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FINITE ELEMENT ANALYSIS OF MAGNETIC FLUX LEAKAGE DETECTION: CHARACTERIZING DEFECT SIZE AND DEPTH EFFECTS

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Abstract:

The analysis and identification of defect signals in magnetic flux leakage (MFL) inspection are crucial aspects of MFL detection technology. To investigate the impact of defect size and depth on magnetic flux density in steel pipes, this paper creates 100 finite element models of MFL detection for defects with lengths and depths ranging from 1 to 10 mm. Simulation results show that the radial component of the magnetic flux leakage field exhibits two peaks near the defect edges, while the axial component has a peak at the defect center. As the defect size increases, the peak-to-peak distance of the radial component increases, while its peak value decreases; the peak value of the axial component increases with defect length within a certain range. These findings enhance the understanding of MFL detection and its relationship with defect size and depth, providing insights that can inform the development of more accurate and efficient detection techniques.

Keywords:

Magnetic Flux Leakage; Ansys; Finite Element

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Introduction

Oil and gas represent significant sources of the world's energy today. Available data show that over 90% of the world's natural gas and 70% of its oil resources are transported through long-distance pipelines Nuan (2022). However, these pipelines are susceptible to various conditions, such as deformation, corrosion, and damage due to operating environments and service life. Consequently, leakage in oil and gas pipelines poses significant risks to the environment, economy, and human health.

In current engineering practice, detecting defects in oil and gas pipelines is vital to mitigate or eliminate potential risks and accidents Shaoxing, Fan, Jun, & Wei (2022). Nondestructive testing methods play a crucial role in identifying flaws in materials, components, and parts without causing damage to the assessment objects Wanjun, Xibin, & Changyu (2024). In general, non-destructive testing should encompass two main aspects: defect detection (such as flaw detection) and the testing of other material properties (such as mechanical properties, microstructure, and stress）. As a vital means of ensuring product quality and safe equipment operation, NDT technology finds wide application in various industries Equipment (2021).

Various NDT techniques exist, where the American National Aeronautics and Space Administration – NASA research categorises approximately 70 different techniques. Practical applications commonly include Ultrasonic Testing (UT), Radiographic Testing (RT), Magnetic Particle Testing (MT), Penetrant Testing (PT), Eddy Current Testing (ET), as well as Acoustic Emission (AE), Leak Testing (LT), Optical Holography, Infrared Thermography, Microwave Testing, and others NDT (2017).

Magnetic flux leakage testing, an electromagnetic nondestructive testing technique, offers distinct advantages such as non-hazardous application, high detection sensitivity, simple detector system, minimal pre-assessment preparation, and absence of coupling agentsYa-ting, Nan, Guo-an, An-liang, & Cheng (2024). This technology finds widespread use in quality inspection and service life evaluation of steel products like rails, iron plates, steel bars, pipes, and wires. This technique is also commonly applied in the nondestructive testing of ferromagnetic materials, such as the bottoms of oil storage tanks and oil and gas pipelines in the petroleum and petrochemical industry. Magnetic flux leakage testing is significant for steel pipeline inspections due to its minimal surface requirements and ability to detect flaws at substantial depths Hao, Li-jian, & Xing-hong (2021).

For this reason, numerous scientists have made extensive efforts to understand the relationship between magnetic leakage signals and defect shapes. In 1947, Hastings designed a magnetic leakage detection system that effectively addressed the limitation of magnetic particle testing in detecting defects on the inner walls of pipes. This marked the beginning of the industrial application of magnetic leakage testing Xinyi (2023).

In 1965, the American company Tubecope Vetco developed the Linalog magnetic leakage pipeline inspection device, which effectively detected various defects such as transverse cracks and corrosion pits in pipes Wang (2015).

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In 1986, Friedrich Förster discovered a linear relationship between the leakage field intensity around defects and the internal field strength, emphasizing the importance of accurately understanding the internal magnetic field strength within defects Friedrich (1986).
Liu Yuming and colleagues Yu-ming, Ji-feng, Xiao-ying, & Yan-tian (2021) analyzed the relationship between defect size and signal characteristic parameters in pipeline magnetic flux leakage detection. They discovered that the main characteristic parameters related to defect length include the axial peak-to-peak distance, differential signal peak-to-valley distance, and the axial peak-to-valley value of magnetic induction intensity. For defect width, the key characteristic parameters are the circumferential peak-to-valley distance, the axial peak-to-valley value of magnetic induction intensity, axial waveform area, and axial waveform energy. Researchers including Yang Yun from Huazhong University of Science and Technology Yun (2017) found that the shape of surface magnetic leakage field signals caused by surface roughness exhibits a characteristic that approximates a sine wave.

At Northeast Petroleum University, Yang Zhijun and his team Zhijun, Peng, Yunhui, Zhilai, & Yuehui (2021) utilized finite element analysis software to conduct finite element analysis on different volume defect models. They observed that as the volume of a hemispherical defect increased, the radial component of the defect's magnetic leakage flux density also increased.

This study aims to employ finite element simulation using ANSYS to systematically address various potential influencing factors, including temperature, humidity, and lift-off distance. The core objective is to investigate the influence of defect depth and length on the magnetic leakage signal within the context of non-destructive testing. The goal is to elucidate the patterns governing the variation in magnetic leakage signal magnitude in response to changes in defect dimensions. This research is intended to establish a theoretical foundation for future applications of artificial neural networks and related methodologies, providing a basis for defect size recognition through magnetic leakage signal analysis.

Principles of Magnetic Flux Leakage Detection

Magnetic flux leakage testing is a non-destructive testing method that utilizes magnetic phenomena to detect surface and near-surface defects in ferromagnetic materials. When there are no defects in ferromagnetic materials, their magnetic permeability is very high, and all magnetic lines of force are confined within the material without any magnetic field leakageKim & Park (2018), as illustrated in Figure 1.

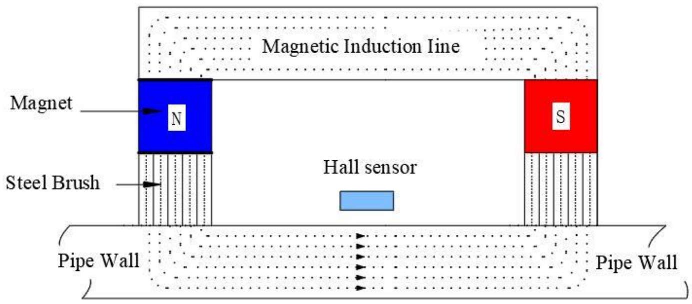

Figure 1. Magnetic Field Distribution Without Defect

When encountering small defects such as air voids or inclusions, the magnetic field tends to diffuse. This is because the magnetic permeability of air is much lower than that of ferromagnetic materials, causing magnetic lines of force to preferentially pass through the high magnetic permeability workpiece. Part of the magnetic lines of force are forced to flow beneath

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the defect, leading to compression of the magnetic lines of force. Another portion of the magnetic lines of force bypasses the defect, enters the surrounding air, and then returns to the workpiece, forming a magnetic leakage field, as shown in Figure 2.

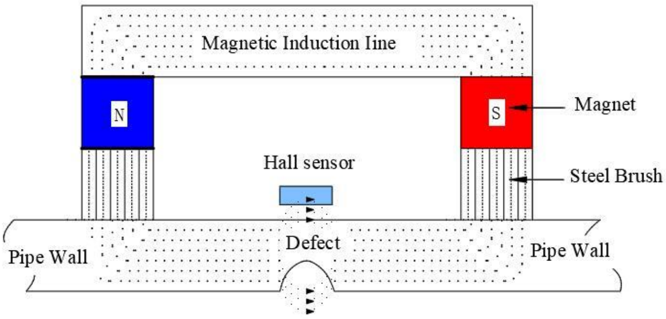

Figure 2. Magnetic Field Distribution with Defects

Magnetic Flux Leakage Detection Via Finite Element Analysis

There are three methods for studying the relationship between steel pipe defect sizes and magnetic leakage detection signals. The first method involves detecting actual pipeline defects in production practice, the second method involves detecting artificial defects, and the third method uses ANSYS to simulate defects. All three methods are commonly used but considering the complexity of actual pipeline defects and the multitude of influencing factors, the fabrication of artificial defects is challenging, and it involves high costs. Therefore, this paper employs the finite element method in ANSYS to analyze the relationship between pipeline defect sizes and the magnetic leakage field. The analysis preparation involving three main tasks:

i. Boundary Conditions
ii. Discretization Model
iii. Simulation result plot

The specific process is shown in Figure 3.

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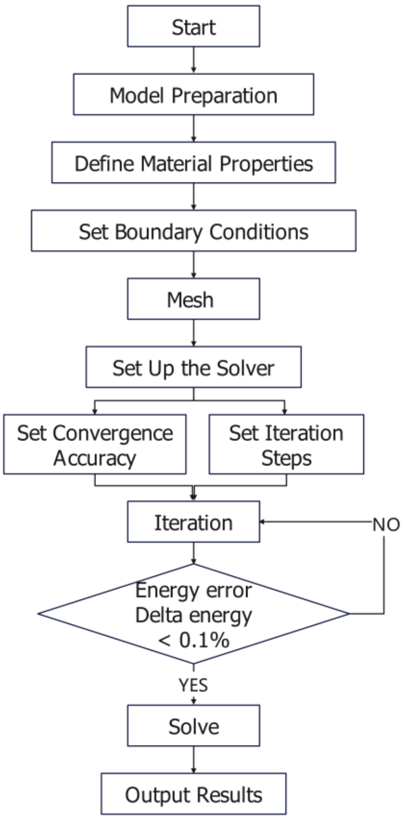

Figure 3. ANSYS Analysis Flowchart

Boundary Conditions

Model Preparation

In this study, a virtual model of a pipe with a defect that mimics a physical pipe. There are many kinds of pipeline defects. In engineering practice, corrosion and external forces will cause metal loss defects on the pipe wall, forming pits of different sizes. Here, for the convenience of modeling, it is assumed that the pit is a semicircle, and the comparative analysis is carried out by changing the length and depth parameters of the circular pit Guoguang (2010).

The two-dimensional model of magnetic flux leakage detection (Figure 4) for defects in the steel pipeline is composed of a pipe wall, defect, steel brush, permanent magnet, yoke iron and air. Their dimensions are as followsWenlai (2009):
i. Pipe wall: length 900mm, thickness 25mm.
ii. Defect: the radius is 10mm (that is, the defect depth is 40% of the pipe thickness).
iii Steel brush: length 100mm, width 10mm.
iv Permanent magnet: length 100mm, width 40mm.
v Yoke iron: length 600mm, width 160mm, groove depth 70mm.

This study employs the widely adopted direct modeling method, specifically the bottom-up modeling approach. This approach involves creating each node first and then generating the required lines and surfaces. Figure 4 depicts the two-dimensional solid model of defects in pipelines obtained using this method.

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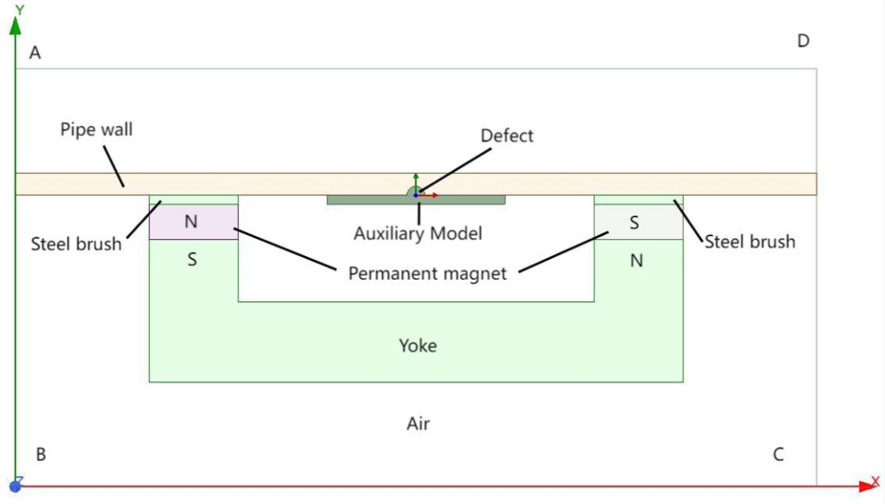

Figure 4. Two-Dimensional Solid Model of Pipelines With Defects

In the working plane, the horizontal direction to the right is the positive direction of the X-axis, that is, the BC side is on the X-axis and the AB side is on the Y-axis. This model is defined in the first quadrant.

To extract magnetic field data along the pipe wall and refine the subdivision, a rectangular auxiliary model was established below the defect. The rectangular body length is 200mm, the width is 10mm, and the material is air. When the data is extracted, the model is dissected, and the data will be more accurate.

Defining Material Properties

The pipe wall under test, the permanent magnet of the test device, the yoke iron, the steel brush, and air are the materials to be defined in this model. The relative permeability of air is 1.0.
In this model, X52 steel, which is commonly used in oil and gas pipelines at present, is adopted, and single permeability is simplified to meet the requirement of solving static magnetic fields Shaoxing et al. (2022). Figure 5 and Table 1 give the B-H curve and magnetic characteristics of X52 steel.

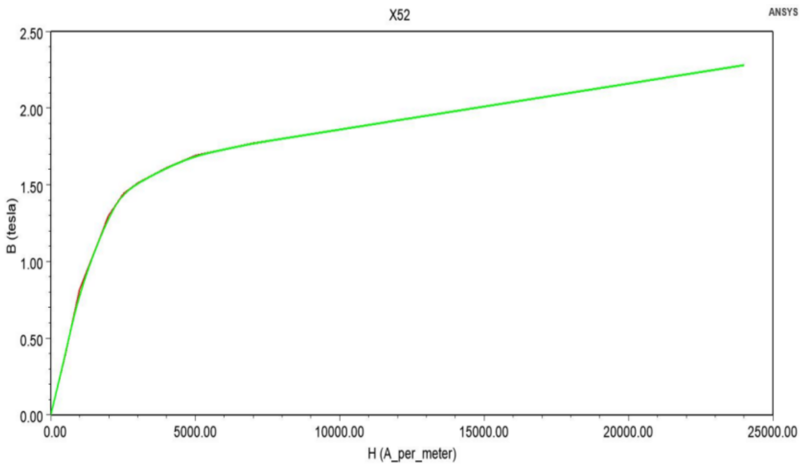

Figure 5. B-H Curve of X52 Steel

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Table 1. X52 Magnetic Properties of Steel

H (A/m)	B (T)	H (A/m)	B (T)	H (A/m)	B (T)
500	0.39	2500	1.44	5000	1.69
1000	0.82	3000	1.51	6000	1.73
2000	1.3	4000	1.61	7000	1.77

The permanent magnet is the emission source of the magnetic field, which is mainly required in terms of magnetic permeability, volume and performance. Ndfeb magnet has excellent magnetic permeability and a large magnetic energy product. It is the first choice for magnet materials Yunhui (2021). Its relative permeability is 1.05 and its coercivity is 896000.

The yoke iron used in the detection device is mainly used to conduct the entire magnetic circuit, so materials with good magnetic permeability are needed. Q235 has excellent magnetic permeability, good machining performance and high-cost performance, so it is the first choice of yoke iron materials with a permeability of 200.

The steel brush was replaced by the same magnetic characteristic curve as the yoke iron in this model, which has been proved by practice Xiuqing, Songwei, & Lijian (2001) to have little influence on the result and is feasible.

The above materials are all isotropic. However, for the description of the permanent magnet, not only the magnetic characteristic curve should be given, but also its magnetisation direction. The Ndfeb permanent magnet used in the detection device is set as N-pole permanent magnet -Y Component is 1; S-pole permanent magnet -Y Component is -1.

Discretization Model

ANSYS software is based on small elements to calculate the finite element model. The number of small elements will directly affect the efficiency and accuracy of the model calculation. The finite element model can be decomposed into many small elements through meshing.

There are 13 boundary conditions corresponding to Maxwell. The boundary of this model is set as the Balloon boundary, and the Balloon boundary condition is the infinitely far boundary condition. The effect is like Vector Potential, but the magnetic field can cross the boundary. The magnetic field is relatively open under the Balloon boundary conditions. In the same Region, the solution result of the Balloon boundary conditions is closer to the actual situation. ANSYS Initial Mesh Settings has two meshing rules, TAU and Classic. Classic was selected for meshing in this model. Next, the refined meshing is carried out on the auxiliary model at the defect and the Maximum number of additional elements is set at 4000.

There are three types of solvers available in ANSYS software: Magnetostatic, Eddy Current, and Transient. In this model, Magnetostatic is selected, the Maximum Number of Passes is set at 20 (number of iteration steps) and the Percent Error is set at 0.1 (convergence accuracy). The magnetostatic solution is an adaptive iterative solution in which the meshing unit is refined over the course of a calculation as the number of iterations increases.

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In the first step of the calculation, ANSYS software will create an initial meshing itself, and then calculate according to the initial meshing. After calculation, it will judge whether the Energy error and Residual error are both less than 0.1%. If the requirements are not met, the second iteration will be carried out.

In the second iteration, it will refine the meshing unit of which part of the field is rough and the accuracy is poor. The calculation will not stop until the accuracy of both parts is less than 0.1%.

If the results are not less than 0.1% after 20 steps of iteration, the results of the 20th step will be presented. Therefore, there is no need to refine the meshing in other parts of the model and set up manual meshing. Manual meshing will bring some negative things, for example, the direction of the magnetic circuit is not very clear, resulting in excessive meshing. There is no need for so much meshing.

Figure 6 is the effect diagram of four iterations of ANSYS. As can be seen from the figure, the meshing unit is gradually refined with the increase in the number of iterations. (The iteration effect of the second step is not obvious, so no effect diagram is given.)

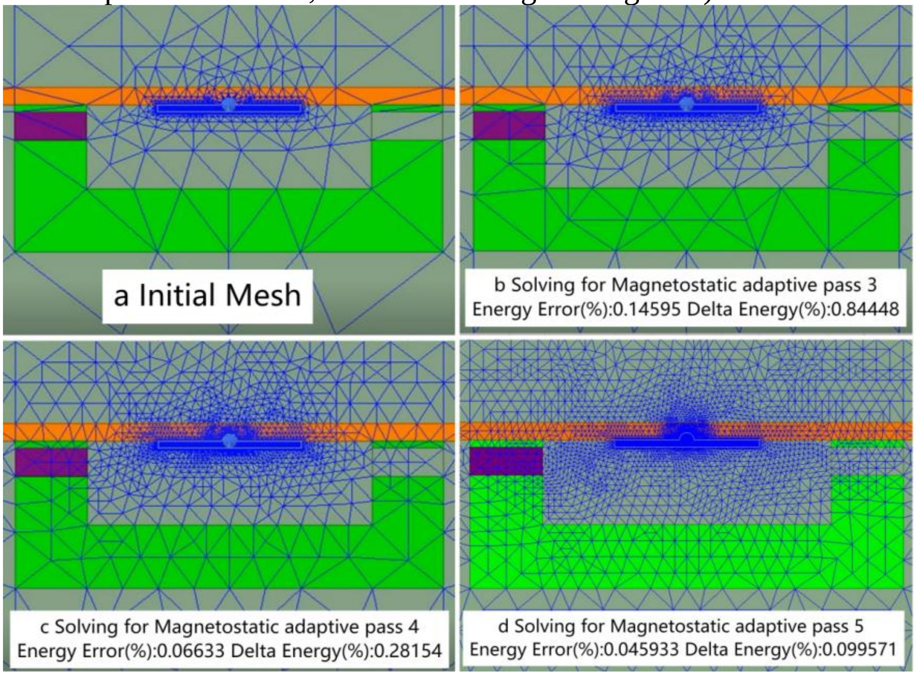

Figure 6. Meshing And Solving

As can be seen from Table 2, ANSYS software has carried out five times of adaptive iterations in total. The Energy error of the fourth iteration is 0.06633%, which is lower than 0.1%. However, the Delta energy of 0.28154% is still higher than 0.1%, so it needs to continue iteration. In the fifth iteration, both values are lower than 0.1%, and the iteration stops.

Table 2. Convergence

Pass	Triangles	Total energy(J)	Energy error (%)	Delta energy (%)
1	6020	1448.3	1.9173	N/A

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2	7940	1403.6	0.41638	3.0889
3	10327	1391.7	0.14595	0.84448
4	13427	1387.8	0.06633	0.28154
5	17457	1386.4	0.045933	0.099571

Simulation Result Plot

Figure 7 shows the distribution diagram of magnetic lines of steel pipeline defects. If the number of magnetic field lines is set to 100, the magnetic field distribution can be clearly seen from the figure. Some magnetic field lines leak out of the upper and lower surfaces of the pipe wall near the defects. In this way, the magnetic sensor can be used to detect the size of the magnetic leakage signal in practical engineering.

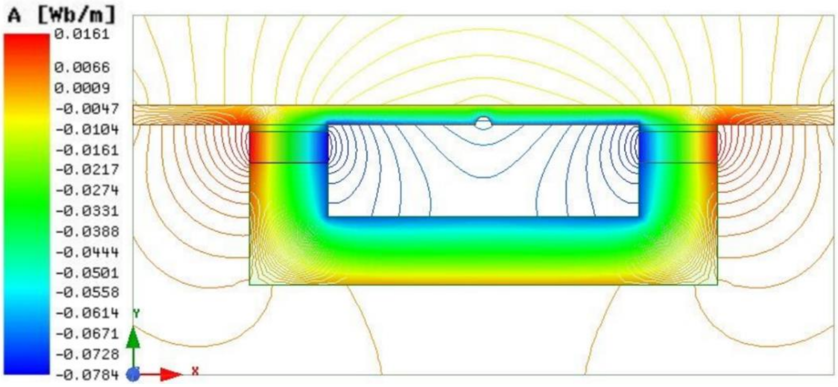

Figure 7. Distribution Diagram of Magnetic Lines of Force

Because the leakage magnetic field of the defect is a vector, the axisymmetric pipe can be decomposed. The horizontal tangential component is also called the axial component, which is measured by the axial Hall sensor in pipeline detection. The vertical normal component, also known as the radial component, is measured by radial Hall sensors in pipeline testing Yining & Fengming (2008).

Figure 8 is the radial magnetic leakage distribution of a semi-circular defect with a radius of 10mm. The polarity of the radial magnetic leakage field on both sides of the defect is opposite, so the signs on both sides of the radial magnetic leakage signal are opposite, and the maximum value appears at the edge of the defect. The radial magnetic flux leakage signal of the defect has obvious positive and negative peaks, which is easy to observe.

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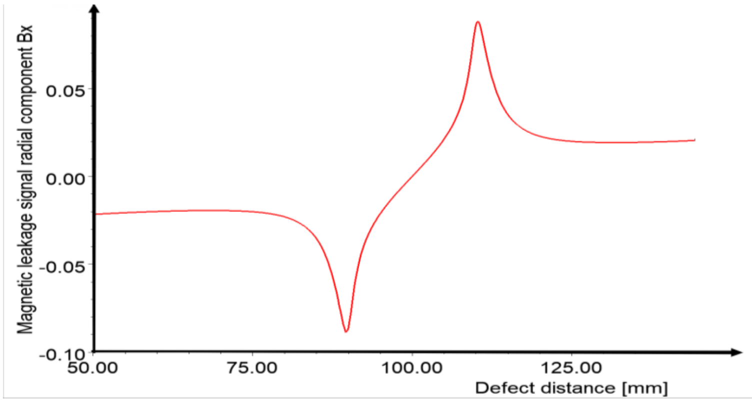

Figure 8. Radial Distribution Diagram of Magnetic Flux Leakage

Figure 9 shows the axial magnetic leakage distribution of a semicircular defect with a radius of 10mm. It can be seen from the figure that the axial magnetic leakage signal has a maximum value above the defect center line and is symmetrical from left to right. The amplitude decreased from the defect center to the defect edge.

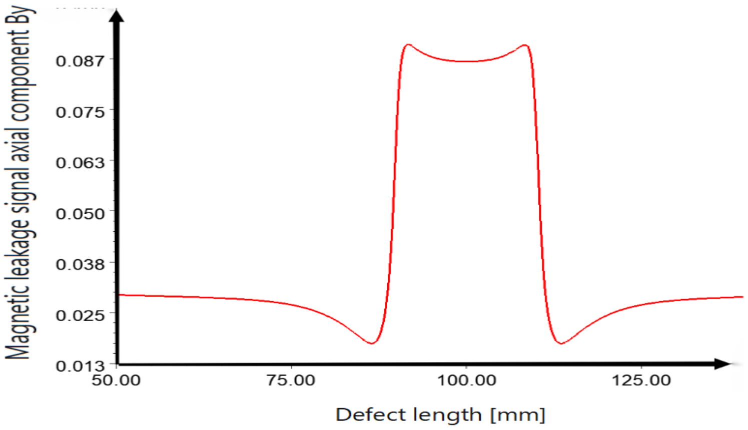

Figure 9. Axial Distribution of Magnetic Flux Leakage

Therefore, in the actual detection, the radial detection signal can be adopted as the main detection method and the axial detection signal as the auxiliary detection method, and the defect shape can be determined by the two signals comprehensively.

To better study the relationship between defect size and magnetic flux density, based on the previous finite element analysis of a single defect, different defect geometric parameters were added to provide basic data for the extraction of magnetic flux density features.

As shown in Figure 10, two geometric parameters of defect depth W and defect length L were set. The depth and length of defects are integers ranging from 1 mm to 10mm, so there are 100 defect models with different depths and lengths. The two-dimensional finite element simulation analysis of pipeline magnetic flux leakage internal detection was carried out on these 100 models respectively. Through the path operation function of ANSYS finite element analysis software, the radial magnetic flux density data of 100 groups of defects could be obtained.

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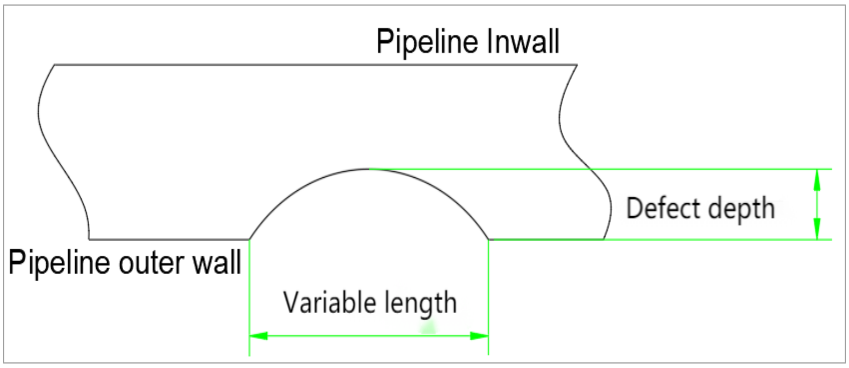

Figure 10. Defect Parameter

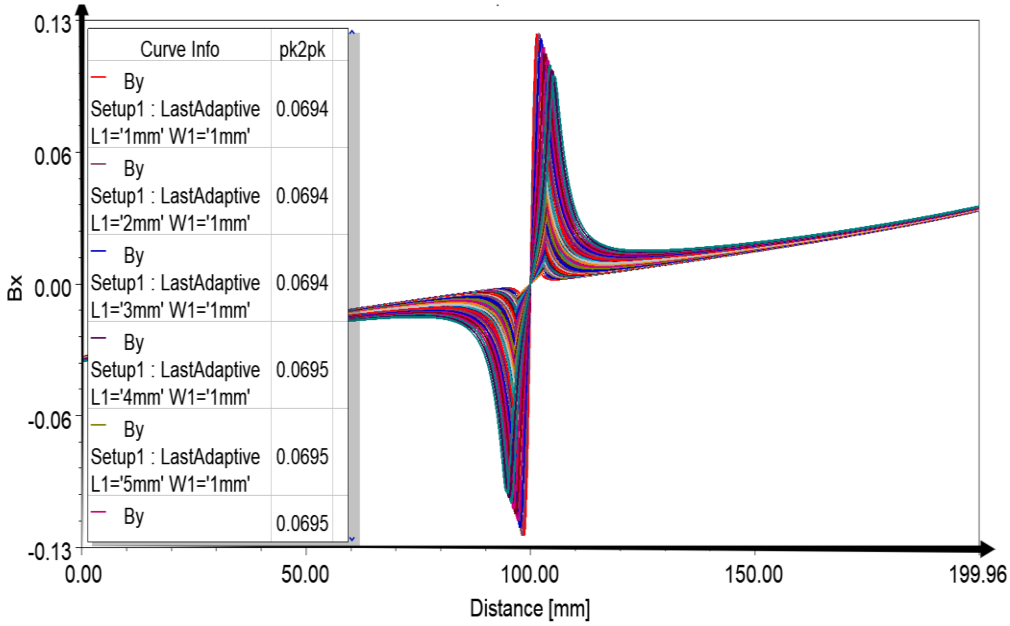

Figure 11. Radial Distribution of Magnetic Flux

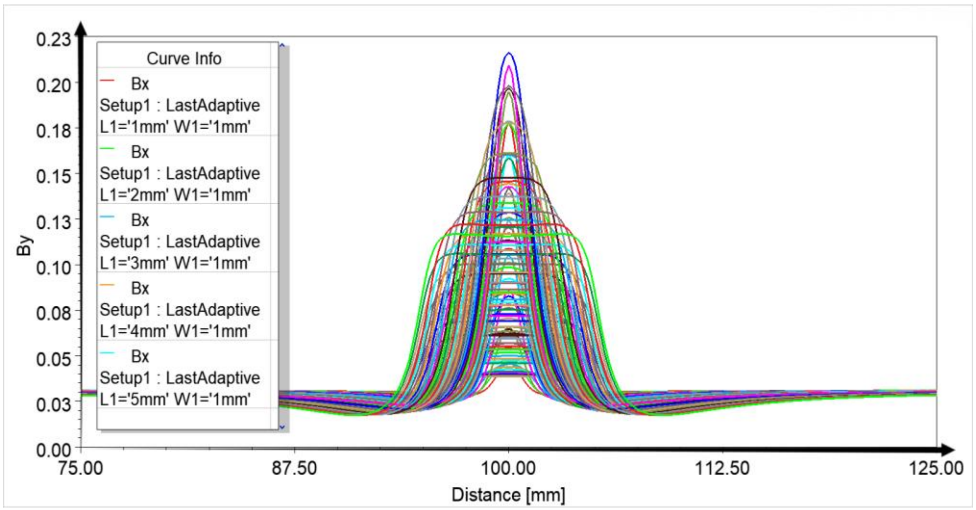

Figure 12. Axial Distribution of Magnetic Flux

100 sets of data are too crowded in a single graph to see the relationship between defect size and magnetic flux density (Figure 11, Figure 12).

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Two sets of data are set below: one set of defect depth W is constant at 5mm, and the length L is 2mm, 4mm, 6mm, 8mm, and 10mm respectively; the other set of defects had a constant length of 5mm and depth of 2mm, 4mm, 6mm, 8mm and 10mm, respectively. The relationship between defect size and magnetic flux density is analyzed below.

Result And Discussion

The study results elaborated with correlating the defect geometry parameters (size and depth) with the magnetic flux leakage and density, respectively.

Effect of Defect Length on Leakage Magnetic Field

The length of the defect is the dimension of the defect along the axial direction. Because the magnetization direction is along the axial direction, the signal characteristics reflecting the defect length parameter are relatively stable. Therefore, it is easiest to determine the length parameter of the defect.

It has been proved by experiments Lijian, Dawei, & Songwei (2009) that when a defect is detected, the magnetic leakage axial signal will mutate at the edge of the defect, and the position of the mutation is not affected by the width and depth of the defect. Therefore, the axial magnetic flux leakage signal is selected as the basis for quantifying defect length.

According to the magnetic flux density curve, the distribution law of the magnetic leakage field of the defect was analyzed. To obtain the information on the magnetic leakage field, the dynamic finite element analysis results of magnetic leakage detection were used to extract: at any time, the radial and axial components of the magnetic flux density of the defect magnetic leakage field were obtained from the extraction path. Then, the extraction line across the defect was taken as the abscissa and the magnetic flux density component as the ordinate to make a curve (see Figure 13).

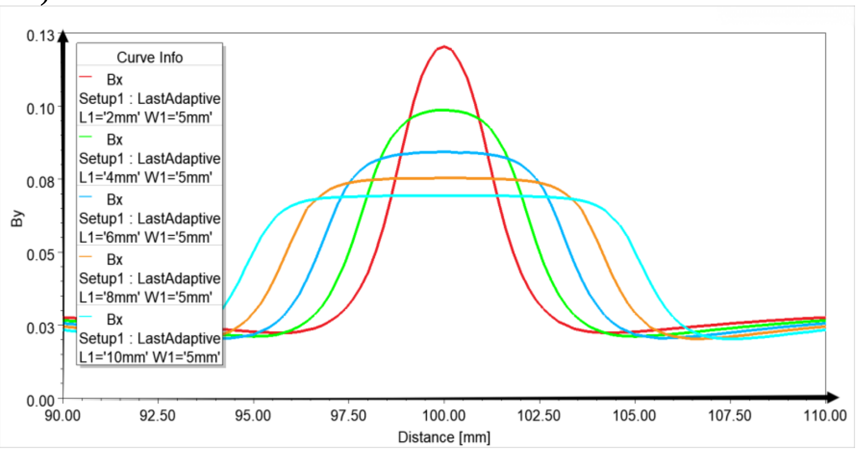

Figure 13. Variation Curve of Axial Magnetic Flux Density of Leakage Field with Length

It can be seen from Figure 13 that the change in defect length direction size has a great influence on the By component. With the increase in defect length size, the signal waveform width gradually increases, and the signal peak gradually decreases.

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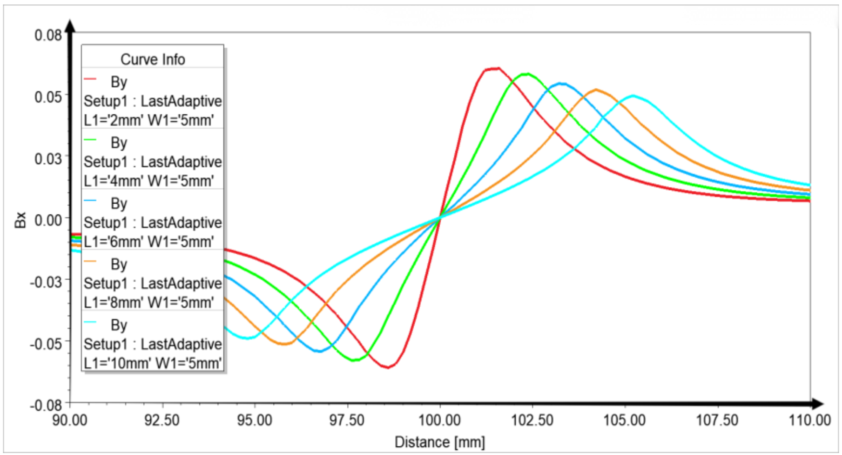

Figure 14. Variation Curve of Radial Magnetic Flux Density Of Leakage Field With Length

As can be seen from Figure 14, with the increase in defect length size, Bx peak-to-peak value decreases accordingly， the peak-to-peak distance of the Bx component increases, and the peak-to-peak distance is about equal to the length size of the defect. However, the peak value of the magnetic leakage signal gradually decreases, and the signal shows a gentle trend overall. In magnetic leakage detection, the detection signal of the Bx component is relatively obvious, so the peak-to-peak distance of the Bx component is mainly selected as the quantitative basis for defect length direction Yunhui (2021).

Effect of Defect Depth on Leakage Magnetic Field

As can be seen from Figure 15, the axial component By of the leakage magnetic field of the defect has only one positive peak value, which is about the central part of the defect.

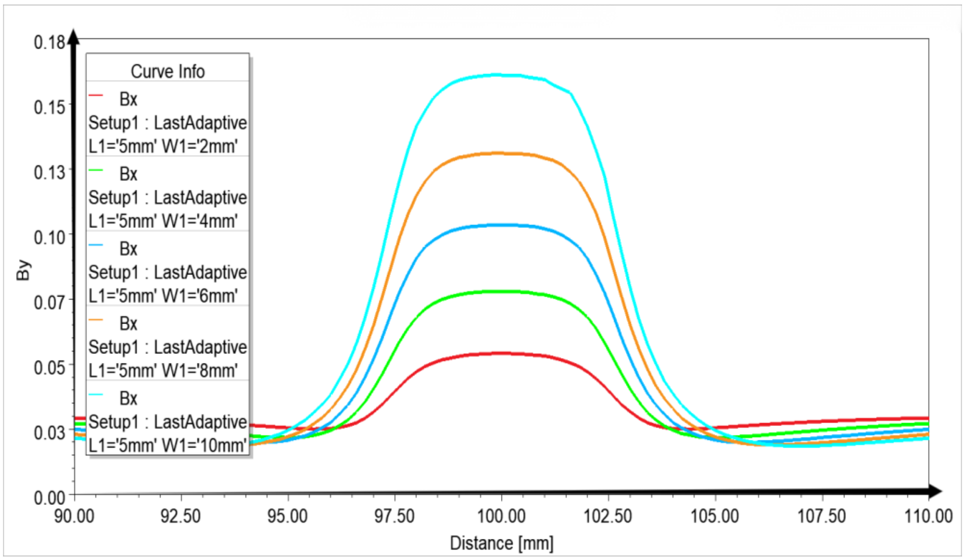

Figure 15. Variation Curve of Axial Magnetic Flux Density Of Leakage Field With Depth

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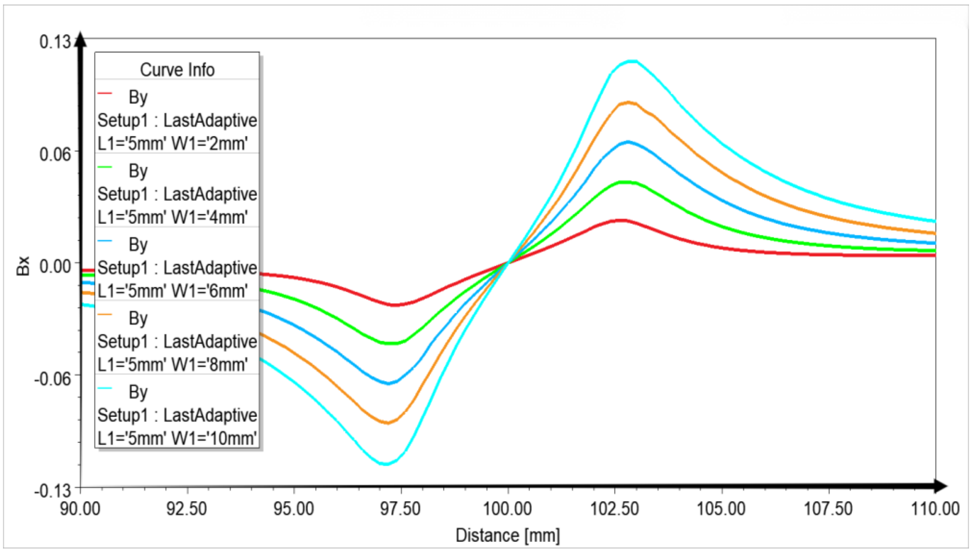

Figure 16. Variation Curve of Radial Magnetic Flux Density Of Leakage Field With Depth

In Figure 16, the radial component Bx has two peaks, one positive and one negative, which are approximately located at the defect edge. With the increase of defect depth, the curves of radial component Bx and axial component By of the leakage magnetic field flux density basically remain unchanged, and the peak value of the signal increases gradually with the increase of defect depth.

It can be concluded that the leakage magnetic field of defects varies with the depth and length of defects. The variation in peak value of the radial component is mainly caused by the variation of depth, and the variation of peak-to-peak distance is mainly caused by the variation of length, so the depth and length of defects can be quantified according to their respective laws Guang, Haiying, & Yongliang (2010). Both vertical component By and horizontal component Bx of defects have obvious peak value characteristics, which are easy to observe so that defects can be comprehensively determined by the two defect signals in actual detection Daoyi (2016).

Conclusions

The rapid development of the petroleum industry has raised higher demands for the quality of oil and gas pipelines. To improve pipeline quality and prevent leakage accidents, it is particularly important to conduct regular magnetic flux leakage (MFL) inspections on finished oil and gas pipelines. This paper discusses the principle of magnetic flux leakage generation in steel pipe defects, the basic steps of ANSYS finite element analysis, and the creation of 100 finite element models for magnetic flux leakage detection of steel pipe defects with lengths and depths ranging from 1 to 10 mm. By solving these models and analyzing the simulation results, the following conclusions were drawn：

i. The magnetic flux density of the radial and axial components of the defect gradually increases with an increase in the depth of the defect. The two peak values of the radial component are observed near the edges of both sides of the defect, while the peak values of the axial component are found around the center of the defect.
ii. As the size of the defect length increases, the peak-to-peak distance of the radial component signal gradually increases, while the peak value decreases gradually. Within a specific range

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of length dimensions, the peak value of the axial component increases with the length dimension.

The simulation results revealed the distribution patterns of magnetic flux leakage signals under different influencing factors, verifying the capability of pipeline magnetic flux leakage detection technology to detect defects of various sizes. This provides a reference for the precise quantification of defect dimensions.

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