Simulation and Experimental Research on Magnetic Flux Leakage Detection Method of Long-distance Pipeline Local Dents Stress

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Abstract. The mechanical damage of the pipeline will cause local dents of the pipe wall, accompanied by different levels of localized stresses. In this paper, the magnetic flux leakage detection technology is used to simulate and test the local dents of pipeline mechanical damage. The magnetic field distribution of the magnetic leakage detection is observed in the local stress loading state of the pipeline mechanical damage. Meanwhile, it is modeled and analyzed the equivalent change and detection effect of the magnetic flux density in the leakage magnetic field in the state that the pipeline mechanical damage is at different degree stress loading. Then the experiment is conducted with reference to the simulation results. Simulated artificial injuries with different deformation degrees of local dents are processed on the Φ323.9 steel pipe. It conducted magnetic flux leakage detection on local dents of pipeline mechanical damage by parameters of different DC magnetization strength. It showed that the leakage magnetic field effect of 5% OD pipeline mechanical damage local dents is better than 0.5% OD and 1% OD.

1. Introduction
As a common form of pipeline geometric defects, dents may cause localized significant stresses in the pipeline, which cause its loadbearing capacity to reduce. It also brings huge safety hazards for the normal operation of the pipeline. At the same time, when the degree of dent is serious, the pig cannot pass through the pipeline, hindering the normal operation of the inner detector. It causes the pipeline to fail, and must be repaired or replaced immediately. Some dents will not cause immediate failure of the pipeline. But on the one hand, the presence of dents affects the carrying capacity of the pipeline. On the
other hand, under the action of alternating forces, it will cause fatigue failure of the pipeline and seriously threatening the pipeline safe operation [1-3].

According to ASME B31.8 standard [4], dent refers to the radial displacement of the cross-section of the pipe wall caused by external extrusion or collision of hard objects. The pipeline dent is shown in Figure 1. Among them, H is the depth of the dent. In the evaluation of the pipeline dent, the depth is the main measurement parameter of the pipeline dent. The formation of dents runs through the entire pipeline operation cycle and is widely distributed, threatening the safe operation of oil and gas pipelines at all times [5].

In recent years, with the development of science and technology, pipeline dent detection technology has been developed comprehensively. The detection methods have become increasingly comprehensive and diversified. According to different detection technologies, the detection of pipeline dents can be roughly divided into magnetic flux leakage detection and geometric deformation detection. The pipeline deformation detector can detect the geometric deformation of the pipeline, thereby effectively distinguishing the pipeline dent deformation from the pipeline ellipse deformation. But it cannot detect the pipeline stress and the internal small deformation. Magnetic flux leakage can detect the internal stress and deformation of the pipeline. The advantage of the magnetic flux leakage method is that it can detect the geometric deformation of the pipeline, thereby distinguishing the dent and dent damage of the pipeline. However, the level of stress magnetization and dent stress signal recognition of magnetic flux leakage detection are still under study at present [6-7].

![Figure 1: Definition of Pipeline Dent.](image)

2. PRINCIPLE OF MFL

The basic condition for the formation of the leakage magnetic field is that the ferromagnetic material has a high magnetic permeability. The steel pipe is made of ferromagnetic material. So in the electromagnetic field or permanent magnetic field, and under the appropriate magnetization strength, the test piece with uniform material and no obvious defects can be magnetized. The test piece can be uniformly magnetized and the magnetic field lines is neat with certain regularity. The direction of magnetization is perpendicular to the cross section of the test piece. In the absence of interference from the external magnetic field, the magnetic field lines can be constrained inside the specimen, and its number is large. However, once the test piece is defective or deformed, the magnetic permeability changes, which in turn will cause the discontinuity of the steel pipe test piece. The magnetic field lines will not be completely constrained inside the material, and the magnetic permeability change will occur at the deformation of the material. Therefore, the leakage magnetic flux can be detected on the outside of the test piece, forming a leakage magnetic field different from the original magnetic field [8].

The formation principle of the leakage magnetic field can be explained by Maxwell’s equation and the boundary conditions of the decomposition surface of the electromagnetic field medium. The so-called magnetic leakage detection is a practical nondestructive detection technology that detects the magnetic leakage field to find defects through the sensor technology. Magnetic flux leakage detection is a product of the development of modern technology. It realizes online detection of pipelines and brings a lot of
economic benefits. According to the formation principle of the magnetic leakage field, when a ferromagnetic object contains defects, stresses and losses, it generates magnetic leakage at the defects and localized significant stresses subjected to the external magnetic field. Due to the complex geographical environment for laying natural gas and oil pipelines, and the varied geological conditions, the pipelines are susceptible to material corrosion and manmade external forces. The magnetic flux leakage method mainly uses the principle of magnetic field leakage to detect the current status of the pipeline online and formulate corresponding maintenance and evaluation plans [9]. The basic principle diagram of magnetic flux leakage detection defects is shown in Figure 2 and Figure 3.

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Figure 2 Schematic Diagram of the Magnetic Leakage Field Distribution of Intact Pipes.

Figure 3 Schematic Diagram of Magnetic Leakage Field Distribution of Defective Pipes.

Magnetic leakage field detection technology can be widely used in pipeline online inspection. An indispensable condition is that we need to magnetize the steel pipeline reasonably and effectively. When the pipeline steel is magnetized to full saturation, if the pipeline steel is a uniform and defect-free steel pipe, the generated magnetic lines of force are all uniformly distributed in parallel and orderly along the wall of the steel pipeline. There are no extra magnetic lines of force outside the pipeline wall. If there is stress or metal loss in it, the distribution of magnetic field lines will no longer be uniform, and the magnetic field lines will change the original direction. The types are roughly divided into three categories. The first one is that a large part of the magnetic field lines still pass through the inside of the tube wall. The second is that some magnetic field lines cross the defect or localized significant stresses, and the magnetic field lines pass through the defect site. The third is a small part of the magnetic field lines are occurred physical phenomenon of refraction at the edge of dents. It causes some lines to pass through the outer space of the pipe [10].

3. SIMULATION

3.1. Simulation Model Parameters

Adopting COMSOL finite element simulation software, the electromagnetic field and solid mechanical field in the AC / DC module. The two-dimensional model has fewer convergence times than the three-dimensional model, higher calculation accuracy and can improve the calculation efficiency. So a two-dimensional simplified model of DC magnetic flux leakage detection is established based on the counter magnetostriction effect of magneto mechanical coupling, as shown in Figure 4. It mainly includes two parts: a DC detection sensor and a pipeline test piece to be tested. The excitation part of the sensor is an
electromagnet, which is mainly composed of an excitation coil wound on U-shaped magnetic core (the coil is simplified as a rectangle in a two-dimensional model). The core material is manganese zinc ferrite. The signal acquisition element can be simplified into a one-dimensional node (or two-dimensional cross-section) in the model, located in the air domain above the tested piece.

In order to get a clear simulation cloud picture, the mesh size in the tested part and the magnetic core are smaller than the surrounding air area when meshing. In addition, the stress is applied above the dent surface to analyze the influence of the local stress of the dent on the leakage magnetic field. The grid is locally refined in the area near the pickup point (point or line) of the magnetic flux leakage signal in the air domain. Its size is generally set to the minimum mesh size in the model. The main parameters of the model are shown in Table I.

![Two-dimensional model.](image)

**Table.1  COMSOL Simulation Model Parameter**

| Parameter Name                  | Parameter Settings       |
|--------------------------------|--------------------------|
| Simulation Module              | AC / DC Module           |
| Physics                        | Magnetic Field (mf) and Solid Mechanics |
| Stress                         | 0-90MPa                  |
| Excitation Coil Turns          | 450 turns                |
| Excitation Coil Diameter       | Φ0.75mm                  |
| U-shaped Core Conductivity     | 10 S/m                   |
| U-shaped Magnetic Core Relative Permeability | 3000 |
| Conductivity of Test Piece     | 8.4×10⁶ S/m              |
| Relative Magnetic Permeability | 129                      |
| Minimum Grid Size              | 0.5mm                    |
| Solution Method                | Steady State Solution    |
| Signal Pickup Method           | 2D Cut Line              |
| Observation Signal             | Magnetic Flux Density    |

Under the above model parameters, set the test piece in the model to be a pipe with a thickness of 7mm, and there is a groove defect with a width of 30mm and a depth of 3mm on the upper surface.

3.2. **Magnetic Field Distribution of the Magnetic Flux Leakage Signal in the Local Dent Stress of the Pipeline**

In order to correctly identify the stress leakage magnetic field signal of the local dent of the pipeline, it is simulated its magnetic field distribution in the pipeline local dent first. The response signal characteristics of the leakage magnetic field are correctly identified. Figures 5 and 6 show the distribution of the magnetic and stress fields of this model for DC magnetism.
3.3. Simulation Results

The simulation model in section A is calculated and simulated. The local dent of the pipeline is loaded with different stresses. It is observed and analyzed the changes in the radial direction of the magnetic flux leakage signal at the stress load. The simulation results of the radial direction of the magnetic flux leakage signal at the stress load are shown in Figure 7.

The simulation results of the radial direction of the magnetic flux leakage signal at the dent depth of 0.5%, 1%, and 5% under different direct Current in Figure 8, Figure 9 and Figure 10.
Figure 8  Radial magnetic flux density of the dent depth of 0.5% under different direct Current.

Figure 9  Radial magnetic flux density of the dent depth of 1% under different direct Current.

Figure 10  Radial magnetic flux density of the dent depth of 1.5% under different direct Current.
Figure.11 Relationship between radial magnetic flux and stress.

It can be observed from Figures 7 that the sensitivity of magnetic induction to defects is different under different stress conditions. The shoulder peak appears on both sides of magnetic flux leakage signal and with the increase of stress, the amplitude of radial magnetic induction increases quite obviously. In addition, it’s main amplitude becomes lower gradually with the increase of stress. So, its intensity has a higher sensitivity to changes in stress. Comparing Figures 8, 9 and 10, as the direct Current increases, the radial magnetic induction intensity increases more significantly in the dent of the same depth. It can be got that the relationship between the magnitude of magnetic flux and the stress is positive from Figures 11.

4. experiment

4.1. The Pipeline Specimen of Local Dents
A mechanical indenter is used to apply different amounts of pressure to produce geometric dents of different depths on the pipe wall.

Figure.12 Schematic diagram of specimen processing method.

Figure.13 Local dent specimen of pipeline.
4.2. Magnetic Flux Leakage Probe and Device
The main components of the sensor include manganese zinc ferrite core, multiturn coil of enameled wire, Hall element, PCB printed circuit board and polyethylene package shell, as shown in Figure 14. Among them, the characteristic parameters of the Hall element are shown in Table II.

![Magnetic leakage sensor parts.](image)

**Table.2  HALL ELEMENT CHARACTERISTIC PARAMETER**

| Name               | Parameter        |
|--------------------|------------------|
| Model              | UGN3503          |
| Input Voltage      | 4.5-6 V          |
| Linear Range       | -90 to +90 mT    |
| Operating Temperature | -20 to +85 °C  |
| Sensitivity        | 7.5 to 30 V/mT   |
| Static Output Voltage | 2.25 to 2.75 V |

In the experiment, it establish a low-frequency electromagnetic detection test system. The experimental system of DC magnetic flux leakage detection is shown in Fig. 15, which is mainly composed of a DC source, an acquisition card, an acquisition interface, a DC magnetic flux leakage detection sensor and a piece to be tested. Among them, the tested pipeline specimen has an outer diameter of 325mm, a wall thickness of 7mm, a length of 1000mm, and a material of X52. There are three local dent stress deformation defects processed on the dent depth of 0.5%, 1%, and 5%, respectively.

![Experimental system of magnetic flux leakage detection.](image)

According to the excitation conditions shown in Table III, it scans the test piece containing stress defects in the pipeline. The defect is located on the upper surface of the test piece. In order to simulate the situation that the inner detector detects in the pipeline, the Hall element is close to the surface of the pipeline.
4.3. Result Analysis

It uses the results of amplitude scanning of local dent magnetic flux leakage signals in different excitation current pipes as Figure 16 to 19 show. Since the Hall element measures voltage in the experiment, it is converted to the value of magnetic induction $B_G$, where $B_G = \frac{\text{detection voltage} - \text{paranoid voltage}}{\text{sensitivity}}$.

![Figure 16](image16.png)

Figure 16: The magnetic flux leakage signal of the local dent of pipeline with a current of 0.6A.

![Figure 17](image17.png)

Figure 17: The magnetic flux leakage signal of the local dent of pipeline with a current of 0.8A.

### Table 3  EXPERIMENTAL PARAMETER

| Name            | Parameter                        |
|-----------------|----------------------------------|
| Core Shape      | U-shaped Magnetic Core           |
| Sensor Fixed Parameters | All windings, 450 turns       |
| Direct Current  | 0.1 to 2 A                      |
Figure 18 The magnetic flux leakage signal of the local dent of pipeline with a current of 1.4A.

Figure 19 The magnetic flux leakage signal of the local dent of pipeline with a current of 2A.

Figure 20 Radial magnetic leakage signal of 0.5% OD local dent under different current excitation magnetic fields.

Figures 20 shows the detection effect of large current excitation strength is better than the small one when local dent of long-distance pipelines is detected under different current excitation magnetic fields.
5. CONCLUSION
In this paper, the magnetic flux leakage detection technology is used to simulate and test the local dent of the pipeline mechanical damage. The magnetic field distribution of the magnetic leakage detection is observed in the local stress loading state of the pipeline mechanical damage. Meanwhile, it is modeled and analyzed the equivalent change and detection effect of the magnetic flux density in the leakage magnetic field in the state that the pipeline mechanical damage is at different degree stress loading. Then the experiment is conducted with reference to the simulation results. Simulated artificial injuries with different deformation degrees of local dents are processed on the Φ323.9 steel pipe. It conducted magnetic flux leakage detection on local dents of pipeline mechanical damage by parameters of different DC magnetization strength. The following conclusions are drawn through simulation and experiment:

1) Under different stress conditions, the sensitivity of magnetic induction to defects is different. The radial magnetic induction has high sensitivity to changes in stress, and the magnitude of magnetic flux is positively related to stress.

2) The leakage magnetic field effect of 5% OD pipeline mechanical damage local dents is better than 0.5% OD and 1% OD.

3) The detection effect of large current excitation strength is better than the small one when dents with localized stresses of long-distance pipelines are detected by MFL detection method under different current excitation magnetic fields.

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