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Research on positioning and velocity assessment technology for pipeline inspection gauges in long-distance pipelines based on acoustic-magnetic fusion

Badania nad technologią wyznaczania położenia i oceny prędkości tłoków inspekcyjnych w rurociągach dalekosiężnych z wykorzystaniem fuzji akustyczno-magnetycznej

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ABSTRACT: Aiming at the problems existing in the tracking and positioning technology during pigging and internal inspection operations of long-distance oil and gas pipelines, such as being limited by the large burial depth of pipelines and being susceptible to environmental interference, a ground tracking and positioning technology for pipeline inspection gauges based on acoustic-magnetic fusion is proposed. This technology uses non-contact high-precision magnetic sensors and acoustic-vibration sensors to synchronously collect external magnetic field and vibration signals of the pipeline. Through the spatiotemporal response of the magnetic field and vibration when the pipeline inspection gauge passes, as well as the signal time difference of dual magnetic sensors, it realizes the passage indication of pipeline inspection gauges and internal detectors and real-time monitoring of their operating speed. Field test results show that this technology can realize the tracking and positioning of pipeline inspection gauges under different environments, with a high signal-to-noise ratio. Meanwhile, there is a significant difference between the passage signal and the interference signal. The instantaneous speed can be calculated according to the time difference when the pipeline inspection gauge passes, which provides effective technical support for the safe operation and maintenance of pigging operations in long-distance pipelines.

Keywords: long-distance pipelines, pipeline inspection gauges, pnternal detectors, pcoustic-magnetic fusion, pracking and positioning, velocity assessment.

STRESZCZENIE: W artykule zaproponowano naziemną technologię śledzenia i pozycjonowania tłoków inspekcyjnych, opartą na fuzji akustyczno-magnetycznej. Rozwiązanie to stanowi odpowiedź na problemy występujące podczas tłokowania i inspekcji wewnętrznej dalekosiężnych rurociągów ropy naftowej i gazu, w szczególności ograniczenia wynikające ze znacznej głębokości posadowienia rurociągów oraz podatności stosowanych metod na zakłócenia środowiskowe. Technologia wykorzystuje bezkontaktowe, wysokoprecyzyjne czujniki magnetyczne oraz czujniki akustyczno-wibracyjne, które synchronicznie rejestrują sygnały zewnętrznego pola magnetycznego oraz drgania rurociągu. Analiza czasowo-przestrzennej odpowiedzi pola magnetycznego i drgań towarzyszących przejściu tłoka inspekcyjnego, a także różnicy czasowej sygnałów rejestrowanych przez dwa czujniki magnetyczne, umożliwia detekcję przejścia tłoków inspekcyjnych i detektorów wewnętrznych oraz bieżące monitorowanie ich prędkości przemieszczania się. Wyniki badań terenowych wskazują, że omawiana technologia pozwala na śledzenie i pozycjonowanie tłoków inspekcyjnych w zróżnicowanych warunkach środowiskowych, zapewniając wysoki stosunek sygnału do szumu. Jednocześnie sygnał przejścia wyraźnie różni się od sygnałów zakłócających. Prędkość chwilową można wyznaczyć na podstawie różnicy czasu rejestracji sygnału podczas przejścia tłoka inspekcyjnego. Rozwiązanie to zapewnia skuteczne wsparcie techniczne dla bezpiecznego prowadzenia i utrzymania operacji tłokowania w rurociągach dalekosiężnych.

Słowa kluczowe: rurociągi dalekosiężne; tłoki inspekcyjne; detektory wewnętrzne; fuzja akustyczno-magnetyczna; śledzenie i pozycjonowanie; ocena prędkości.

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Introduction

Long-distance oil and gas pipelines are critical infrastructure for ensuring energy security. Pigging operations and internal inspection are core measures for pipeline maintenance and safe operation, as they can effectively remove internal deposits and detect pipeline defects (Zhang et al., 2015a, 2015b; Liu et al., 2024). However, blockage accidents of pipeline inspection gauges or internal detectors occur frequently during operations. Once a blockage happens, rapid and accurate positioning is a prerequisite for efficient unblocking; otherwise, it will lead to transportation interruption and even serious safety accidents (Vinogradova et al., 2015; Verma et al., 2022). Therefore, developing efficient and reliable tracking and positioning technology is crucial for pipeline safety.

Currently, the most commonly used method in engineering is the low-frequency electromagnetic pulse method for tracking the position of pipeline inspection gauges (Rao et al., 2023). That is, a low-frequency electromagnetic transmitter is installed on the pipeline inspection gauge, and a receiver is used to detect low-frequency electromagnetic waves to achieve positioning. However, affected by pipeline wall thickness and burial depth, its positioning capability is greatly limited. It can only achieve positioning under conditions of shallow burial depth and thin wall thickness, and cannot obtain the instantaneous operating speed of the pipeline inspection gauge, thus failing to meet the needs of on-site engineering.

In recent years, pipeline inspection gauge positioning technology has shown a diversified development trend, and the core technical system has formed a technology matrix dominated by electromagnetic pulse technology, noise and vibration technology, pressure fluctuation technology, isotope tracing technology, ultrasonic technology, and distributed optical fiber sensing technology (Olugboji et al., 2015; Piao et al., 2019; Guan et al., 2019, 2020; Huang et al., 2021; Long et al., 2021; Du et al., 2024). A comparison of various technologies and an analysis of their advantages and disadvantages are shown in Table 1.

Benefiting from the gradual improvement of accompanying optical cables for long-distance pipelines, distributed optical fiber sensing technology has become a research hotspot in pipeline inspection gauge tracking and positioning technology in recent years, with technical advantages such as online real-time tracking and low operation costs (Kim et al., 2003; Bernasconi and Giunta, 2020). However, distributed optical fiber sensing technology is more used to monitor behaviors such as earth-moving construction, oil theft, and pipeline leakage in pipeline areas, ensuring that the pipeline structure is not damaged by external factors. There are still many shortcomings in its application to the tracking and positioning of pipeline inspection gauges:

(1) Some long-distance pipelines are laid parallel to roads, expressways, and railways, so optical fiber vibration signals are easily affected by vibrations generated by passing cars and trains; moreover, the essence of optical fiber sensing is to realize vibration detection by using phase changes of Rayleigh scattered light. Limited by its principle, its ability to distinguish and identify different vibration signals is

Table 1. Comparison of technologies and analysis of advantages and disadvantages

Technology type	Applicable scenarios	Advantages	Limitations
Electromagnetic pulse	Gas pipelines, regular monitoring	Low cost, wide application range	Serious signal attenuation, environmental interference from high-voltage wires may cause false alarms
Noise and vibration	Large-diameter, high-pressure pipelines	No need to set up monitoring points along the pipeline	Detectable pipeline length is short, early-stage work is cumbersome, poor universality for different pipelines
Pressure fluctuation	High-speed tracking, blockage positioning	Simple principle, no complex calculation required	Pressure transmitters need to be installed on the pipeline, can only be installed in stations and valve chambers, cannot accurately locate the blockage position of pipeline inspection gauges or internal detectors
Distributed optical fiber sensing	Long-distance, complex terrain pipelines	Anti-electromagnetic interference, high real-time performance, wide coverage	High initial deployment cost, requires a professional operation and maintenance team, low accuracy, large signal interference
Isotope tracing	Gas pipelines, regular monitoring	High signal-to-noise ratio, without external interference	There is a radiation risk and it is harmful to the human body
Ultrasonic	Liquid medium pipelines	Wide monitoring range	Active type, applicable only to liquid-filled pipelines on the ground. Currently, it is used less frequently.

poor. Therefore, in areas with frequent human activities, the tracking and positioning signals are severely interfered, and problems such as false alarms and misreports are unavoidable.

(2) Distributed optical fiber sensing technology is highly sensitive to vibrations. When the pipeline inspection gauge travels in the pipeline, the optical fiber can detect vibration signals within a large range before and after the position of the pipeline inspection gauge, making it impossible to achieve accurate positioning and to accurately perceive the real-time operating speed of the pipeline inspection gauge.

(3) Distributed optical fiber sensing technology requires that the accompanying optical cables of long-distance pipelines have at least one spare core for connecting multiple optical modems along the route. Some accompanying optical cables have no extra cores, and due to the laying conditions of different pipelines, this technology has significant limitations in practical applications.

(4) Distributed optical fiber sensing technology involves a large amount of monitoring data and high algorithm complexity, which leads to high performance requirements for servers and hardware equipment, high deployment costs, and the need for professional personnel for maintenance.

Currently, “multi-technology fusion” is a new development direction for pipeline inspection gauge tracking and positioning devices. Based on addressing practical engineering problems in pigging operations, this study proposes an acoustic-magnetic fusion technology that realizes coordinated collection and analysis of ground acoustic-vibration signals and magnetic anomaly signals. Without the need to modify pipeline inspection gauges, it achieves full-coverage positioning of both metal internal detectors, and enables accurate analysis of instantaneous velocity by precisely capturing the time difference of the gauge passing. The main work and innovations of this study are as follows:

1. Based on the behavioral characteristics of pipeline inspection gauges and internal detectors in pipelines, this study integrates two physical principles – acoustics and magnetism – and innovatively proposes an acoustic-magnetic fusion technology capable of tracking and positioning under conditions of large burial depth and large wall thickness.
2. Through monitoring tests, the fluctuation characteristics of magnetic signals and acoustic-vibration signals when the pipeline inspection gauge passes through are revealed.
3. The effectiveness of the acoustic-magnetic fusion technology under different working conditions is verified, providing a new technical solution for realizing the intelligent tracking and safety management and control of pipeline inspection gauges and internal detectors.

Technical principle

Acoustic-magnetic fusion perception mechanism

In pigging and internal inspection operations of long-distance pipelines, the acoustic-magnetic fusion technology constructs a passive positioning system without external active excitation by accurately capturing the characteristics of acoustic-vibration signals caused by structural irregularities of pipeline girth welds and the fluctuation characteristics of static magnetic field superposition signals during the operation of pipeline inspection gauges. When pipeline inspection gauges or internal detectors pass through girth welds, geometric irregularities in the weld area – such as reinforcement and misalignment – will cause periodic mechanical impact between them and the pipe wall, exciting broadband acoustic-vibration signals containing rich information, which propagate to the ground through coupled propagation in multiple layers of media such as the pipeline itself and soil, forming abnormal acoustic-vibration signals detectable on the ground. Meanwhile, according to the principle of static magnetic field superposition, when pipeline inspection gauges with metal components are in operation, their own magnetic fields superimpose with the geomagnetic field to form a magnetic anomaly gradient field, generating monitorable fluctuating magnetic anomaly signals on the ground; the acoustic-magnetic fusion technology uses high-precision acoustic-vibration sensors and magnetic sensors to capture the abnormal signals when the pipeline inspection gauge passes through on the ground, and through in-depth decoupling of acoustic-vibration characteristics and static magnetic field superposition effects, it constructs a multi-physical field mapping relationship of “mechanical vibration-electromagnetic signal-spatial position”.

A schematic diagram of the technical principle is shown in Figure 1.

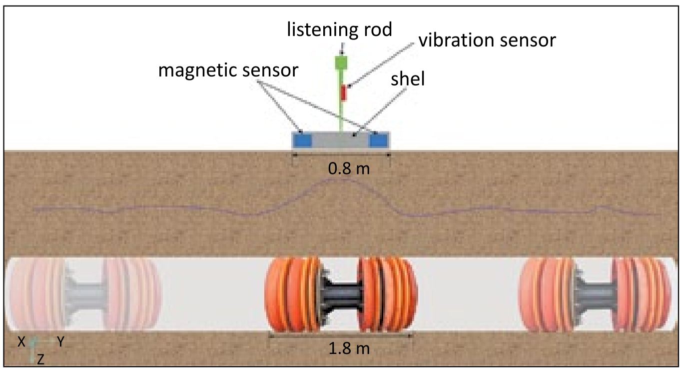

Figure 1. Acoustic-magnetic fusion perception mechanism

Instantaneous velocity assessment principle

The core of velocity assessment is based on time difference measurement over a fixed spatial baseline. On the ground directly above the pipeline, two identical magnetic sensors are deployed at a fixed interval *d*. When the pipeline inspection gauge passes through, the same magnetic anomaly feature is captured by the two sensors successively. Record the moments t_1 and t_2 when this feature arrives at the two sensors; then the instantaneous velocity *v* can be expressed as:

$$v = \frac{d}{t_2 - t_1} \quad (1)$$

Experimental design and methods

Experimental equipment

Experimental data collection uses high-precision three-axis fluxgate sensors and millivolt-level acoustic-vibration sensors as data perception interfaces. Monitoring experiments require collecting weak magnetic signals on the ground when the pipeline inspection gauge passes through, which imposes high requirements on the accuracy of magnetic sensors. The application team independently developed three-axis fluxgate sensors to collect weak magnetic signals, which mainly consist of four parts: high-permeability magnetic core, excitation coil, induction coil, and modulation and filtering circuit, with main performance parameters shown in Table 2.

Table 2. Main technical parameters of sensors

Number	Technical indicator	Parameter value
1	Acquisition accuracy	±0.02 nT/m
2	Signal range	±100 μT
3	Sampling frequency	100 Hz
4	Data format	16-bit; 28 bytes/packet
5	Supply voltage	±12 V ~ ±15 VDC
6	Noise	≤20 pTrms/√Hz@1Hz

The experiment utilized the fluxgate sensor independently developed by the team. The magnetic sensor is based on the transformer effect and Faraday's law of electromagnetic induction; it measures the magnetic field by utilizing the nonlinear relationship between magnetic induction intensity and the intensity of the external measured magnetic field when the magnetic core, in the external measured magnetic field, is under the saturation excitation of the alternating magnetic field generated by the excitation coil. Its magnetic field measurement accuracy can reach ±1 nT. Two three-axis fluxgate sensors are used to form a magnetic gradient measurement device, with a distance of 1 m between the two sensors, and the magnetic field detection direction is shown in Figure 2.

The vibration sensor is a commercially available piezoelectric acceleration sensor of CRY433-IEPE from Hangzhou

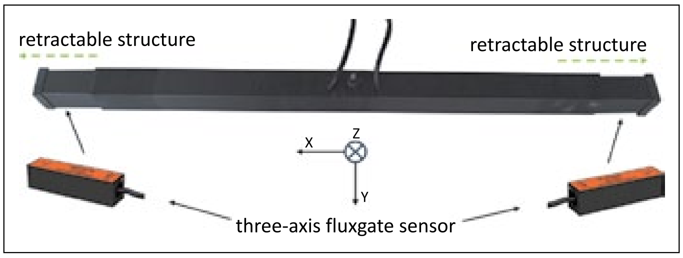

Figure 2. Fluxgate Sensor

Table 3. Dynamic indicators of the acoustic-vibration sensor

Serial number	Technical indicator	Parameter value
1	Axial sensitivity (23 ±5°C)	Approximately 100 mV/g
2	Measurement range	±50 g
3	Linearity	<1%
4	Maximum lateral sensitivity	<5%
5	Frequency response (±10%)	1–10000 Hz
6	Mounted resonant frequency	>25 kHz
7	Resolution	0.0004 g
8	Polarity (Acceleration direction from bottom to sensor)	Positive

Zhaohua Electronic Technology Company. The acoustic--vibration sensor features a wide measurement range and a low-impedance voltage design; the total weight of the sensor is 5.5 g, and its appearance is a φ 20 mm cylindrical shape, making it easy to arrange.

Specific dynamic indicators are shown in Table 3.

The host computer system consists of a laptop computer and a high-precision, high-speed acquisition device. The acquisition device converts analog signals into digital signals; after receiving the data, the host computer software plots fluctuation curves in real time and automatically saves them.

Experimental objects

The experiment was conducted synchronously during the actual pigging operation of a long-distance pipeline in China. The pipeline for this pigging operation is an X70 steel straight-seam pipe, with an outer diameter of 1016 mm, a nominal wall thickness of 17.5 mm, and a 3PE external anti-corrosion coating. It has a design pressure of 10 MPa and an operating pressure of 6.5 MPa, with natural gas as the transport medium. The operational pipeline inspection gauge is a combined diameter-measuring type with polyurethane cups and a straight plate, featuring an interference fit of 3% and a length of 1.46 m. Dispatched from the pig launcher station at 13:18 on March 27, 2025, it entered the pig receiver of the terminal station at 05:42 on March 28, covering an operation distance of 107.5 km with a total operation time of 16 hours and 24 minutes, and a start-

Figure 3. Appearance of the pipeline inspection gauge

ing pressure difference of 0.31 MPa. The pipeline inspection gauge is shown in Figure 3.

Experimental methods

During the experiment, a total of 8 monitoring points were set along the pipeline, including 4 turning points, 2 uphill and downhill sections, and 2 straight pipe sections. According to the pipeline construction data, the burial depth of the monitoring points ranges from 1 m to 2.5 m. The surrounding environments of the monitoring points include farmland, areas near village roads, national highways, and streams, etc., to verify the feasibility of monitoring signals in areas with frequent human activities. The geology of the monitoring points mainly includes farmland, depressions, cement roads, and stone-brick roads, aiming to explore the impact of geology on signals. During monitoring, first, a pipe locator is used to locate the position and direction of the pipeline on the ground. Second, the magnetic gradiometer is placed directly above the pipeline along its axial direction. For the installation of the acoustic vibration sensor, a probe made of acoustic monitoring steel was used for auxiliary fixation; this steel needle has a total length of 1 meter and is inserted into the ground approximately 10 cm. The acoustic vibration sensor is fixed at a position 50 cm away from the steel needle to indirectly transmit the acoustic vibration information to the acoustic vibration sensor, thereby achieving signal acquisition. The installation position of the sensor is shown in Figure 4.

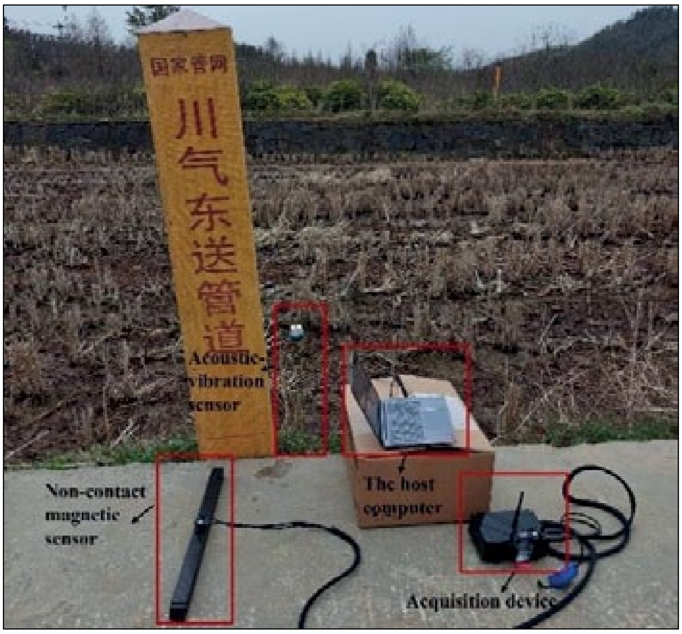

Figure 4. Sensor placement method

Results and discussion

Analysis of monitoring signals in straight pipe sections

This monitoring point is 23 km away from the pig launcher station of the pipeline inspection gauge, with a pipeline burial depth of 2.5 m and farmland as the underlying geology. When the pipeline inspection gauge passes through, the magnetic fluctuation signals in the X, Y, and Z directions are shown in Figure 5 (a, b, c), and the acoustic-vibration signal is shown in Figure 5 (d). It can be seen from the figures that when the pipeline inspection gauge passes through, the magnetic signals in the three directions and the acoustic-vibration signal all show significant fluctuations.

For the magnetic field signals, the X-direction signal shows a unimodal fluctuation: it first decreases slightly, then rises rapidly with an amplitude of approximately 600 nT, and finally returns to the original magnetic field amplitude and remains stable. The Y-direction and Z-direction signals exhibit bimodal fluctuations similar to sine waves, with opposite fluctuation directions; the fluctuation amplitude of the Y-direction is about 750 nT, and that of the Z-direction is about 1100 nT. Observing the signals from the two sensors, it can be seen that when the pipeline inspection gauge passes through, the signal waveforms of the two sensors in all directions are identical, with roughly the same amplitudes, but there is a misalignment in peak positions. This is because the pipeline inspection gauge passes directly below the two sensors successively. Extract the extreme points of the Z-axis signal fluctuations. The time point of sensor 1 is 50.29 s, that of sensor 2 is 49.92 s. The distance between the two sensors is 0.8 m. Thus, the instantaneous speed of the pig can be calculated as 2.162 m/s. The speed of

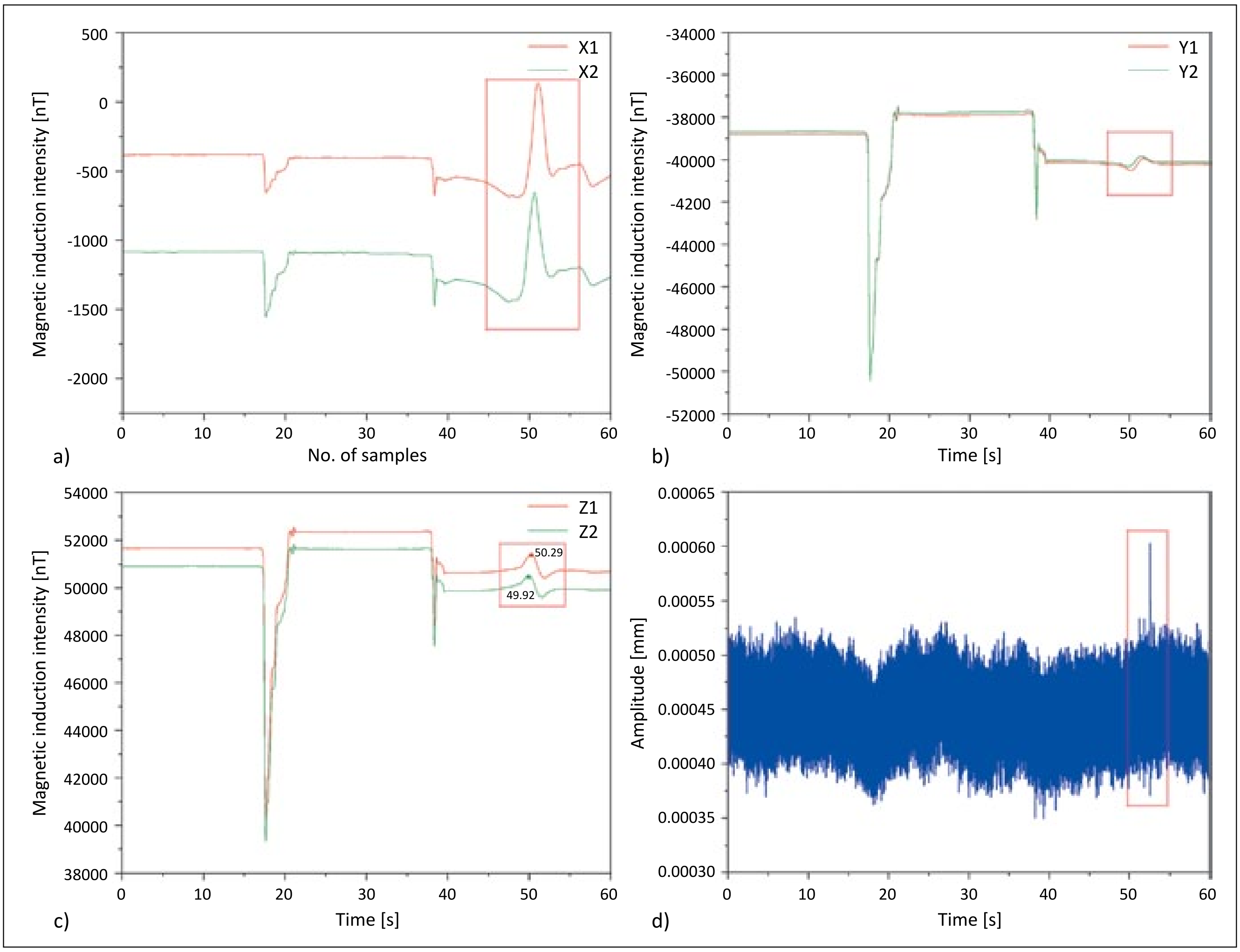

Figure 5. Monitoring signals of the straight pipe section

the pigging device in the pipeline section is 2.216 m/s, with an error rate of 2.4%.

For the acoustic-vibration signal, the acoustic-vibration noise caused by the environment fluctuates within the range of approximately 0.0004–0.000525 mm. When the pipeline inspection gauge passes through, the amplitude of the acoustic-vibration signal increases to 0.0006 mm. The signal-to-noise ratio is high, which indicates that the acoustic-magnetic fusion technology is feasible for tracking and locating the pipeline inspection gauge. It can be seen from the magnetic signals that there are also many fluctuations in all directions before the pipeline inspection gauge passes through, which are caused by human activities near the monitoring and positioning area. However, these fluctuations differ from the signals generated when the pipeline inspection gauge passes through. Firstly, the interference signals from human activities are random: in all directions, the waveforms of the interference signals from the two magnetic sensors are different, and their amplitudes also vary. In addition, the positions of the fluctuation peaks of the interference signals are roughly the same, with no time difference, which is the most significant difference from the passing signals. Meanwhile, since the monitoring point is located in farmland with few close-range human activities, the acoustic-vibration signal does not fluctuate due to interference.

Analysis of monitoring signals in turning pipe sections

This monitoring point is 41 km away from the pig launcher station of the pipeline inspection gauge, with a pipeline burial depth of 2 m. The monitoring point is located on a cement pavement. When the pipeline inspection gauge passes through, the magnetic fluctuation signals in the X, Y, and Z directions are shown in Figure 6 (a, b, c), and the acoustic-vibration signal is shown in Figure 6 (d).

For the magnetic field signals, the fluctuations in all three directions at the turning section show unimodal characteristics, with the Y and Z directions exhibiting a slight concave fluctuation trend before the main fluctuation. In terms of amplitude, the fluctuation amplitude in the X direction is approximately 600 nT, that in the Y direction is about 350 nT, while the Z direction has the largest fluctuation amplitude at 1100 nT. When the pipeline inspection gauge passes through, there is still a time difference between the positions of the fluctuation

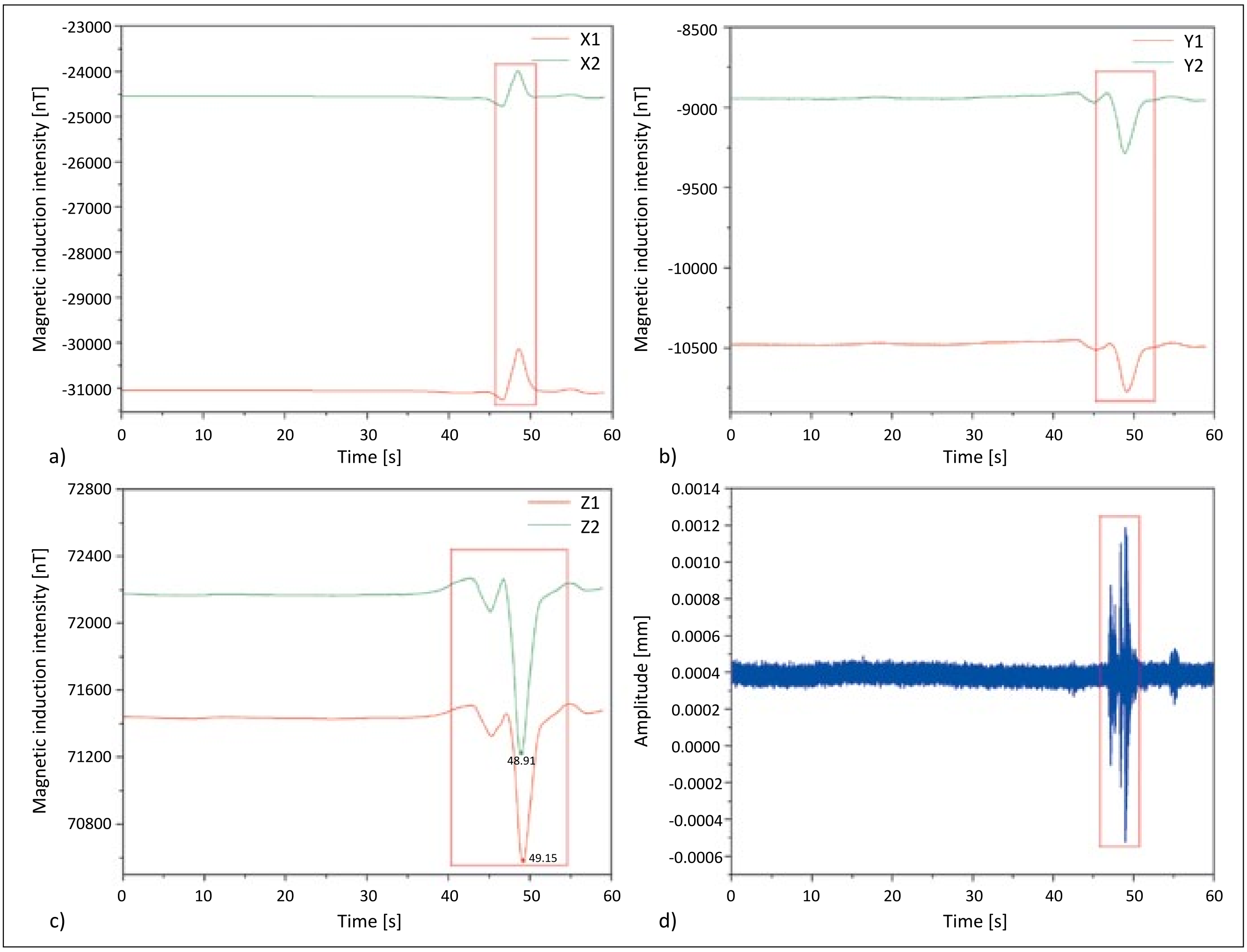

Figure 6. Monitoring signals of the turning pipe sections

peaks in each direction. Extract the extreme points of the Z-axis signal fluctuations. The time point of sensor 1 is 49.15 s, that of sensor 2 is 48.91 s. The distance between the two sensors is 0.8 m. Thus, the instantaneous speed of the pig can be calculated as 3.333 m/s. The speed of the pigging device in the pipeline section is 3.172 m/s, with an error rate of 5.1%.

For the acoustic-vibration signal, the amplitude of the passing signal at the turning section is significantly larger compared with that in the straight pipe section, fluctuating within the range of –0.0006 mm to 0.0012 mm. This is caused by the pipeline inspection gauge impacting the pipeline at the turning section. In addition, there are two stages of fluctuations in the acoustic-vibration signal when the pipeline inspection gauge passes through: the first stage has a smaller fluctuation, ranging from –0.0001 mm to 0.0009 mm.

Long-distance pipelines in China are double-end welded at turning points, with circumferential welds present both at the entrance and exit of the bend. The monitoring point is located between these two welds, and due to the different distances from the two welds, two stages of fluctuations with unequal amplitudes are generated.

Analysis of monitoring signals in downhill pipe sections

This monitoring point is 72 km away from the pig launcher station of the pipeline inspection gauge, with a pipeline burial depth of 1.3 m. It is located at the inflection point between a downhill section and a straight pipe section, and the underlying geology is paddy field. When the pipeline inspection gauge passes through, the magnetic fluctuation signals in the X, Y, and Z directions are shown in Figure 7 (a, b, c), and the acoustic-vibration signal is shown in Figure 7 (d).

For the magnetic field signals, due to the shallow burial depth here, the static magnetic field intensity of the pipeline is relatively high, resulting in signal saturation of the Y-direction magnetic sensor. For the X and Z directions, significant fluctuations occur when the pipeline inspection gauge passes through. Specifically, the X-direction first shows a slight concave fluctuation, then rises sharply, followed by a fall, and then rises slightly back to the original magnetic field intensity, with a fluctuation amplitude of 2100 nT. The Z-direction exhibits a unimodal fluctuation with an amplitude of 2200 nT, and there is a slight concave fluctuation before approaching the peak, which is caused by the distance variation between the pipe-

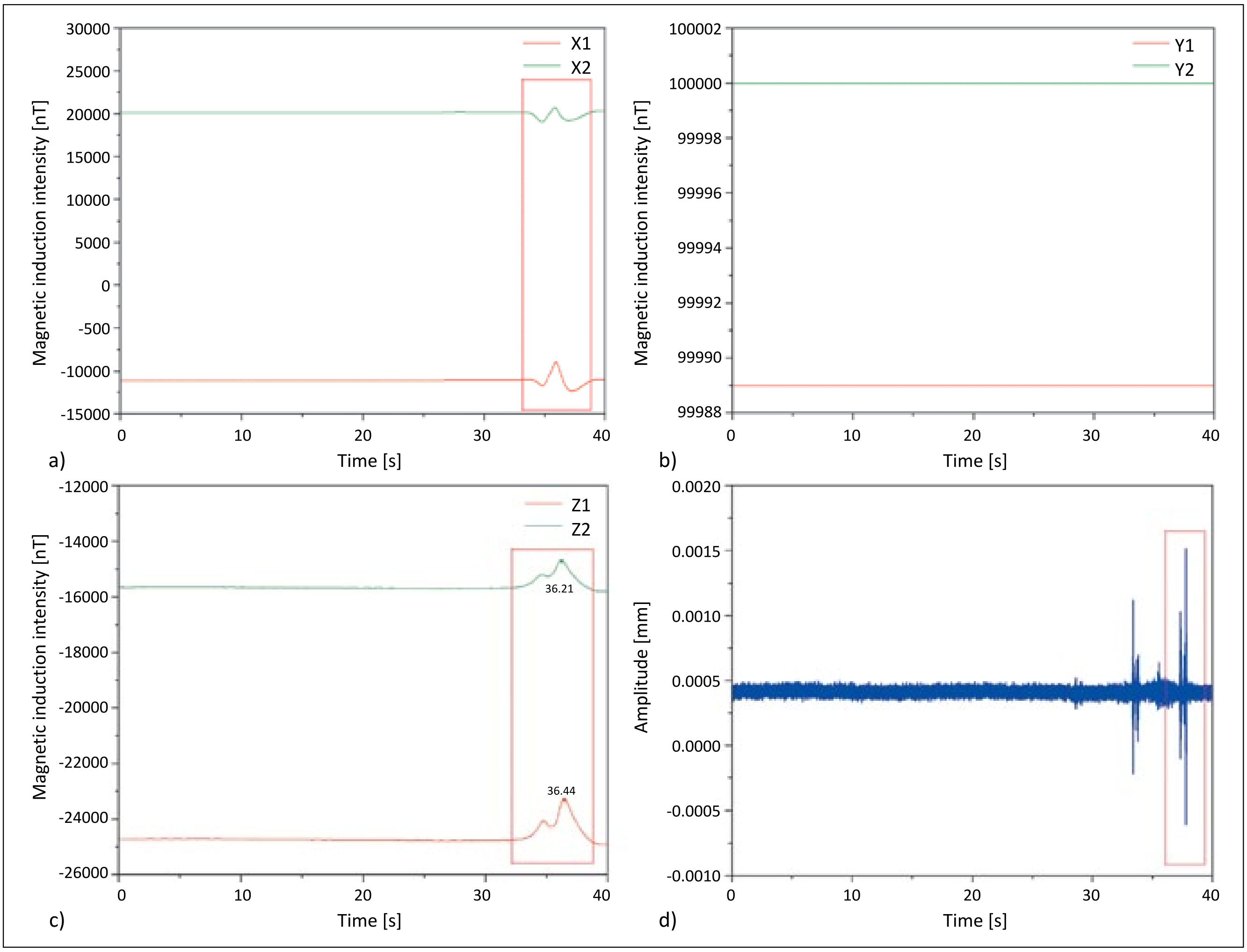

Figure 7. Monitoring signals of the downhill pipe sections

line inspection gauge and the magnetic sensor at the downhill inflection point. It can be seen from the magnetic signals in the X and Z directions that at shallow burial depth positions, the amplitude of the pipeline inspection gauge passing signal increases significantly. Extract the extreme points of the Z-axis signal fluctuations. The time point of sensor 1 is 36.44 seconds, that of sensor 2 is 36.21 seconds. The distance between the two sensors is 0.8 meters. Thus, the instantaneous speed of the pig can be calculated as 3.478 meters per second. The speed of the pigging device in the pipeline section is 3.239 meters per second, with an error rate of 7.4%.

For the acoustic-vibration signal, in the downhill section, due to the temporary increase in the speed of the pipeline inspection gauge, the impact acoustic-vibration when passing through the circumferential weld increases significantly, with a fluctuation range of –0.0007 mm to 0.0016 mm. In addition, during the process from the pipeline inspection gauge approaching to moving away from the monitoring point, the acoustic-vibration sensor collected continuous impact acoustic-vibration signals generated by the pipeline inspection gauge hitting the circumferential weld: the impact amplitude gradually increases when approaching and gradually decreases when moving away. It can be seen from Figure 7 (d) that at shallow burial depth positions, the acoustic-vibration sensor can capture the corresponding impact information when the pipeline inspection gauge is approaching.

Characteristics of pipeline inspection gauge passing signals

By analyzing the pipeline inspection gauge passing signals under different conditions, the typical characteristics of the passing signals can be summarized as follows:

1. For magnetic signals: when the pipeline inspection gauge passes through, the static magnetic field in each direction will show significant fluctuations, but the waveform is not unique; the amplitude of the magnetic signal in the Z direction is the highest and remains stable under different monitoring conditions; the two groups of magnetic signals have the same waveform, similar amplitudes, and a time difference when the pipeline inspection gauge passes through – this is an obvious difference from other magnetic interference signals. The instantaneous speed of the

pipeline inspection gauge can be calculated based on this time difference.
2. For acoustic-vibration signals: when the pipeline inspection gauge passes through, the acoustic-vibration presents an impact signal waveform; moreover, continuous impact responses will be detected when the burial depth is shallow.
3. The magnetic signals and acoustic-vibration signals will respond synchronously at the same time or within a short time period. The coupling of these two physical fields can not only avoid interference from other human activities but also improve the confidence level of the pipeline inspection gauge passing signals.

Conclusions

This study addresses engineering pain points in the tracking and positioning of pigging tools and in-line inspectors for long-distance oil and gas pipelines, such as deep burial depth limitations, strong environmental interference, and difficulty in speed monitoring. It proposes and systematically verifies a ground-based tracking, positioning, and speed evaluation technology based on acoustic-magnetic fusion. Through theoretical construction, experimental design, and on-site validation, a practical technical scheme has been formed. The main research conclusions are as follows:

1. Based on the mechanical vibration and magnetic field superposition effects during the operation of the pipeline inspection gauge, an innovative "acoustic-vibration + magnetic anomaly" dual-signal collaborative sensing mechanism is proposed. Passive positioning can be achieved without active modification of the pipeline inspection gauge. This system resolves the issues of rapid signal attenuation in traditional electromagnetic pulse technology and high false alarm rates in distributed optical fiber sensing technology by analyzing broadband acoustic-vibration signals induced by pipeline circumferential welds and superposed static magnetic field signals from metal components of the pipeline inspection gauge, thereby establishing a "mechanical vibration-electromagnetic signal-spatial position" multi-physical field mapping relationship.
2. In terms of magnetic signals: when the pipeline inspection gauge passes through, magnetic signals in all directions exhibit characteristic fluctuations; the signals from dual magnetic sensors have consistent waveforms, similar amplitudes, and a fixed time difference, providing a reliable basis for calculating instantaneous speed. Compared with the interval speed, the error rate is less than 10%.
3. In terms of acoustic-vibration signals: continuous impact responses can be captured in areas with shallow burial depth, and they respond synchronously with magnetic signals, significantly enhancing anti-interference capability.
4. This technology requires no modification to the pipeline itself, features low deployment cost and easy operation, and can provide real-time data support for the rapid positioning of pipeline inspection gauge stuck accidents and plugging removal decision-making. It effectively reduces the risk of transportation interruption and holds significant engineering value for ensuring the safe and efficient operation of long-distance oil and gas pipelines.

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