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Research and Application of Low-Pressure High-Passability Tri-Axial Magnetic Flux Leakage Internal Detection Technology

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Abstract: Aiming at the practical problems of subsea long-distance pipelines, such as generally low operating pressure, widespread complex working conditions including local diameter reduction, oval deformation, and small-radius bends, conventional magnetic flux leakage (MFL) internal detectors cannot pass through some pipelines due to insufficient pressure. This paper conducts a research on the tri-axial MFL internal inspection technology with low pressure and high passing ability. Firstly, the working conditions of subsea pipelines and the applicable conditions of traditional MFL internal detectors are analyzed. Based on the mechanism of magnetic flux leakage detection, key technical approaches including low-friction MFL structure and low-friction large-deformation dynamic cups are proposed. Secondly, the finite element method is used to compare and analyze steel-brush-type and yoke-type MFL structures. Combined with the B-H curve of steel and the requirements of MFL sensitivity, the dual-section yoke-type low-friction magnetic circuit is optimized from the balance among magnetization depth, peak leakage magnetic field, and friction resistance, and the structural design of the MFL unit system is completed. Based on contact mechanics theory, the contact stress and contact length of typical cup structures (conical, straight-plate, circular, and dished cups) under different interference fits are simulated. A cup optimization criterion indexed by "unit circumferential driving force vs. average contact stress per unit length" is proposed, and a multi-diameter dynamic cup combination is developed to meet the passing requirements of over 30% diameter reduction and 1.5D bends. The two major technical difficulties of stable operation at low pressure and high passing ability are solved. The structural reliability and passing performance of the internal detector are verified through 323 mm test pipeline and 12-inch loop tests. A low-pressure tri-axial MFL inspection of approximately 2.1 km pipeline is successfully conducted in the sea trial of a 12-inch water injection subsea pipeline in an offshore oilfield. The test and sea trial results show that the developed 12-inch tri-axial MFL internal detector with low pressure and high passing ability operates stably under low pressure and small pressure fluctuation conditions, and its passing capacity reaches the level of geometric detectors. It can effectively expand the applicable scope of MFL internal inspection for subsea pipelines and provide reliable technical support for the integrity management of offshore oil and gas long-distance pipelines.

Keywords: Tri-axial Magnetic Flux Leakage; Low Pressure and High Passability; Dynamic Cup; Magnetic Circuit Structure; Internal Inspection of Long-distance Pipelines.

1. Introduction

Subsea long-distance pipelines are critical infrastructure for the development and export of offshore oil and gas fields, known as the "lifeline of offshore oil and gas fields"[1]. With the increase of service life, factors such as corrosion, welding defects and third-party damage tend to cause pipe wall thinning, cracks and leakage accidents, posing serious threats to production safety and the marine environment.[3] Therefore, regular in-line inspection (ILI) has become one of the key procedures in pipeline integrity management.

Magnetic Flux Leakage in-line inspection technology uses permanent magnets or electromagnets inside the pipeline to locally saturate the pipe wall. When anomalies such as corrosion thinning or cracks exist, magnetic flux leaks out of the pipe wall at defects, forming a measurable leakage magnetic field at sensor positions inside the detector. The amplitude of magnetic flux leakage is closely related to defect parameters including depth, width and orientation. For tri-axial MFL inspection, the radial (Br), axial (Bx) and circumferential (By).[2]

components exhibit different sensitivities to defects of various orientations and shapes. A comprehensive balance among magnetization intensity, sensor resolution and passing resistance must be achieved within the limited installation space.

Traditional MFL in-line detectors are mainly designed for onshore long-distance pipelines, and generally have the following limitations:

The designed minimum stable operating pressure is relatively high, so MFL inspection cannot be directly performed on many low-pressure water injection, multiphase transportation or gas subsea pipelines under normal operating pressure.

The tool body has high rigidity and limited passing capability, making it difficult to safely traverse high-risk pipe sections such as local diameter reduction, oval deformation and small-radius bends.

Some old pipelines have undergone frequent modifications and feature complex geometric characteristics. The oversized MFL unit and driving unit tend to cause sticking or stalling near bends and fittings.

Based on the research project, this paper systematically carries out theoretical analysis and finite element simulation focusing on two key technologies: low-friction MFL structure and low-friction large-deformation dynamic cups. The engineering applicability and promotion value of the low-pressure high-passability tri-axial MFL in-line inspection

technology are verified through loop tests and offshore field applications.

Key Technical Routes

Based on the above analysis, the key technical routes determined in this project are as follows:

Design of low-friction magnetic flux leakage structure: On the premise of satisfying the magnetization level of 10–20 kA/m, the steel-brush-type and yoke-type magnetic circuit structures are compared. The arrangement of magnetic steel and the shape of magnetic yoke are optimized via finite element analysis to reduce the contact pressure and frictional resistance between the structure and the pipe wall.

Design of low-friction large-deformation dynamic cups: Based on contact mechanics theory and finite element simulation, the structural shape and interference fit of the cups are optimized. Constrained by the traction demand and allowable contact stress, the dynamic cup combination that meets the requirements of large-deformation passing capability is obtained.

2. Design of Low-Friction Magnetic Flux Leakage Structure

(1) Optimal Design of 2D Magnetic Circuit

To generate sufficient magnetic field signals that can be measured and distinguished in the pipeline under test, thereby analyzing the parameters of pipe wall defects, the research group further optimized the magnetic circuit of the non-destructive internal inspection device, so that the pipe wall of the tested pipeline can reach the critical magnetic saturation state.

Since the purpose of magnetic circuit optimization is to achieve better magnetic circuit performance, the optimization design process does not need to consider defects, but the following conditions shall be taken into account:

The pipe wall reaches magnetic saturation; The magnetic flux density in the air domain is close to 0; Attention shall be paid to the lightweight and miniaturization of selected materials;

Attention shall be paid to the cost performance of selected magnetic circuit materials.

The premise of conducting magnetic circuit optimization within a given range is to understand the influence of changing the structural dimensions of the magnetic circuit on the generated magnetic flux density B. Through 2D simulation of magnetic circuit structures with different dimensions and distances, the optimal parameters of the magnetic circuit structure are finally determined.

Factors to be considered include: the thickness and length of the yoke, the thickness and length of the permanent magnet, the thickness of the magnetic conductor, and the thickness of the gasket.

For a given defect depth, the valley spacing of the axial component of magnetic flux density increases with the increase of defect length, and the peak spacing of the radial component of magnetic flux density also increases with the increase of defect length.

When the defect length is fixed, the peak value of the axial component of magnetic flux density increases with the increase of defect depth, and the peak-to-peak value of the radial component of magnetic flux density also increases with the increase of defect depth.

(2) 3D Finite Element Simulation and Analysis

Through simulation using a three-dimensional finite element model, the magnetic vector distribution of defects inside the pipeline and the three-dimensional curve distribution of magnetic flux density of the magnetic flux leakage signal were obtained, and the three-dimensional simulation results were achieved. Simulation experiments show that pipeline defects have an influence on the magnetic field distribution. Through three-dimensional simulations of defects with different parameters, the magnetic flux leakage patterns under different defects were obtained, and the relationship between defect size and the characteristic values of magnetic flux leakage signals was found, which lays a foundation for the subsequent identification of defects using magnetic flux leakage signals.

The signal strength in the magnetic flux leakage region is determined not only by defect parameters but also by various other factors, [5]including pipeline wall thickness, pipe wall magnetization level, residual magnetism, pipeline material, magnetization system structure (magnet type selection, coupling method, pole spacing), lift-off value, operating speed, pressure fluctuation, and so on. Under given conditions such as pipeline wall thickness, material, magnetic saturation level, and operating speed, the optimal and reasonable arrangement of the magnetic circuit structure—including parameters of the iron core, magnets, wear-resistant plates, and pole spacing—determines the magnetization capability and overall size of the magnetic circuit, and also ensures that the collection of magnetic flux leakage signals is in an optimal state.

A good magnetic circuit design, while meeting design requirements, should not only bring the magnetic field of the steel pipe to a near-saturation level but also make full use of the magnet energy as much as possible to achieve a lightweight and miniaturized overall magnetic circuit.[4] Therefore, in magnetic circuit design, after the magnet material is selected, the operating point of the magnet should be close to the maximum energy product point, and the iron core should also be in a magnetization state with high magnetic permeability.

A good magnetic circuit design should also ensure that the signal-to-noise ratio (SNR) of the signal collected by the sensor is maximized. In the magnetic circuit design, the air-coupled magnetic field should be reduced, and the sensor should not be placed in regions where the direct air-coupled magnetic field is stronger. Increasing the pole pitch helps reduce the air-coupled magnetic field, but it also reduces the magnetic field strength inside the pipe wall.

Therefore, the pole pitch should be reasonably arranged to minimize the influence of the air-coupled magnetic field on the SNR of the sensor, without significantly reducing the magnetic flux leakage signal strength at the defect. Previous work has shown that, in magnetic circuit design, the pole pitch should be increased as much as possible on the premise that the magnetic field strength inside the pipe wall is sufficient to achieve saturation, so as to improve the SNR. Reducing the radial length of the backing iron can decrease the magnetic flux leakage from the backing iron, but it also shortens the radial distance from the sensor to the iron core, which relatively moves the sensor toward regions with a stronger direct air-coupled magnetic field. Thus, the radial length of the backing iron should be properly defined to improve the SNR of the signal collected by the sensor. Previous work has shown that, at low detection speeds, the SNR of the measured signal can be improved by appropriately shortening the radial length of the backing iron, provided that the traveling

capability of the detector is guaranteed.

Since the detector needs to meet the inspection requirements for different pipe diameters from 10 inches to 12 inches, the magnetic circuit of the detector is designed so that the permanent magnets can magnetically saturate the pipe walls with different wall thicknesses from 10 inches to 12 inches. Based on 2D and 3D finite element modeling methods, the system structure of the pipeline internal inspection equipment is designed. By using the corresponding relationship between defect size and the characteristic quantities of magnetic flux leakage signals, a theoretical basis is provided for the quantitative analysis of defect size.

The design process starts from a simplified 2D model according to the working principle, carries out 2D simulation, then establishes a 3D model for further simulation and optimization.

The influences of factors such as permanent magnet thickness, permanent magnet length, component materials, pole pitch, iron core thickness, and the number of steel brush bundles are analyzed, and the optimized physical parameters of the magnetic circuit part for the experimental platform are summarized.

The simulation results are shown in Figure 1.1 to Figure 1.9:

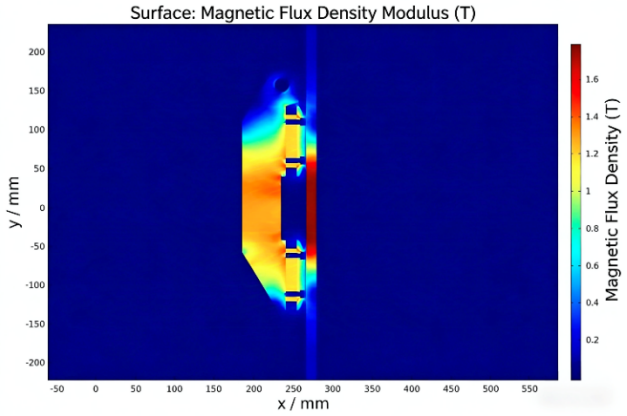


Fig 1. Magnetic flux density norm of the finite element simulation model for the yoke-type magnetic circuit in a 12-inch pipeline

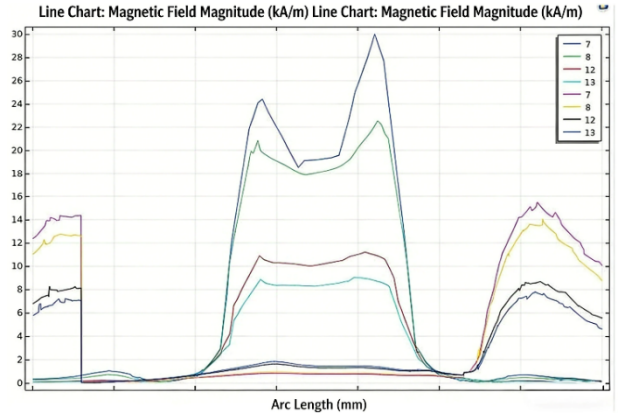


Fig 2. Magnetic induction intensity curves of the pipe wall and iron core for the yoke-type magnetic circuit in a 12-inch pipeline;

Based on the above simulation results, it is found that the size of the steel brush magnetic circuit core is too large to meet the structural requirements. Therefore, the yoke-type magnetic circuit is adopted.

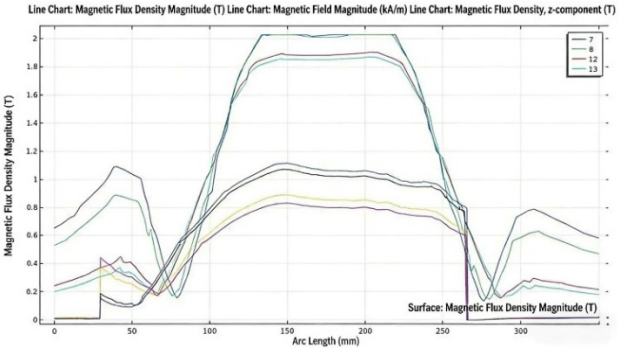


Fig 3. Magnetic field intensity curves of the pipe wall and iron core for the yoke-type magnetic circuit in a 12-inch pipeline;

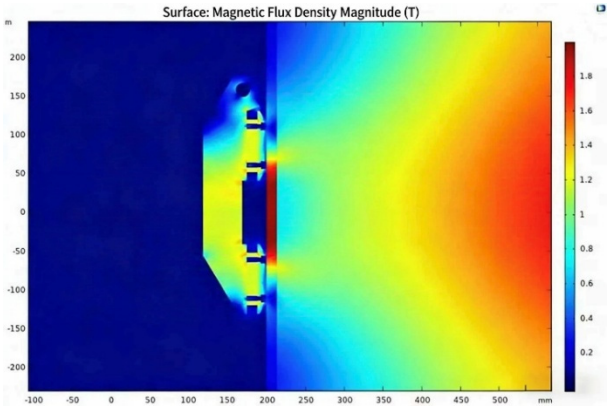


Fig 4. Magnetic flux density norm of the finite element simulation model for the yoke-type magnetic circuit in a 10-inch pipeline;

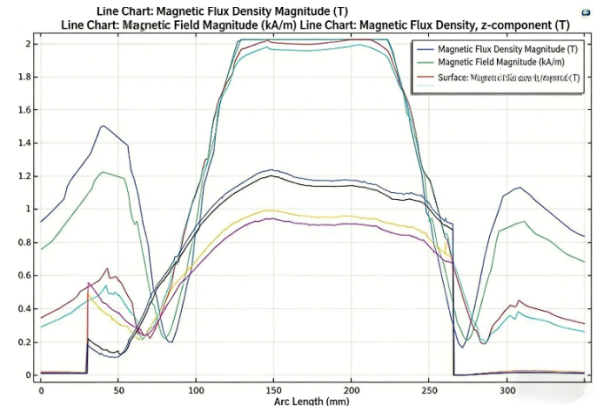


Fig 5. Magnetic induction intensity curves of the pipe wall and iron core for the yoke-type magnetic circuit in a 10-inch pipeline;

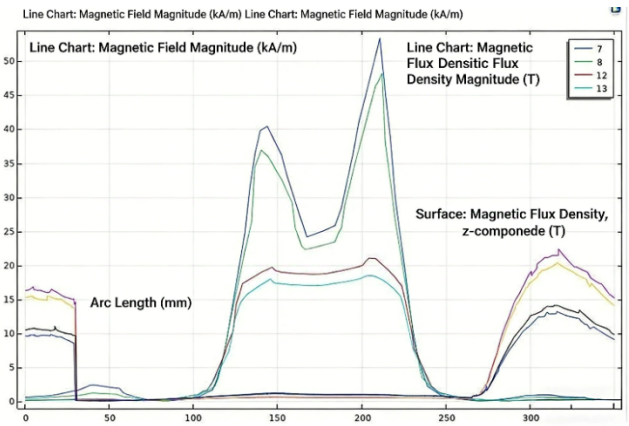


Fig 6. Magnetic field intensity curves of the pipe wall and iron core for the yoke-type magnetic circuit in a 10-inch pipeline;

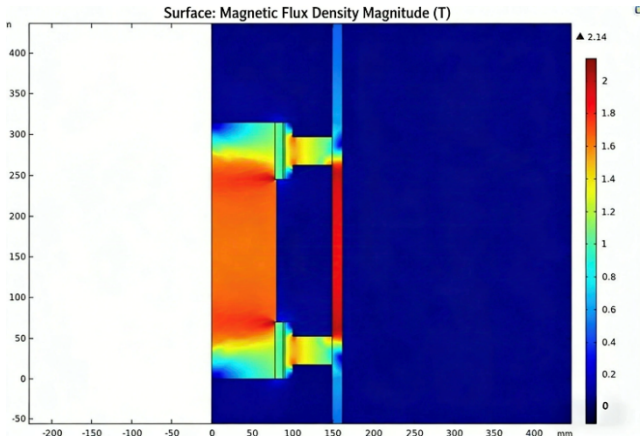


Fig 7. Magnetic flux density norm of the finite element simulation model for the steel-brush-type magnetic circuit;

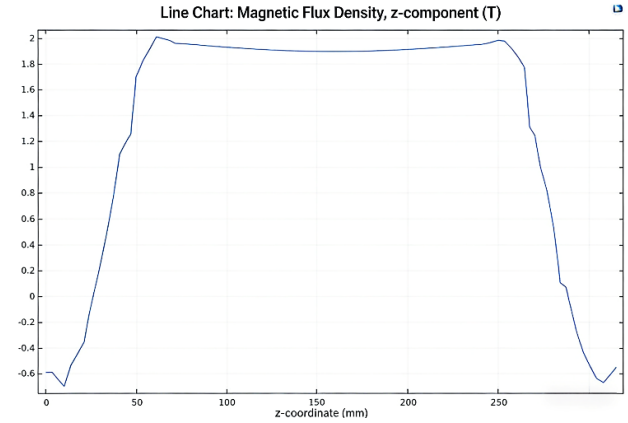


Fig 8. Magnetic field intensity curve of the pipe wall for the steel-brush-type magnetic circuit;

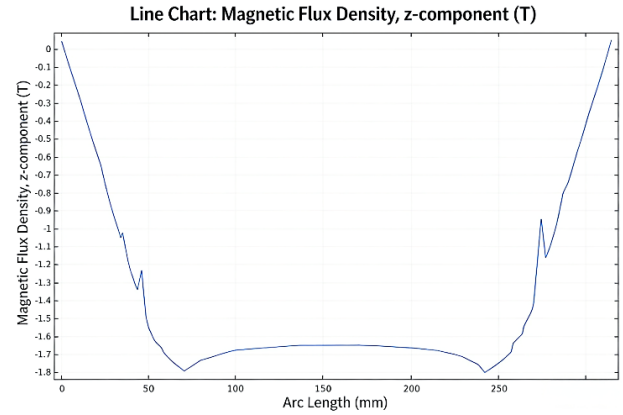


Fig 9. Magnetic field intensity curve of the iron core for the steel-brush-type magnetic circuit.

The specific parameters of factors such as the thickness and length of the permanent magnet, component materials, pole pitch, and core thickness, as well as the number of turns and current parameters of the eddy current coil, are obtained, which provides a theoretical basis for the design of the magnetoelectric composite heterogeneous field multifunctional sensor.

3. Design of Low Friction and Large Deformation Dynamic Cup

(1) Contact Mechanics Analysis and Design Index

The dynamic cup is responsible for the sealing and traction of the internal detector. Its structural shape and interference amount are directly related to the traction force and passing capability. The contact between the cup and the pipe wall can be regarded as an axisymmetric contact problem, and its contact pressure distribution is closely related to the cross-sectional shape of the cup, material elastic modulus and interference amount. Under the assumption that the pipe stiffness is much greater than that of the cup and only the elastic deformation of the cup is considered, the contact pressure distribution p(x) and contact length Lc under different structures and interference conditions can be obtained by the finite element method.

To balance driving force and service life, two design indicators are introduced in this paper:

• Unit circumferential driving force

$$f_\tau = \mu \int_0^{L_c} p(x)\,dx$$

It reflects the traction capacity that the cup can provide per unit circumference, and shall meet the driving force requirement of the internal detector at the minimum operating pressure.

• Average contact stress per unit length

$$\bar{p} = \frac{1}{L_c}\int_0^{L_c} p(x)\,dx$$

It is closely related to the material fatigue life and wear degree, and shall be controlled below the allowable stress of the material.

In essence, the design of the dynamic cup is to minimize $\bar{p}$ on the premise of satisfying f_τ, so as to achieve a balance between traction force and durability.

(2) Finite Element Comparison of Typical Cup Structures

Typical cup structures, including conical, straight-plate, circular and dished cups, were selected for finite element simulation under various interference conditions. The variation laws of maximum contact stress, contact length, f_τ and $\bar{p}$ were compared.

The results show that:

The conical cup is prone to form high stress concentration at the fillet under large interference, resulting in a high maximum contact stress. The straight-plate cup has a long contact length and high driving force, but risks local instability and edge turning in deformed pipe sections. The circular and dished cups feature a relatively gentle contact pressure distribution, which can significantly reduce the maximum contact stress under the same driving force requirement, thus contributing to a longer service life.

(a) Maximum Contact Stress of Cups under Different Interference Fits

The maximum contact stress between the cup and the pipeline can be derived from the maximum contact stress of the cup, representing the maximum interaction force under varying interference fits. The maximum contact stress of dished and tapered cups follows the same trend with interference fit. When the interference fit ranges from 1% to 5%, the increment of maximum contact stress is relatively large; when the interference fit exceeds 5%, the increment of maximum contact pressure becomes gradual. For straight-plate cups, the maximum contact stress varies approximately linearly within an interference fit range of 2%–10%, and increases with the interference fit. Round cups exhibit low maximum contact stress with a small increment as the interference fit increases.

(b) Contact Length of Cups under Different Interference Fits

The contact length between the cup and the pipeline reflects the interaction length under different interference fits, corresponding to the wear length of the cup during pig motion. The contact length of straight-plate cups is mainly determined by their thickness and changes slightly with the interference fit. The contact length of round cups increases approximately linearly with the interference fit. Dished and tapered cups show nearly identical trends in contact length versus interference fit: a linear variation with a small increment when the interference fit is below 5%, and a larger increment when exceeding 5%.

Under the premise of ensuring sufficient traction force, a comprehensive optimization of different cup structures and interference fit combinations is carried out, constrained by "maximum contact stress not exceeding the allowable value" and targeted at "maximum unit circumferential driving force and minimum average contact stress per unit length", forming a multi-diameter collapsible power cup design scheme.

(3) Multi-Diameter Power Cup Combination and Experimental Verification

Based on the operating conditions of straight and deformed pipe sections, a combined design of driving and sealing cups is adopted: dual-diameter cups are arranged at the front and rear to provide primary traction force, while multi-diameter collapsible cups are arranged in the center to enhance adaptability to deformed pipe sections.

Comparisons between simulation and prototype tests demonstrate that, under the premise of sufficient driving force, the maximum contact stress of the multi-diameter combined cup is significantly lower than that of a single-structure cup.

In 12-inch loop tests, the power cup operated smoothly in a 260 mm large-deformation pipe section and undulating pipelines without flipping or severe wear. This verifies that the cup structure and interference fit are reasonably designed, meeting the high passability requirements under reduction of more than 30% and 1.5D elbow conditions.

4. Loop Test and Sea Trial Application

(1) 323 mm Test Pipeline Loop Test

Eight test pipe sections with artificial defects were arranged on the onshore 323 mm test pipeline, with an outer diameter of 323 mm and a wall thickness of 12.7 mm, including various metal loss defects. Water injection circulation was used as the power source, and the three-axis magnetic flux leakage internal detector conducted multiple round-trip tests on the test pipeline to check structural reliability and basic passability.

The test results show that the internal detector operated stably within the set speed range, without jamming or abnormal vibration. All sections were structurally intact, and the power cups worked normally, providing basic data and experience for the design of the 12-inch low-pressure high-passability prototype.

(2) 12-Inch Loop Test

More than 10 tests were carried out on the 12-inch low-pressure high-passability three-axis magnetic flux leakage internal detector at the 12-inch loop test site. Typical working conditions such as 1.5D back-to-back elbows, 260 mm large-deformation pipes (12-inch loop), and 232 mm undulating deformation pipes (10-inch loop) were set in the test pipeline to verify the overall passability and structural strength of the detector.

The test results indicate that the internal detector could pass smoothly under the above working conditions without jamming or severe structural damage; the power cups had no flanging or abnormal wear, and the stress levels of key parts of the magnetic flux leakage section and the driving section met the strength requirements. The test phenomena were consistent with the conclusions of the aforementioned magnetic circuit design, cup design, and rigid-flexible coupling analysis of the floating mechanism.

(3) 12-inch Offshore Trial Application

The offshore trial of the 12-inch low-pressure high-passability tri-axial MFL internal detector was carried out in an offshore oilfield. The test pipeline is a 12-inch subsea water injection pipeline with a total length of approximately 2.1 km. The wall thickness is about 11.1 mm for the horizontal section and 14.3 mm for the vertical section.

The detector was launched at 13:51 and received at 14:21, with a running time of about 30 minutes. During the detection, the pipeline pressure remained stable with a fluctuation of only 0.03~0.06 MPa.

After the offshore trial, the cabin was opened for inspection. The mechanical appearance of the internal detector was intact without water ingress or structural damage. Approximately 11.7 GB of tri-axial MFL detection data was successfully obtained on site, which can clearly identify welds and suspected defect locations. This verifies the engineering applicability and reliability of the low-pressure high-passability tri-axial MFL internal detection technology in actual subsea pipelines.

5. Conclusion

(1) Based on the magnetic flux leakage mechanism and the B-H curve of steel, the magnetic field and friction force of the steel-brush type and yoke-type magnetic flux leakage structures were compared and analyzed by finite element method. A two-section yoke-type low-friction magnetic flux leakage structure suitable for 12-inch long-distance pipelines was proposed. On the premise of ensuring a magnetization level of 10~20 kA/m and sufficient magnetic flux leakage sensitivity, the contact pressure and friction resistance between the detector and the pipe wall are effectively reduced, providing a magnetic circuit foundation for low-pressure and high-passability performance.

(2) Based on contact mechanics theory, the contact stress and contact length of various typical cup structures under different interference amounts were analyzed by finite element method. A design index combining the unit circumferential driving force and the average contact stress per unit length was proposed, and the multi-diameter foldable dynamic cup combination was optimized. It achieves high passability under working conditions of more than 30% diameter reduction and 1.5D elbows, which has been verified in loop tests.

(3) The results of the 323 mm test pipeline, 12-inch loop test and Penglai 12-inch offshore trial show that the developed low-pressure high-passability tri-axial MFL internal detector can operate stably under low-pressure and small pressure fluctuation conditions, with passing performance reaching the level of geometry detectors, and the tri-axial MFL signals are of good quality. The test phenomena are consistent with the conclusions of magnetic field simulation and mechanical analysis in the design stage, providing a feasible and promotable technical method for the integrity management of offshore oil and gas long-distance pipelines.

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