High-Speed MFL Method Based on Multistage Magnetization Structure

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Abstract. In the process of magnetic flux leakage (MFL) testing, the leakage magnetic field decreases as the testing velocity increases, which leads to the severe detection omission. To address this issue, factors affecting high-speed magnetic flux leakage testing are analyzed, multistage magnetization structure is then proposed. By comparing magnetic flux leakage signals characteristics on the surface of steel pipe with high speed and low speed, effectiveness and feasibility of multistage magnetization structure are analyzed. Results show that multistage magnetization structure can effectively extend magnetization time. Compared with single magnetization, the magnetic flux leakage signal of the inner wall of the steel pipe can be detected effectively with multistage magnetization structure at high speed, and the magnetic flux leakage testing precision is improved.

Keywords. High-speed MFL testing, Multistage magnetization, Helmholtz, Eddy current

1. Introduction

With the rapid development of modern industrial technology, the ferromagnetic metal materials have been widely used in construction, aerospace, energy, transportation and other fields. In the use of ferromagnetic material components, the damage produced by external forces, corrosion and other factors will make the health of metal components gradually deteriorated, which leads to great potential dangers. As an efficient nondestructive testing method, it realizes nondestructive detection of components by identifying magnetic flux leakage field signals at defects. It can not only detect many types of defects, but also determine the geometric shape of defects. Magnetic flux leakage testing technology has been widely used in many industrial fields, magnetic flux leakage testing technology can realize the on-line nondestructive testing of the pressure pipeline, steel pipe, rail and other pressure equipment. However, in various applications, the magnetic flux leakage testing technology will be affected by the same factor, that is the detection speed. The pipeline magnetic flux leakage detector is usually running at 5m/s, and the defect will be seriously missed if the speed exceeds 5m/s. And in other applications, the same phenomenon occurs. The on-line detection speed of steel pipe is about 3m/s, and the running speed of rail inspection vehicle is about 10m/s.

However, in the process of magnetic flux leakage testing, the components must be firstly magnetized to saturation and then the defects can be detected effectively, which

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severely limits the testing speed and testing effect of the magnetic flux leakage testing technology\cite{1-3}.

In this paper, a high-speed dynamic experimental platform of magnetic flux leakage detection is built, and the multistage magnetization structure is proposed firstly. The multistage DC (direct current) magnetization coil can make steel pipe arrive saturated, and three-dimensional high speed magnetic flux leakage detection sensors are used to detect magnetic flux leakage signal of surface defects. By comparing the characteristics of magnetic flux leakage field signals of the defects in same steel pipe at high speed and low speed operation, the influences of magnetizing coil with different magnetization are analyzed.

2. Theoretical analysis of high speed dynamic magnetization

High speed magnetic flux leakage testing schematic diagram as shown in Figure 1, the principle of magnetic leakage detection technology based on the high magnetic permeability of the ferromagnetic material. In high speed magnetic flux leakage detection process, detection device will move at a certain speed along the specified direction of the measured component\cite{4}. In Figure 1, \( L \) represents the distance between the magnetization device and the detection sensor, and the \( v \) represents the forward speed of the detector.

![Figure 1. Schematic diagram of high speed magnetic flux leakage testing](image)

From the magnetization to the leakage signal detected by detector, the effective magnetization time of the component can be expressed as:

\[
t = \frac{L}{v}
\]  

(1)

In static or low-speed magnetization process, \( v=0 \) or \( v \) is very small, the magnetization time is enough and the measured component is easy to achieve magnetic saturation. With the speed increase of detection, the effective magnetization time is reduced greatly. And when the magnetic flux leakage detector through the defect area, the measured components have not yet reached the magnetic saturation, which lead to severe detection omission even serious missed detection at high speed.

According to the Stoner criterion, the magnetization of the measured component can be expressed as\cite{5}:
\[ B = B_0 + B_1 \]  
\[ B_0 = \mu_0 H \]  
\[ B_1 = \mu_0 M \]

Where \( B_0 \) represents magnetic induction intensity produced by the external magnetic field, and \( B_1 \) represents magnetic induction intensity produced by solid itself.

The magnetic signal detected by the magnetic leakage detection sensor can be expressed as:

\[
B = \mu_0 (H + M) = \mu_0 \left( H + \frac{d}{dV} \sum \mu_i \right)
\]

Where \( \mu_0 \) represents magnetic permeability in vacuum, \( M \) represents magnetization intensity of the component, \( \mu_i \) represents the magnetic moment of the atom, \( H \) represents the applied field strength.

3. Multistage coils magnetization principle

In high speed testing process, the magnetization time is very short, and magnetization will take a certain time to reach a stable state. The "delay phenomenon" caused by the rapid relative movement between the detection device and component will seriously affect the detection effect\(^6\). In addition, the eddy current effect caused by the relative movement will also prevent the detection of defects at high speed testing process. In order to solve the problem that the component is not easy to be saturated, the multistage magnetization structure is proposed, which uses multistage direct current magnetization coils to magnetize the component.

The multistage magnetization structure is based on Helmholtz coil principle, as shown in Figure 2, the two coils are coaxially arranged, the distance is equal to the radius of the coil and the same current \( I \) is put into the coil.

![Schematic diagram of Helmholtz coil](image)
Where $R$ represents the radius of coil, $x$ represents the distance from any point on the axis of coil to the center.

The magnetic induction intensity $B$ of any point on the coil axis can be expressed as:

$$B = \frac{\mu_0 NR^2 I}{2 \left[ R^2 + \left( \frac{R}{2} + x \right)^2 \right]^{\frac{3}{2}}} + \frac{\mu_0 NR^2 I}{2 \left[ R^2 + \left( \frac{R}{2} - x \right)^2 \right]^{\frac{3}{2}}}$$  \hspace{1cm} (6)

Where $N$ represents the number of coil turns, and $\mu_0$ represents magnetic permeability in vacuum.

By Eq. (6), magnetic field variation curve of two-stage coils is shown in Figure 3.

![Figure 3. The magnetic field variation curve of two-stage coils](image)

Where $O_1$ and $O_2$ respectively represent the two-stage coils center point. As shown in Figure 3, the magnetic field produced by the superposition of two coils is approximately uniform magnetic field, and the magnetic field intensity is the maximum value of the whole magnetic field.

The eddy current intensity in the steel pipe is related to the change rate of the axial component of the external magnetic field when the steel pipe is magnetized at high speed\(^7\). The eddy current intensity is stronger when the change rate of the external magnetic field is larger. The multistage magnetization coils which produce a uniform magnetic field will reduce the eddy current effect and prolong the excitation time effectively at the same detection speed.

4. Experiment and results analysis

4.1 Experiment

In order to verify the effectiveness of the multistage structure, the high-speed magnetic flux leakage detection platform is built.

The schematic diagram of multistage magnetization structure is shown in Figure 4.
The experiment adopts 20# seamless steel pipe, the length of steel pipe is 1200mm, the diameter is 102mm, and the wall thickness is 10mm. And in order to verify the magnetization effect of the multistage magnetization structure, the defects are made inside the steel pipe and the sensors are placed on the outer wall of the pipe. The depth of the defect is 0.2mm, the width is 10mm and the two defects are axially spaced 1m. As shown in Figure 5, the multistage magnetization structure adopts the form of 5 direct current coils arranged coaxially, and the number of coil turns is consistent and the current with same direction and size is passed into the coils. As shown in Figure 6, in order to improve the reliability of the detection, four detection sensors which can detect three axis magnetic leakage signals are placed at the end of each coil.
Five sets of circuit device are designed to supply power to the coil, each device include voltage regulator, rectifier bridge, capacitor, current meter etc. The voltage regulator is used to adjust voltage to change the coil current slowly. And at the same time, the rectifier bridge will convert alternating current to direct current to the magnetization coil.

![Voltage regulator](image1.png)

![Circuit connection](image2.png)

Figure 7. Power supply system

The steel pipe can be gradually saturated by the magnetic field produced by each coil and magnetization time can be extended. With multistage magnetization structure, steel pipe can be quickly saturated and achieve defects detection with high speed.

### 4.2 Results analysis

In order to verify the validity of the multistage magnetization structure, the coils are passed into different current firstly. The change trend of magnetic flux leakage magnetic field signal and current is shown in Figure 8.
Figure 8. Experimental curve of magnetic flux leakage field signal

As can be seen in Figure 8, the magnetic flux leakage field signal is larger with the increase of current. If the current is greater, then the magnetic field generated by the coil becomes stronger, and the magnetic flux leakage field signal is more likely to be detected.

When current is consistent, the axial magnetic flux leakage at different speeds is shown by software in figure 9. The abscissa axis and ordinate axis respectively represent the working time of detection sensor and the digital quantity detected by detection sensors, and the leakage magnetic field can be obtained by the corresponding conversion of digital quantity and chip resolution.

Figure 9. Magnetic flux leakage signal at different speed
As can be seen from Figure 9, when steel pipe operating speed is 0.5m/s, the detection sensor can detect defects in the inner wall of the steel pipe with single magnetization coil, and the two larger signals are produced by weld line, the two smaller signals are produced by defects. However, the detection sensor can't detect signal produced by defects when operating speed is 5m/s.

The experimental results show that the magnetization process has a certain hysteresis, magnetization is not instantaneous. When the multistage coils are used for magnetization, the defects signals detected by sensor are more obvious at high speed.

5. Conclusion

In the process of high-speed magnetic flux leakage detection, the effective magnetization time will be reduced, and the component will not realize magnetic saturation rapidly. Multistage magnetization structure can effectively extend magnetization time. When operating speed of steel pipe is 5m/s, it has remarkable magnetization performance. Compared with the single-stage magnetization structure, multistage magnetization structure can improve testing precision, which provides a feasible solution for the comprehensive detection of defects with high speed. The magnetization effect is good and the magnetic leakage signal of the inner wall of the steel pipe can be effectively detected. Besides, the multistage magnetization structure can improve the accuracy of the magnetic flux leakage nondestructive testing at high speed and provide a feasible scheme for realizing high-speed magnetic flux leakage nondestructive testing.

References