Design of magnetic flux leakage detection device for three dimensional small diameter pipeline based on MEMS

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Abstract. Based on the common pipeline detection device faced with small diameter pipeline space, small turning radius is prone to the problem of stuck pipe phenomenon, this paper combined with the actual production needs, for small diameter pipeline leakage detection based on MEMS technology designed a detection device. COMSOL Multiphysics software was used to create a finite element model to simulate the magnetic flux leakage detection of pipeline defects. The influence of the type, size and location of pipeline defects on magnetic flux leakage signals was discussed. Based on MEMS triaxial magnetic force sensor, a magnetic flux leakage detection device with small volume, high precision and strong adaptive ability was designed. Through experiments, the magnetic flux leakage detection data consistent with the simulation results were obtained, which provided ideas for solving the detection problem of small-caliber pipelines.

Keywords: Small Diameter Pipeline, Magnetic Leakage Detection, MEMS Sensor, Finite Element Analysis, Model Analysis.

1. Introduction

About half of the active pipelines in the world have been used for decades. Pipeline accidents are frequent every year due to pipeline aging, which is potentially dangerous. Oil and gas pipelines are complicated, with small pipeline diameters difficult to detect and inaccurate location information leading to multiple miss excavation and even major safety accidents [1]. At present, the application of pipeline detection technology in the detection of long-distance oil and gas pipelines has been relatively mature [2], but in the detection of small-caliber pipelines such as natural gas, it is faced with such problems as small internal space and small turning radius, which requires high volume and self-adaptation of pipeline detection robots [3]. However, the research direction of pipeline detection mainly focuses on the detection of long distance and large diameter pipeline, and the research of small diameter pipeline detection equipment is very urgent. In pipeline detection, magnetic flux leakage detection technology has advantages such as high reliability, strong adaptability and easy automation control [4]. As the most promising detection method, it has been widely used in the field of pipeline detection [5]. MEMS sensor is a new type of sensor manufactured by microelectronics and micro manufacturing technology, which has many advantages compared with traditional sensors [6]. At present, MEMS sensor is mainly applied to inertial navigation in oil and gas pipeline detection equipment, which can greatly improve the positioning accuracy of detection devices in pipelines. At the same time, the volume of the detection device in the pipeline is reduced to a certain extent [7]. This project designs the detection device in the pipeline based on the magnetic leakage detection technology and combined with the MEMS sensor, which can realize the advantages of high-precision positioning and anti-interference detection as well as lightweight and small size [8].

2. Finite element simulation analysis

2.1. Finite element theory of leakage magnetic field

Compared with the conventional analytical model, finite element model can deal with various irregular shape defects, and can deal with nonlinear and relative motion problems well. [9] Under the condition that the travelling speed of the magnetic leakage detector is not high, the finite element

solution of the magnetic leakage field can be regarded as the solution of the static magnetic field problem. All macroscopic electromagnetic phenomena conform to Maxwell equations.

The prerequisite for solving Maxwell equations correctly is as follows:

$$\nabla \cdot (J + \frac{\partial D}{\partial t}) = 0 \tag{1}$$

Its constitutive equation is:

$$D = \varepsilon E \tag{2}$$

$$B = \mu H \tag{3}$$

$$J = \sigma E \tag{4}$$

Where: ε is capacitance; μ is the permeability; σ is electrical conductivity.

For linear, homogeneous, isotropic media, ε , μ and σ are constant constants. However, in ferromagnetic materials, the relationship between B and H is nonlinear, and μ is uncertain, and is a function of magnetic field intensity:

$$\mu = f(|\mathrm{H}|) \tag{5}$$

The equation $B = \mu H$ should be rewritten as:

$$B = \mu H + \mu_0 M_0 \tag{6}$$

In magnetic leakage detection, when the relative velocity between the pipeline and the detection device is low, the influence of the velocity can be ignored and solved approximately as a static magnetic field problem. For the static magnetic field problem, the factors changing with time can be ignored, and Maxwell's equations can be simplified as:

$$\nabla \times H = J \tag{7}$$

$$\nabla \cdot B = 0 \tag{8}$$

Vector magnetic potential method is adopted, vector magnetic potential A is introduced, and the definition is:

$$\nabla \times A = B \tag{9}$$

$$\nabla \cdot A = 0 \tag{10}$$

It can be obtained:

$$\nabla \times \left(\frac{1}{\mu_r} \times A \right) = \mu_0 J \tag{11}$$

Where, μ_r is the relative permeability of the material, μ_0 is the vacuum permeability. Based on this formula, the finite element simulation model of defect leakage magnetic field is established.

2.2. Create defect leakage magnetic field model

(1) The defect leakage magnetic field model is simplified

Set the wall defects to different shapes. The magnet and sensor in the flux leakage detector are arranged around the center of the pipeline. COMSOL Multiphysics was used to establish the magnetic leakage field model of defects. In order to simulate the influence of pipeline defects on leakage flux, the physical field model was selected as magnetic field and no current (mfnc), the solution type was selected as steady state, and the geometric solid model was created to obtain the magnetization model

size table as shown in Table 1. Finally, the three-dimensional model of pipeline magnetic flux leakage detection device as shown in Figure 1 is obtained.

Table 1. Size table of magnetization model

component	dimension
Pipe wall	Outer diameter 76mm, inner diameter 68mm, height 80mm
defect	The width is 2mm, the height is 5mm and the depth is 2mm
Permanent magnet	Outer diameter 31mm, inner diameter 19mm, height 5mm
Yoke iron	Diameter 68mm height 48mm

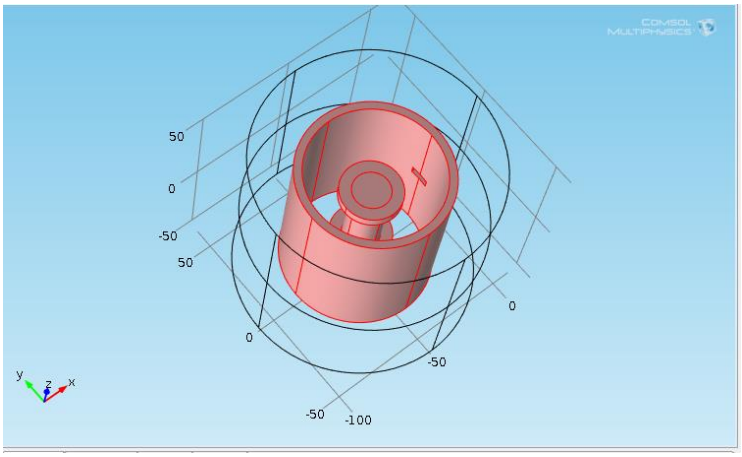


Figure 1. Finite element model of magnetic leakage for pipe wall defects

(2) Setting of boundary conditions

The interface of pipe wall, defect, permanent magnet, yoke and air in Figure 1 is represented by lines in the software. The upper and lower magnetic poles, the yoke iron with high permeability and the wall of the ferromagnetic tube constitute a completely closed main magnetic field circuit. In the simulation plane, the horizontal direction to the right is the positive direction of X-axis, and the center of this model is defined in the space (-50, -50, 0).

The material of tube wall under test was defined as X52 steel, the relative permeability of permanent magnet was defined as 1.05, and the coercivity was set as 900,000. The yoke iron used in the detecting device is A3 steel with a permeability of 20000. After the material attribute parameters are set, the established model is divided into grids. The minimum meshing element of the internal model is much smaller than that of the external air model. In order to get a more accurate conclusion, two sizes are set. After meshing, finite element solution is carried out.

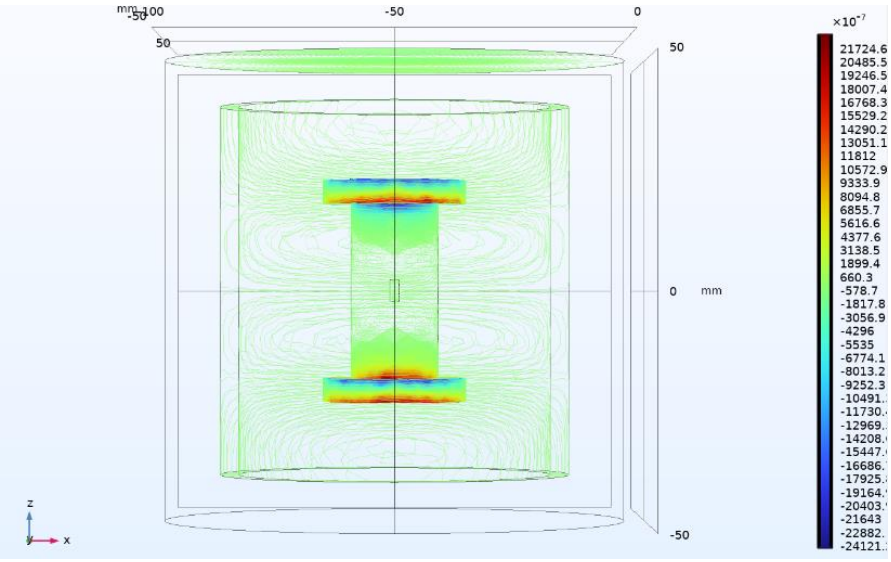


Figure 2. Isoline map of magnetic field in tube

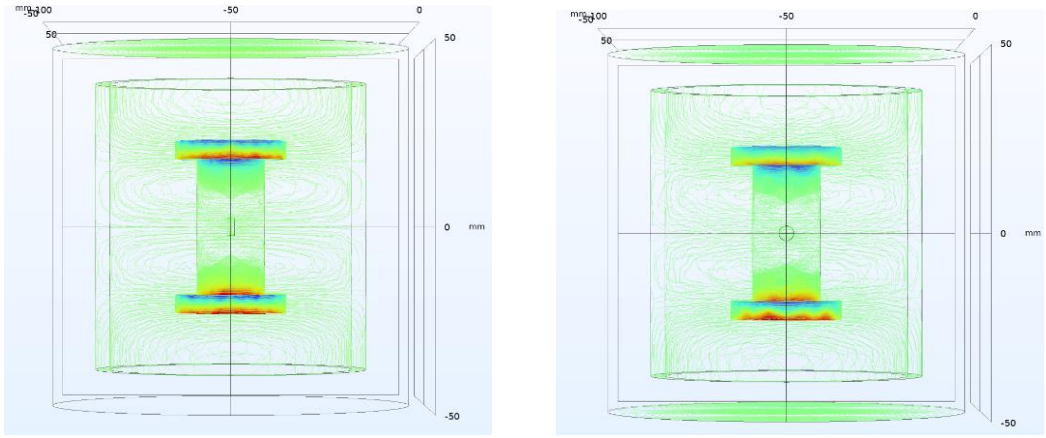
2.3. Three-dimensional simulation analysis

(1) Influence of defect shape on magnetic leakage signal

Firstly, the influence of the shape of the defect on the magnetic leakage signal was analyzed, and the defects were set as cuboid, semi-cylinder, semi-circular platform and semi-sphere on the inner surface of the pipeline respectively. The dimensions were shown in Table 2. After simulation, the triaxial contour map of the magnetic field under different shape defects was obtained. Taking X-axial view 3 as an example, the magnetic sensing lines in the position without defects are distributed evenly without magnetic leakage, while the magnetic sensing lines in the position with defects are dense and change rapidly. The contour of the defect can be inferred from the distribution of magnetic sensing lines.

Table 2. Other shape defect size table

shape	dimension
semi-cylinder	The radius is 2mm and the height is 5mm
Half round table	Bottom circle radius 4mm, height 5mm, top circle radius 2mm
hemisphere	Radius 2.5mm



(a)cuboid defect (b) semi-sphere defect

Figure 3. X-axis view of defects

(2) Influence of defect location on magnetic leakage signal

The model is used to simulate the detection of defects on the inner surface of the pipe wall and the outer surface of the pipe. Compared with the detection results of defects on the inner surface of the pipe, the simulation results can reflect the location and shape of defects. However, as shown in Figure 4, when the cuboid defect is located on the outer surface of the pipeline, the three-axial simulation magnetic leakage signal is weaker than that when the defect is located on the inner surface of the pipeline, so the location of the defect can be further judged by the strength of the signal.

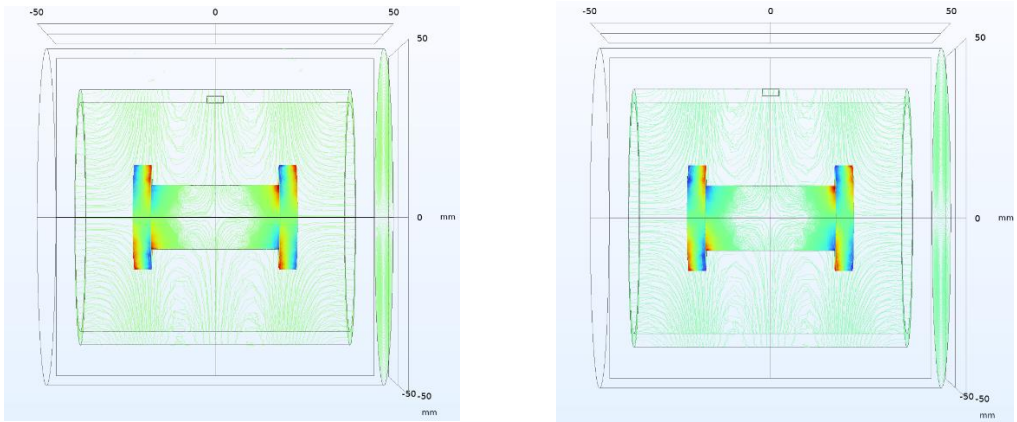


Figure 4. Y axis view of cuboid defects on internal and external surfaces of pipelines

(3) The influence of lifting value on magnetic leakage signal

Different lifting values (distance between probe and tube wall) were taken to simulate the MFL signal. The simulation results show that the smaller the lifting value, the better the simulation results of MFL detection. But considering the presence of welds in the pipeline and the uneven quality of the inner surface of the pipeline, the lift value cannot be set as infinitesimal [10].

(4) Magnetic flux leakage detection analog signal acquisition

Firstly, a path was set in the defect model by using the path operation function in COMSOL Multiphysics software. The path was above the defect, parallel to the pipeline, and the distance from the pipeline was the lift value. In addition, 21 data collection points are set on the path to collect magnetic leakage signals at their respective locations, so as to obtain the distribution of magnetic leakage fields on different paths. Twenty-one paths were set for each shape defect model, numbered 1-21, and each path corresponded to a corresponding lift value. The setting range was 0-10mm, and the change was performed every 0.5mm.

After a specific path operation, the magnetic leakage signal on the path with different lifting values is obtained. The direction along the pipeline was defined as the axial direction. The numerical solution of magnetic flux density was obtained from the COMSOL Multiphysics simulation results in each case, and the data was imported into Matlab to obtain the three-dimensional surface diagram. The three-dimensional surface diagram reflecting the leakage magnetic field distribution at the defect is shown in Figure 5.

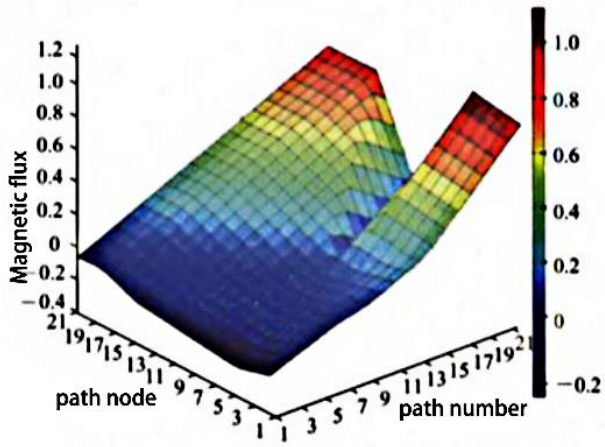


Figure 5. 3D curved surface obtained by simulation

Through the above modeling process, the preliminary conclusion can be drawn: by using COMSOL Multiphysics software, the magnetic flux leakage detection simulation of pipeline defects was carried out, the influence of the type, size and location of pipeline defects on the magnetic flux leakage signal was discussed, and the magnetic flux leakage signal was simulated and collected. Further analysis shows that when the defect is located on the outer surface of the pipeline, the three-axial simulation magnetic leakage signal is weaker than that when the defect is located on the inner surface of the pipeline, and the greater the lift value, the worse the simulation detection effect. The numerical model is used to provide theoretical basis for the subsequent experimental model making.

3. Prototype design and experiment

3.1. Design of magnetic flux leakage test model

Based on the sensing magnetic field characteristics of MEMS sensor, a simple magnetic leakage detection model is made. This model requires small size, light weight, convenient operation, and the magnetic induction intensity cannot exceed the range of MESS sensor.Therefore, in the process of making a simple MEMS magnetic leakage detection model, the circular iron shaft is used to fix and connect the two magnets to ensure that the N and S poles of the magnet are aligned. The MEMS patch sensor is affixed a circle around the iron shaft. In order to prevent the sensor from interference and

short circuit, the iron shaft is wrapped with a layer of insulating material, and then the sensor is affixed to the insulating material. The sensor pin is led out to the access chip through the wire, and the chip is connected with a Bluetooth transmitting device, which can send the collected data to the computer terminal. The model established by soildworks is shown in Figure 6.

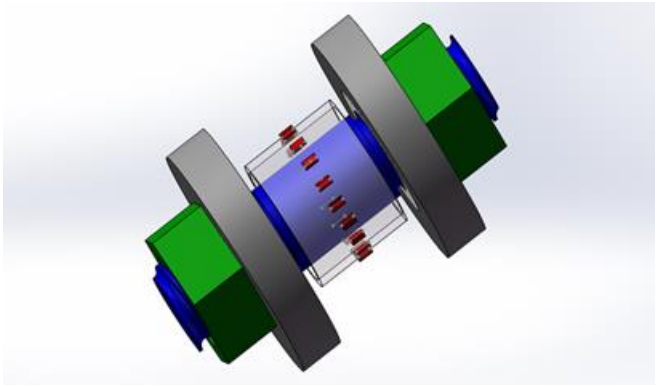


Figure 6. MEMS magnetic leakage detection model

3.2. Prototype design and experiment

In order to get the leakage signal, the HMC5883L MEMS magnetic sensor and MAG3110 are used in the signal acquisition. The stm 32 minimum system board and Bluetooth module are used in signal processing and transmission. The workflow is shown in Figure 7.

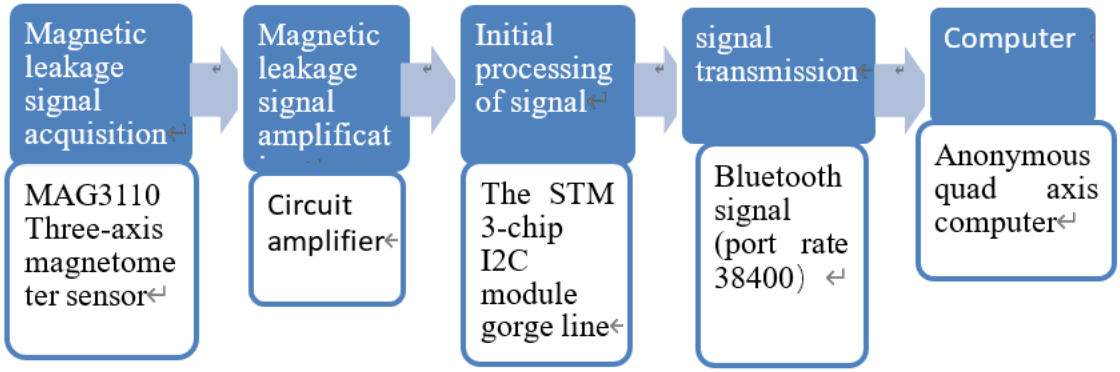


Figure 7. Flow chart of signal acquisition

In the design of magnetic leakage detection device, MEMS triaxial accelerometer sensor, triaxial gyroscope sensor and triaxial magnetic force sensor are combined to form an information perception module, which is combined with Bluetooth module on the lower microcontroller to form the pipeline detection function and device positioning function. MEMS sensor is used to obtain the information of magnetic flux variation in the pipeline and the inertial parameters of the detection device in real time. The information obtained will be preprocessed on the single chip microcomputer to eliminate errors, and then sent to the upper computer through Bluetooth communication for further analysis and establishment of a model, and finally determine the type of pipeline defects.

According to the design of the magnetic leakage detection device and the simulation experiment, the prototype of the detection device is preliminarily produced. The prototype of the detection system board is shown in Figure 8, and the detection device is shown in Figure 9.

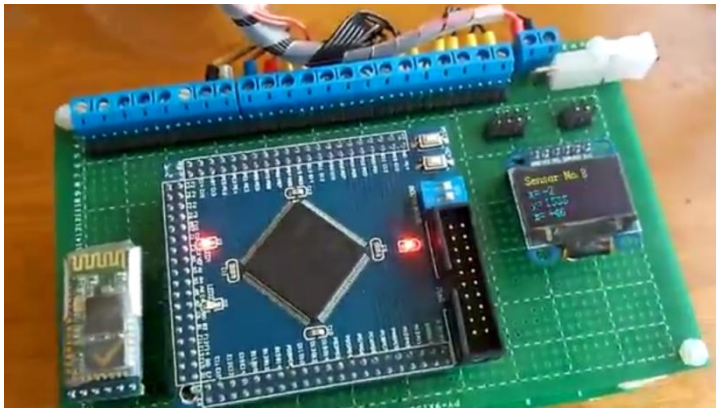


Figure 8. Plate prototype of stm 32



Figure 9. The prototype drawing of the detection device

The experimental model is completely based on the component size in the simulation model, so the signal can be directly collected and analyzed according to the experimental steps of the simulation model, so that the prototype can pass through the pipeline with the same defect as the simulation under different lift values. In order to make a direct comparison with the simulation results, the same processing process was adopted: the magnetic flux density was extracted from the experimental data and imported into Matlab, so as to obtain the three-dimensional surface diagram as shown in Figure 10.

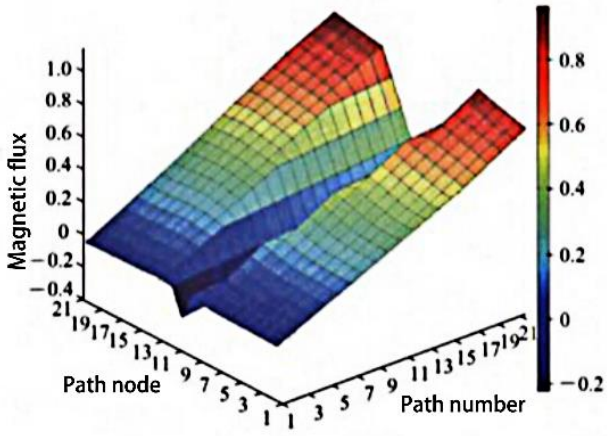


Figure 10. 3D surface plots obtained from the model

By comparing the three-dimensional surface diagram of magnetic flux obtained from the simulation model and the experimental model, it can be obviously observed that the magnetic flux component

increases significantly when the lift value decreases, and the simulation result of magnetic flux leakage detection is more ideal. Secondly, the results obtained from the experimental model and the simulation model are consistent, and the three-dimensional surface diagram obtained from the experiment is closer to the real result, with higher accuracy.The shape and size of the defect can be determined more intuitively from the three-dimensional surface diagram.

4. Conclutions

On the basis of the general magnetic flux leakage detection technology, COMSOL Multiphysics was used to simulate the working process of the magnetic flux leakage detection device in the pipeline, and the simulation results of the leakage magnetic field density in the three axes of pipe wall defects -- axial, radial and circumferential. The influence of pipeline defect type, location and lift value on magnetic leakage signal is analyzed and discussed. The research results can provide reference for the design and development of MFL detection device and MFL signal inversion.

The detection device designed in this project combines the magnetic flux detection function of MEMS sensor with the positioning function. During the process of the detection device moving in the pipeline, the detection device can be located in real time through the positioning system, and the location of the pipeline defect can be obtained by combining the defect analysis, so as to facilitate the subsequent construction and repair work. Due to the characteristics of small size, high detection accuracy and batch production, MEMS sensor can play an important role in the field of small-diameter pipeline detection.

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