

Research Progress on Novel Inspection of Oil and Gas Pipeline Integrity

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Abstract: Oil and gas pipeline integrity is the key to ensure the safety of energy transportation, with the development of science and technology, the research and application of new detection technology has been increasingly emphasized. This paper firstly describes the background and practical significance of the selected topic, aiming at exploring more efficient pipeline inspection methods to ensure the stable operation of energy networks. In terms of theoretical framework, we have sorted out the theoretical system of integrity management, including the core elements of risk assessment, inspection technology, and maintenance strategy, which provides a theoretical basis for the subsequent research. Then, we systematically review the latest progress of oil and gas pipeline integrity testing at home and abroad. From the dimensions of physical principle and application practice, we analyze the advantages and disadvantages of conventional ultrasonic and magnetic particle flaw detection, as well as the emerging acoustic emission and fiber grating inspection technologies, and show the application cases of each technology in actual projects. Through comparative analysis, we find that although conventional technologies meet the inspection needs to a certain extent, new inspection technologies such as remote monitoring based on the Internet of Things (IoT) and artificial intelligence-assisted diagnosis are gradually becoming a research hotspot due to their high precision, high efficiency and intelligent features. The development of these technologies not only improves the comprehensiveness and accuracy of inspection, but also provides strong support for realizing the whole life cycle management of pipelines. In the summary review section, we emphasize the future development trend of oil and gas pipeline integrity inspection, including the integration and intelligence of technology, as well as the deep mining and application of data. At the same time, we also point out the challenges in the current research, such as the unification of inspection standards and the establishment of data sharing mechanisms, which require the joint efforts of the research community and the industry to achieve the continuous improvement of oil and gas pipeline safety. To summarize, this paper aims to comprehensively show the research progress of new detection technology of oil and gas pipeline integrity, provide reference for researchers and engineering practitioners in related fields, and promote the further improvement of China's oil and gas pipeline safety management level.

Keywords: Pipeline integrity; Inspection techniques; Rehabilitation techniques; Oil and gas pipelines.

1. Background and Significance of the Topic

1.1. Background

Oil and gas pipeline integrity is the cornerstone of modern energy networks, and its safe and stable operation has a crucial impact on national energy supply, environmental protection and social stability. With the continuous growth of energy demand and the expansion of pipeline networks, ensuring the integrity of pipeline systems has become an increasingly serious challenge. Traditional inspection methods, such as manual inspections and periodic hydrotests, although guaranteeing pipeline safety to a certain extent, are difficult to meet the needs of modern industry in terms of efficiency, accuracy and comprehensiveness. With the progress of science and technology, especially the rapid development of information technology, Internet of Things, artificial intelligence and other fields, the exploration and application of new inspection technologies have gradually become the key to improving pipeline integrity management.

1.2. Industry needs and challenges

Currently, the oil and gas pipeline industry faces a series of challenges, such as pipeline aging, corrosion, mechanical damage and damage caused by environmental factors. These factors may lead to pipeline failure, which may cause serious safety accidents, such as leakage and explosion, and pose a

great threat to human life safety and the environment. At the same time, as society's demand for energy security and environmental protection increases, how to ensure energy supply while reducing the outage losses and environmental impacts caused by testing is also an urgent problem for the industry to solve. In addition, with the complexity of pipeline networks, how to monitor a large number of pipelines efficiently and accurately, and how to assess and manage the risk of pipelines in their whole life cycle have put forward new requirements on the existing inspection technologies and management strategies.

1.3. Research Necessity and Urgency

The realism of the background of the selected topic lies in the fact that the limitations of traditional detection methods can no longer meet the growing demand for pipeline safety. New inspection technologies, such as remote monitoring based on the Internet of Things, artificial intelligence-assisted diagnosis, acoustic emission detection, fiber grating monitoring, etc., can not only improve the inspection accuracy and realize non-invasive and real-time monitoring, but also help to build a comprehensive pipeline health management system and realize the intelligent management of pipeline's whole life cycle. The application of these technologies not only improves the inspection efficiency and reduces the operation cost, but also warns the potential risks in advance, thus avoiding or mitigating the occurrence of accidents, which is of far-reaching significance for

guaranteeing the normal operation of the social economy and the sustainable development of the environment.

The study of new technologies for oil and gas pipeline integrity testing is not only an inevitable trend of scientific and technological progress, but also an urgent need for the development of the industry. This study aims to systematically explore the performance, application status and potential advantages of these emerging technologies, to provide theoretical support and technical reference for improving the integrity management level of oil and gas pipelines, and to promote the improvement of the safety technology level of oil and gas pipelines in China and even globally, which has important theoretical and practical value.

2. Theoretical Framework

The theoretical framework of integrity testing is the technical cornerstone for ensuring the safe operation of oil and gas pipelines, which covers multiple core elements such as risk assessment, testing technology, and maintenance strategy. These theories provide guidance for the research and development of new inspection technologies, and also provide a theoretical basis for the optimization and integration of existing technologies.

Risk assessment is the starting point of integrity management, which evaluates the impact on system safety by quantifying the various threats that a pipeline may encounter. In the field of signal processing, filtering and signal enhancement techniques are used to eliminate noise and extract useful information to more accurately identify potential defects. For example, signal decomposition techniques based on wavelet analysis can break down complex signals into sub-signals of different frequencies, facilitating the identification of anomalous patterns. In pattern recognition, machine learning algorithms, such as support vector machines, random forests, and deep neural networks, are used to train models to recognize different types of defects.

Data analysis models play a key role in integrity detection. Statistical methods, such as Fault Tree Analysis (FTA), Probabilistic Risk Assessment (PRA), are used to quantify the likelihood and consequences of potential failures. Bayesian networks and Markov chains are used to model the dynamics of pipeline health states and predict future trends. In addition, data mining techniques, such as association rules and cluster analysis, can help discover implicit relationships between data to inform decision making.

The theoretical basis of detection technology is mainly centered around physical principles, such as acoustics, electromagnetism, and optics. Ultrasonic inspection utilizes the propagation characteristics of sound waves to identify defects, while magnetic particle flaw detection is based on the magnetic properties of ferromagnetic materials. The emerging acoustic emission technology, by detecting the sound waves generated when the material is stressed, can monitor the stress changes inside the pipeline in real time. Fiber grating, on the other hand, uses changes in the optical wavelength of optical fibers to sense strain and achieve distributed monitoring. Both the theoretical research and application of these technologies have greatly promoted the accuracy and real-time performance of oil and gas pipeline inspection.

In terms of maintenance strategies, preventive maintenance and predictive maintenance theories provide scientific decision support. Preventive maintenance is based on historical failure data and sets up regular inspection and repair plans, while predictive maintenance predicts the future state

of equipment through real-time monitoring and data analysis to realize early intervention of failures. With the integration of IoT technologies, real-time data collection and remote transmission make predictive maintenance more feasible.

However, despite the continuous enhancement of the theoretical framework, there are still many challenges in practical application. For example, the lack of data standardization and sharing mechanisms makes it difficult to interoperate between different technologies. In addition, the complexity of existing models may bring difficulties in interpretation, and more intuitive and user-friendly interfaces are needed. Future research should continue to deepen the theoretical study to further improve the accuracy and efficiency of inspection, while promoting the close integration of theory and practice to realize the intelligent management of the whole life cycle of oil and gas pipelines.

3. Current Status of Research at Home and Abroad

3.1. Progress of new detection technology

In recent years, a series of new inspection technologies have emerged in the field of oil and gas pipeline integrity inspection, which significantly improve the accuracy and efficiency of pipeline defect identification. Researchers and engineering practitioners at home and abroad continue to explore to cope with the shortcomings of traditional detection means in terms of accuracy, real-time and automation. Among them, acoustic emission, magnetic memory, infrasound, ultrasonic, fiber grating and other technologies have made significant progress in theoretical research and practical application.

Electromagnetic eddy current detection technology [1], as a non-contact detection method, has a high sensitivity to metal loss defects, and is especially suitable for pipelines with small pipe diameters, low pressure and low flow rate, which can realize high-speed and automatic detection. Its determination of material conductivity and inspection of size and shape help to accurately assess the pipe condition. However, the number of sensors, layout and defect characteristics still have a certain impact on the detection results and need to be further optimized.

Magnetic memory inspection technology has been widely used in pipeline integrity assessment abroad [2], especially in magnetic flux leakage detection (MFL), which can effectively detect wall thickness defects and indirectly measure metal loss using the Hall effect. Despite the excellent performance of MFL in pipeline detection, its detection accuracy is constrained by the number of sensors, arrangement, and shape of defects, which need to be reasonably configured in practical applications.

As a leakage detection technology [3], infrasound method has become a remote and real-time means of pipeline leakage detection by virtue of its long wavelength, concentrated energy and long propagation distance. By compensating and noise reduction processing of infrasound signals, the precise location of leaks can be realized, the false alarm rate can be effectively reduced, and an effective tool is provided for in-service monitoring of long-distance pipelines.

The acoustic wave method has received wide attention in pipeline leakage detection at home and abroad, including the combination of acoustic wave leakage detection technology with fluid mechanics and noise science [4]. Studying the leakage flow field through numerical simulation can provide

an in-depth understanding of the velocity field distribution and acoustic field characteristics after gas leakage, and provide a theoretical basis for acoustic signal analysis. The sensitivity of the acoustic method to trace gas leaks and the high localization accuracy make it widely used in gas transmission pipelines.

In the field of oil pipeline leakage detection, the acoustic wave method has also been proved to have excellent performance [5, 6]. It captures the fluctuations generated by leaks through acoustic sensors to realize real-time monitoring and fast localization of leaks. By improving the detection algorithm and denoising technology, the detection accuracy and response time of the acoustic wave method can be improved, and the minimum detectable leakage rate reaches 0.45%, which is suitable for various pipeline environments.

The application of acoustic wave method in leakage detection of long-distance pipeline shows that the pipeline characteristics have a significant impact on the acoustic wave propagation, and the reasonable selection of detection technology and parameter settings is the key to improve the detectable leakage rate [6]. In addition, the acoustic wave method combined with the change rule of pipeline operating pressure and leakage aperture can optimize the detection method and improve the adaptability to different leakage situations [7].

Negative pressure wave method is another detection technique based on leakage pressure change by measuring the local pressure wave propagation caused by the leakage point [8,9, 10]. The coupled use of negative pressure wave and acoustic wave can improve the accuracy of leakage judgment and positioning accuracy, and is not affected by the time synchronization and signal transmission delay of multi-point positioning, so as to realize rapid positioning.

In recent years, the multi-sensor data fusion technology [15] for pipeline detection has also made important progress, which improves the robustness and accuracy of detection by integrating data from different sensors, and provides a new way for quantitative identification of pipeline defects and contour reconstruction. Meanwhile, ultrasonic guided wave technology [16] shows the advantages of high efficiency and low cost in pipeline defect monitoring and radial damage assessment, which, combined with the time reversal method, is valuable for the detection of small defects and the assessment of damage depth.

In terms of other inspection techniques, such as X-ray digital imaging system [17] enhances the automation and productivity of weld NDT, while NDT methods such as ultrasonic method and magnetic anisotropy method show high accuracy and reliability in in-service pipeline stress detection [18]. Ultrasonic guided wave - electromagnetic ultrasonic combined inspection technology, on the other hand, demonstrates dynamic monitoring capability and large area corrosion defects sweeping capability in corrosion detection.

Overall, new inspection techniques such as acoustic emission and magnetic memory show strong potential and continuously promote the innovation of oil and gas pipeline integrity inspection technology. In the future, the integration and intelligence of these technologies, as well as the application of big data and artificial intelligence, will further enhance the level of pipeline safety management and ensure the efficient and stable operation of energy networks.

3.2. Data Analysis and Model Application

With the application of new technologies in oil and gas

pipeline integrity testing, the importance of data analysis and model application is becoming more and more prominent. Researchers at home and abroad continue to explore how to improve the accuracy and efficiency of detection through data processing and model optimization. Among these works, the acoustic wave method has been widely noticed for its excellent performance in oil pipeline leakage detection. Lang et al [5] analyzed the detectable leakage rate of the acoustic wave method on oil pipelines, and found that the pipeline characteristics have a significant effect on it, and the minimum detectable leakage rate can be up to 0.45%. They also pointed out that the acoustic wave method combined with denoising algorithms can effectively eliminate the noise in the signal and improve the accuracy of detection. The propagation characteristics of the acoustic wave method and its coupling with pipeline conditions are crucial for realizing high-precision leakage detection.

The negative pressure wave method, as another leakage detection technique, has also been widely used in domestic and international research. The paper of Su [8] discusses the application of negative pressure wave theory in oil pipeline leakage monitoring system, which determines the leakage volume and location by detecting the local pressure wave propagation caused by the pressure reduction at the leakage point and utilizing the time difference. The system uses the straight-line method, the time-value direct inverse extrapolation method, and the mathematical modeling method to calculate the starting point of the pressure change in order to locate the leak accurately. This method utilizes the complementary nature of negative pressure waves and acoustic waves to reduce the limitations of single signal identification and improve the reliability and accuracy of detection.

Sun [10] proposed a solution to the problem of negative pressure wave system failure in his study of leakage detection in submarine pipelines. He pointed out that field factors such as pressure transmitter pickup position and expansion bend may affect the accuracy and reliability of the negative pressure wave detection system, and proposed to solve these problems by utilizing infrasound leakage detection system, which achieves leakage detection and localization through infrasound sensors. These studies demonstrate the challenges faced by the negative pressure wave method in practical applications and the possibility of performance enhancement through technology integration.

In terms of model application, the leakage detection method combining dynamic micro-pressure excitation and transient flow model, such as the study by Wang and Cong [13], realizes the judgment and accurate localization of tiny leakage by additional dynamic micro-pressure excitation combined with transient flow model. This method combines the theoretical model with the actual pipeline working conditions, which provides a new idea for leakage detection.

The application of ultrasonic C-scan technology in oil and gas pipeline inspection has also made significant progress. The paper by Song et al [14] discussed the advantages of ultrasonic C-scanning technology in corrosion detection in oil and gas pipelines, which has higher detection accuracy and defect detection rate, and can visualize the shape, area and depth of the defects, which provides a strong support for pipeline corrosion monitoring and residual strength assessment. The intelligent and automated features of ultrasonic C-scan technology show great potential in oil and gas pipeline integrity management.

Data analysis and model application play an important role in oil and gas pipeline integrity testing, whether it is acoustic wave method, negative pressure wave method or other emerging technologies, the data processing and model optimization behind it is the key to improve testing accuracy and efficiency. With the further development of IoT, big data and artificial intelligence technologies, future research will integrate these technologies more deeply to realize the intelligence and full life cycle management of oil and gas pipeline inspection.

3.3. Case Analysis and Comparison

Domestic and foreign research cases show the advantages and disadvantages of various methods and practical application effects in the practice of oil and gas pipeline detection technology. Taking the negative pressure wave method as an example, it is widely used in pipeline leakage detection by virtue of its unique detection principle and localization ability. Shao et al [11] pointed out in "Evaluation of Pipeline Leakage Detection and Localization System Based on Negative Pressure Wave" that the sensitivity of pipeline leakage detection is jointly affected by the leakage volume and the pipeline parameters, and the leakage detection effect may be different under different working conditions. In addition, the localization accuracy of the leakage point not only depends on the propagation characteristics of the negative pressure wave, but is also affected by the wave speed and medium flow rate. The ability to resist the disturbance of working conditions is a key indicator of the performance of the leakage monitoring system, and the definition of the false alarm rate should fully consider the impact of non-leakage factors on the system. In practice, the system response time, which includes the computation time of the leak detection algorithm and the localization algorithm, is usually between 1-3 minutes, which affects the real-time detection to a certain extent.

Shi et al [12] proposed an improved negative pressure wave leakage detection method based on the negative pressure wave method and its improvement in "Leakage Detection of Product Oil Transportation Pipeline Based on Negative Pressure Wave Method and Its Improvement", and they combined the flow monitoring technology with the liquid density change to assist the leakage judgment, which compensated for the shortcomings of the single detection method. They also used the first-in-first-out double torsion ring technology and GPS time synchronization server to solve the defects in the traditional negative pressure wave method and improve the stability and accuracy of the system. This coupling method significantly improves the efficiency and reliability of leakage detection and provides a useful reference for other pipeline leakage detection.

Through comparative analysis, it can be seen that the advantages of the negative pressure wave method in leakage detection lie in its intuitive principle, accurate positioning, and the ability to combine with other technologies to improve system performance. However, its application also depends on the working conditions, such as flow rate, medium characteristics and so on. In order to further improve the detection effect, future R&D work may need to optimize the parameter settings of the negative pressure wave method for different pipeline types and working conditions, as well as the integration with other detection techniques, such as acoustic wave method, flow monitoring, etc., so as to achieve multimodal data fusion and improve the robustness and real-

time performance of the overall detection system.

In practical applications, the case study helps to identify and solve technical challenges, and also provides a direction for the development of new detection technologies. With the continuous progress of science and technology and the integration of big data, artificial intelligence and other technologies, future research will focus more on the integration and intelligence of the technology, as well as its adaptability to complex working conditions, in order to realize the intelligent management of oil and gas pipelines, and ensure the safe and stable operation of energy networks.

4. Summarizing Commentary

The research on new technology of oil and gas pipeline integrity testing, as an important means to guarantee national energy security, has made remarkable progress. In this paper, through systematically combing the latest research results at home and abroad, we compare and analyze the advantages and disadvantages of various testing techniques, as well as their application cases in actual projects. In summary, although traditional inspection techniques such as ultrasonic and magnetic particle flaw detection meet the identification of pipeline defects to a certain extent, new inspection techniques such as acoustic emission, fiber optic grating, IoT remote monitoring and AI-assisted diagnosis are gradually becoming a research hotspot due to their high precision, automation and intelligent features.

The integration of IoT, big data and artificial intelligence makes pipeline full life cycle management smarter and improves the comprehensiveness and accuracy of inspection. However, in the face of complex problems such as pipeline aging, corrosion, and mechanical damage, there are still challenges with existing technologies, such as the sensitivity of tiny defect detection, the accuracy of additional stress detection, and the establishment of data standardization and sharing mechanisms. These issues limit the wide application of the technology and place higher demands on the research and industrial communities.

The unique perspective of this study is that we not only focus on the latest advances in the technology, but also delve into the refinement of the theoretical framework, including risk assessment, the physical principles of the detection technology, data analysis models, and repair strategies, which provides theoretical support for the integration of future technologies. Our innovation lies in the fact that we have integrated multidisciplinary knowledge, such as signal processing, pattern recognition, data mining, and intelligent algorithms, in order to improve the accuracy of detection and achieve early warning of failures.

Looking ahead, the research on oil and gas pipeline integrity inspection will focus more on the deep integration of technologies, such as combining IoT, big data and artificial intelligence technologies with traditional inspection technologies to realize automation and intelligence of inspection. In addition, the research direction will pay more attention to the deep mining of data, such as the use of machine learning algorithms to optimize the data analysis model and improve the robustness and predictive ability of inspection. At the same time, how to establish a unified inspection standard, promote data sharing mechanism, and develop new inspection technologies adapted to complex working conditions will be an important topic for future research.

The research of new technology for oil and gas pipeline

integrity testing is a dynamic and interdisciplinary field, which requires a close combination of theory and practice to promote the continuous innovation of technology and ensure the safe and efficient operation of energy networks. Through continuous exploration and optimization, we expect to make greater breakthroughs on the road to improving the safety management level of oil and gas pipelines in China and even globally.

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