opposite symbol. On the cross section of pipeline, the flexural strain $\varepsilon(\alpha)$ at any point of outer wall is as follows:

$$\varepsilon(\alpha)=\varepsilon_v \sin(\alpha)+\varepsilon_h \cos(\alpha) \tag{18}$$

In which, α is the angle formed by the cross section of pipeline and the 12 o'clock clockwise direction.

TEST AND ANALYSIS

To verify the accuracy of detector performance and algorithm, traction test is carried out. The test pipeline is around 100m long, so 5 buttresses are placed at the bottom of pipeline to support it and keep it smooth and straight. The supporting buttress in the middle can be adjusted to mark the settlement of pipeline, while the strain gages are attached at different positions to compare the strain data obtained in the in-line detection, as shown in Fig. 3:

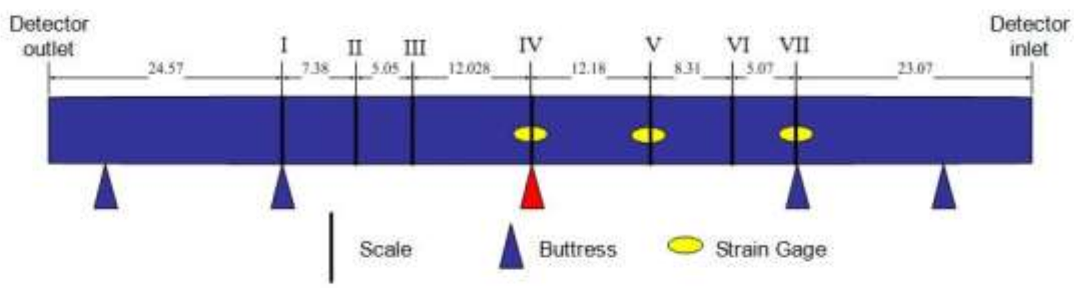

Figure 3. Traction test.

To verify and detect the accuracy of displacement, the buttress in the middle is adjusted to obtain different displacements by causing the settlement of pipeline, while level and standard are employed for accurate measurement. The settlement is caused by several heights, including 5cm, 10cm, 15cm and 25.5cm. Measurement is carried out twice for each height of settlement as given in Table 1. As shown in Fig. 4, the confidence of detection results obtained by internal detector is 87.5% when the interval of confidence is within ±2.5cm. As for slight displacement (<5cm), it may be discovered by internal detector, but there is still some deviation in the detection. When the displacement of pipeline is larger than 5cm, the displacement obtained by internal detector is accurate.

TABLE I. COMPARISON OF DETECTION DATA UNDER DIFFERENT DISPLACEMENT.

	1st	**2nd**	**3rd**	**4th**	**5th**	**6th**	**7th**	**8th**
Actual Displacement (cm)	5	5	10	10	15	15	25.5	25.5
Calculated Displacement (cm)	-2.8	4	11	7.6	14.7	13.5	25.9	25.5
Deviation（cm）	-7.8	-1	1	-2.4	-0.3	-1.5	0.4	0

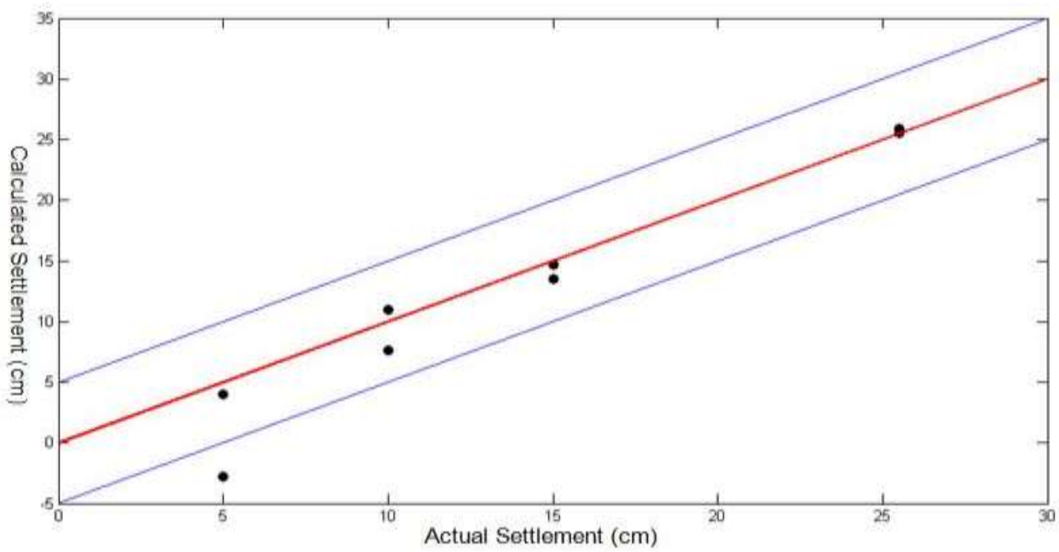

Figure 4. Comparison of actual settlement and detected settlement.

To verify the results of strain detection by internal detector, strain gage is installed at the place where the maximum displacement of pipeline (46.63m) occurs to measure the strain after pipeline displacement and compare it with the result of in-line detection. The measured strain of strain gage is compared with the measured strain of internal detector as presented in Table 2. As revealed in the results of comparison, the detected strain by internal detector can be used to calculate it at 9:00, 0:00 and 3:00 orientations, so the measurement is accurate.

TABLE II. COMPARISON OF MEASURED STRAIN BY STRAIN GAGE AND CALCULATED STRAIN BY IMU.

	4# Position (46.63m)		
	9:00 orientation	0:00 orientation	3:00 orientation
Measured strain by strain gage (%)	-0.023	0.049	0.030
Calculated strain by IMU (%)	-0.019	0.047	0.019

Fig. 5 shows the results of strain detection through repeated operation of internal detector. As revealed in these results, strain detection has good consistency and high repetition rate, so it can be applied in the displacement and strain inspection of pipeline in seismic area. As we see in Fig.6 that the vertical strain of one pipeline in permafrost area remains the same except for some settlement points.

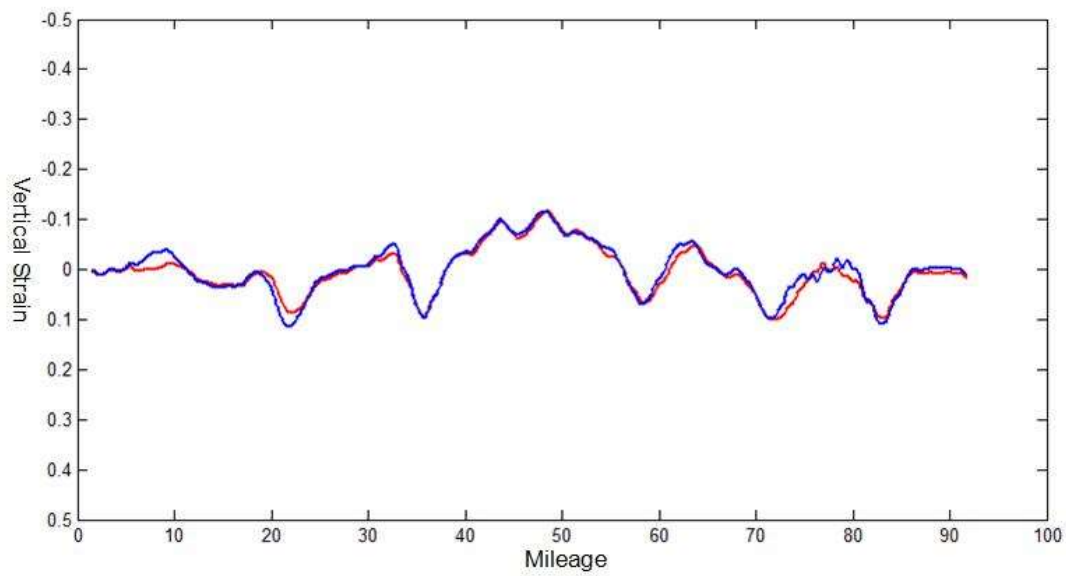

Figure 5. Strains after repeated operation of ILI tool.

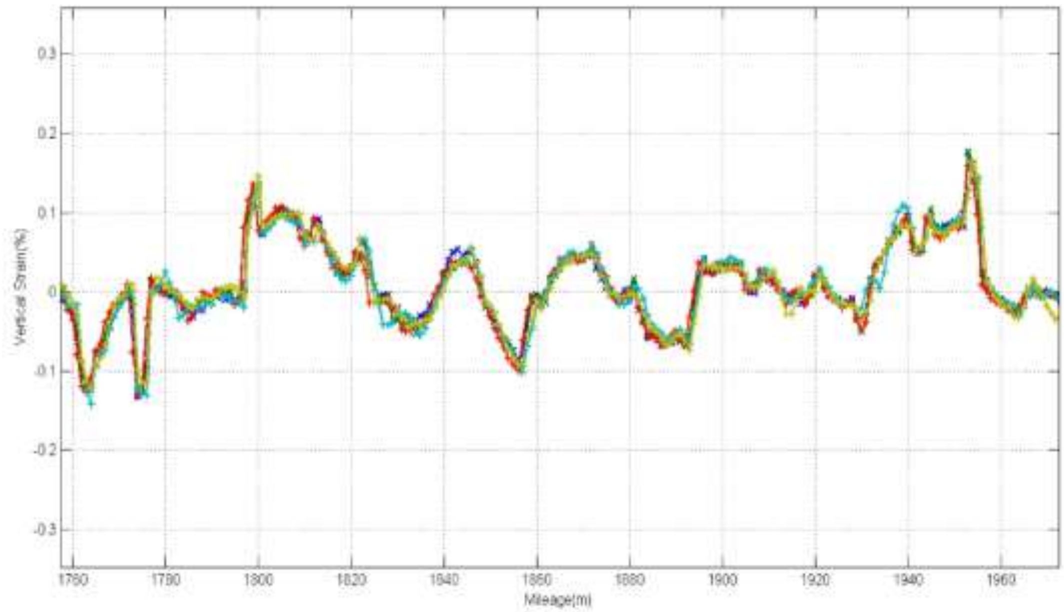

Figure 6. Pipeline vertical strain during 2011-2016.

CONCLUSIONS

Severe longitudinal displacement is caused to the buried long-distance oil & gas pipeline in seismic area due to its features including geological instability, and places strong additional stress on pipeline, which brings very high risks to safe operation of pipeline. The existing technology for displacement and strain monitoring is highly restricted, so it cannot perform the effective detection in pipeline in an all-round way and in a timely manner. This paper puts forward an in-line detection method based on inertial navigation, which can be employed to perform the all-round detection of flexural strain and displacement in long-distance pipeline, and provide the coordinates of pipeline centerline. With this method, it is able to not only effectively monitor the state of pipeline, but also identify the points where the risk of displacement and strain exists in pipeline in a timely manner. Moreover, this method facilitates the accurate positioning of pipeline in mountainous areas, so as to take measures for pipeline protection.

Through the study, this paper gives a detailed introduction to the structure of internal detector based on inertial navigation system, the method for calculation of pipeline centerline, and the method for calculation of pipeline flexural strain. Moreover, traction test is carried out at the site to verify the effectiveness and accuracy of the method, so it provides an effective method for monitoring the displacement and strain of pipeline in seismic area. This detection method is also applicable to local deformation and displacement of pipes in long-distance oil & gas transportation pipeline in service due to soil settlement, move of seabed, swelling by freezing and thawing settlement in frozen soil area, collapse in mined-out area, and temperature load.

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