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An Eddy Current Flaw Detection System for Real-Time Monitoring of Metal Structure Cracks

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Abstract

In order to meet the in-service inspection requirements in practical applications, an eddy current inspection system for real-time monitoring of cracks on the surface of metallic structures of port machinery was developed. The system is designed based on the eddy current detection principle and adopts a new differential bridge circuit consisting of a detection coil, a reference coil and a balancing coil to improve the detection accuracy; the ZigBee wireless communication technology is used to achieve wireless transmission of the detection data; finally, the WPF-based monitoring software is developed to complete the real-time processing of the detection data, thus realizing the real-time monitoring of the surface cracks on the metal structure of the port machine. The experiments proved that the eddy current flaw detection system could detect the surface cracks of metal specimens quickly and accurately, and the monitoring software could also store the crack data in real time and issue real-time alarms accurately.

Keywords

Eddy Current; Wireless Communication; Differential Bridge; Real-Time Monitoring.

1. Introduction

With the development of the economy, China's port industry is developing rapidly, and the port machine, as the main mechanical equipment for port operations, plays a vital role in the daily operation of the port. The port machine is mainly composed of metal structure, which is the supporting frame of the whole port machine, and its main role is to bear and transmit various loads [1]. The metal structure is the supporting frame of the whole machine and its main role is to support and transmit various loads [1]. According to the investigation, the damage can be divided into four main categories: cracking, fracture, deformation and rusting, with cracking being the main defect, accounting for more than 80% [3]. Especially in the welding of metal structures, it is very easy to produce cracks. The width of these cracks is usually about 1mm, while the length varies from a few centimeters to tens of centimeters.

At present, the conventional nondestructive testing methods for crack detection of metal structure of port machinery require the machine to be shut down [4], which greatly reduces the efficiency of operation and detection efficiency of port machinery and causes certain economic losses. Therefore, it is necessary to develop an in-line flaw detection system that can meet the requirements of real-time field monitoring.

There are several methods for NDT of metals, such as ultrasonic detection (UT), radiographic detection (RT) and eddy current detection (ET) [5]. In this paper, eddy current detection is used, which has the advantages of easy to use, no coupling agent, high sensitivity, fast detection speed and non-intrusive compared to other NDT methods, and is easy to realize surface non-contact measurement and online inspection [6][7].

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The flaw detection system designed in this paper is based on the eddy current detection principle and combined with wireless transmission technology to complete the real-time online monitoring of the surface cracks on the metal structure of the port machine.

2. Principle of Eddy Current Flaw Detection Systems

When the eddy current detection technique is used to detect cracks on the metal surface, the magnetic field generated by the coil induces eddy currents in the metal, and the eddy currents change due to the existence of cracks on the metal surface, resulting in the formation of an alternating magnetic field, or "secondary magnetic field", which couples with each other to change the impedance of the coil [8][9]. Therefore, by analyzing the impedance of the coil, the defect situation on the metal surface can be obtained.

The equivalent circuit and analysis is as follows.

Due to the existence of resistance and inductance of the coil itself, the impedance of the coil can be expressed as [10]

$$Z = R + j\omega L \tag{1}$$

It is also assumed that the eddy current formed on the metal conductor under test is the current in a short-circuit loop, so that the eddy current detection can be equated to the transformer model shown in Figure 1 [11] [12].

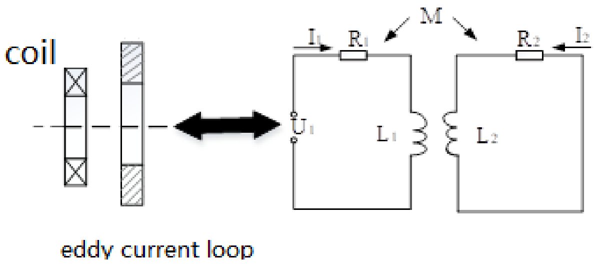

Figure. 1. Eddy Current Equivalent Transformer Model

From Kirchhoff's law, the basic equation for this transformer model is as follows.

$$(R_1 + j\omega L_1)I_1 - j\omega M I_2 = U_1 \tag{2}$$

$$(R_2 + j\omega L_2)I_2 - j\omega M I_1 = 0 \tag{3}$$

Where R_1 is the resistance of the detection coil, L_1 is the inductance of the detection coil, R_2 is the equivalent resistance of the eddy current loop, L_2 is the equivalent inductance of the eddy current loop, ω is the angular frequency of the excitation voltage, and M is the coupling coefficient.

From the transformer equivalent circuit and the above formulas, it can be concluded that the equivalent impedance of the detection coil after being affected by the secondary magnetic field is:

$$\begin{aligned} Z &= R_1 + j\omega L_1 + \frac{\omega^2 M^2}{R_2^2 + \omega^2 L_2^2} R_2 - j\omega \frac{\omega^2 M^2}{R_2^2 + \omega^2 L_2^2} L_2 \\ &= R_1 + \frac{\omega^2 M^2}{R_2^2 + \omega^2 L_2^2} R_2 + j\omega\left(L_1 - \frac{\omega^2 M^2}{R_2^2 + \omega^2 L_2^2}\right) \end{aligned} \tag{4}$$

It can be seen from the above formula that the change of the equivalent impedance of the detection coil is affected by the eddy current loop parameters R_2, L_2 and the coupling coefficient M .

When a crack is detected in the test coil, both the resistance and reactance of the vortex ring will change, resulting in a change ΔZ in the impedance of the test coil, which contains the crack information. Therefore, the crack information can be detected by measuring the change in impedance with the subsequent circuit.

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3. Composition of eddy current flaw detection system for real-time monitoring

3.1 System Configuration

The eddy current inspection system developed in this paper includes an excitation signal generation module, excitation signal amplification module, sensor probe, differential bridge circuit module, acquisition signal amplification module, acquisition signal filtering module, acquisition signal rectification module, A\D conversion module, controller module, wireless transmission module, and upper computer system monitoring software.

The excitation signal generation and amplification circuit is mainly used to provide a sinusoidal signal of a certain amplitude, frequency and power to drive the sensor coil. And the sensor module is mainly used for crack signal acquisition. After a series of filtering, rectifying and amplifying processing, the collected signal is delivered to the monitoring software of the host computer via wireless transmission module. Finally, the monitoring software completes the real-time analysis and processing of the crack signal.

The overall design block diagram of the system is shown in Figure 2.

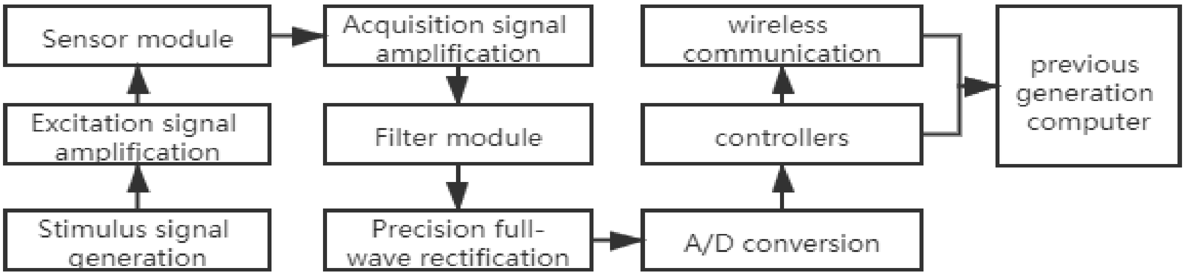

Figure. 2. Eddy Current Equivalent Transformer Mode

3.2 Selection of parameters and excitation frequency of the sensing coil

Sensors are an important part of the inspection system, and the sensitivity and accuracy of metal crack detection is causally related to them. Therefore, the selection of sensor probe is very important. In this paper, the sensor coil is simulated with finite element based on Ansoft Maxwell simulation software to determine the size of the coil. By simulating and calculating the magnetic field of sensor coils of different sizes, it is found that increasing the size of sensor coils within a certain range can effectively improve the detection sensitivity of amplitude response, which is consistent with the findings in reference [13]. At the same time in view of the port machine metal structure appears on the surface of the crack size varies, but generally its order of magnitude of centimeters. Therefore, the sensor coil used in this paper has dimensions of 23mm outer diameter, 18mm inner diameter, 8mm thickness, and 500 turns.

In addition, the choice of the excitation frequency of the sensor coil is also very critical. Excitation signals of different frequencies have different sensitivity to cracking parameters at different depth locations [14]. Due to the skin effect, the high frequency excitation signal is more sensitive to the metal surface defects, and the low frequency excitation signal is more sensitive to the metal internal defects [15]. At the same time, combined with the group of different frequencies of the excitation signal magnetic field strength of the simulation study, then the paper selected the frequency of 50 kHz sinusoidal excitation signal.

3.3 Design of a new differential bridge circuit

The differential bridge circuit is the core part of the detection system, which determines the accuracy of the detection results of the whole system. The commonly used differential bridge circuit is shown in Figure 3.

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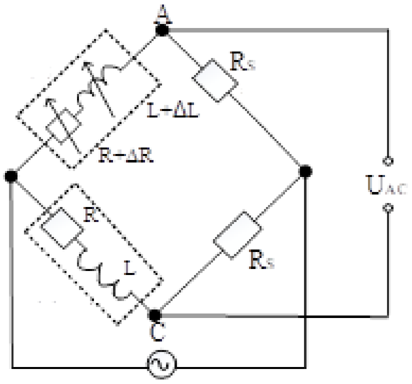

Figure. 3. Eddy Current Equivalent Transformer Mode

As can be seen in Figure 3, the differential bridge circuit consists of two coils (reference coil and detection coil) and two resistors of the same resistance value. In the normal state, the bridge is balanced and once the detection coil detects a crack on the surface of the metal structure, the bridge loses balance and generates a small output signal, which is the signal we need to detect.

However, in actual testing, it is difficult to reach the equilibrium state of the bridge, the main reason is the presence of the lifting effect. The lifting effect is mainly caused by the uneven roughness and unevenness of the metal surface, which seriously affects the balance of the bridge [16][17]. Therefore, this paper introduces a "balancing coil" into the ordinary differential bridge circuit to form a new type of differential bridge circuit, the circuit schematic diagram of which is shown in Figure 4.

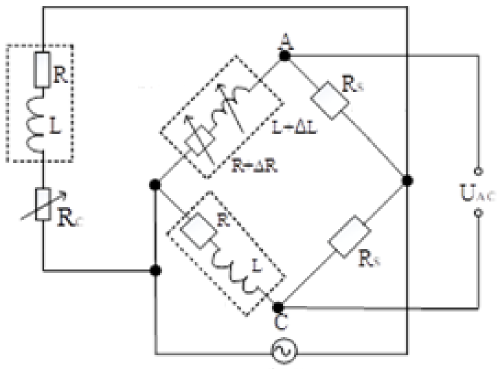

Figure. 4. Eddy Current Equivalent Transformer Mode

Experiments have shown that the balancing effect of the new differential bridge circuit with the addition of the "balancing coil" is much better than that of the ordinary differential bridge circuit. It reduces the "unbalanced voltage" that exists in the ordinary differential bridge circuit by more than ten times, and although the "unbalanced voltage" still exists in the new differential bridge circuit, it has almost no effect on the cracking information of the metal. Therefore, we can consider the bridge to be approximately balanced.

The improvement of the differential bridge circuit greatly improves the detection accuracy of the system.

3.4 Design of signal wireless transmission module

The actual application of large mechanical equipment similar to the port machine often has a complex structure, and the location of cracks in its metal structure usually has a certain distance from the on-site control room, from as little as tens of meters to as much as hundreds of meters. If you use wired communication technology for data transmission, although it can better guarantee the signal transmission accuracy, the field wiring has certain difficulties, and more importantly, the field wiring may bring considerable safety hazards to the normal work of other transportation tools.

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ZigBee wireless communication technology has the advantages of low cost, low power consumption, strong self-organization, and reliable data transmission [18]. Therefore, this paper designs a UART-interface serial wireless communication module based on the principle of ZigBee wireless communication technology. It mainly employs a CC2530 data processing chip and a CC2591 RF chip. The latter enables the output power of the wireless module to be greatly enhanced.

The wireless transmission rate of the module has been tested to reach 20dBm, and its communication distance can reach about 1000m without solid object obstruction. Therefore, when the monitoring position and the control room are within 1000 meters, the wireless transmission module can better complete the signal transmission.

4. Real-time monitoring software programming

In this paper, we have developed a PC software with Microsoft Visual Studio 2013 Ultimate as the platform and under WPF (Windows Presentation Foundation) framework, which can realize real-time monitoring, data storage and alarm function.

The crack monitoring software has strong compatibility and can run on many platforms, such as Windows XP, Windows 7, Windows 8, Windows 10, etc. It is a practical and convenient software for upper computer, which meets the practical needs.

The development of the monitoring software is divided into two parts: one is the design of the software front-end, and the other is the design of the software back-end.

The software front-end design is the preparation of some. xamal files, which mainly includes the following four aspects.

(1) Application file.

(2) Main Window.

(3) Waring Window.

(4) About Window.

The design of the software backend refers to the real-time processing and preservation of data. The real-time data processing adopts the process of "cache - decoding - processing".

Among them, data decoding using multi-threaded technology to achieve, will be time-consuming, computationally large amount of work on the sub-threaded processing, so that not only can achieve real-time data processing, but also to avoid software stuck, improve the utilization of CPU resources.

The data processing process mainly includes steps such as data pre-processing, determining whether cracks occur based on thresholds, reprocessing the data, and keeping it updated in real time. The data preservation is done by file manipulation, and the data decoded in the new thread is updated directly into the *.txt file.

5. Experimental testing

The metal structure to be monitored is within 100 meters from the control room (either vertically or horizontally), according to the field investigation of the group to the loading dock of Zhejiang Zhenneng Jiahua Power Generation Co. This meets the requirements of the eddy current detection system for wireless signal transmission distance in this paper. In the experiment, the sample specimen brought back from the dock site was used as the test piece, and the test steel plate was made of Q235, which is a common material used in port machine metal structures. According to the on-site investigation of the actual crack size of the metal structure of the port machinery, a crack of length of 50mm, width of 0.5mm and depth of 20mm is artificially processed on the test steel plate in this paper. The tested steel plate and the flaw detection hardware system were placed at a location 100 meters away from the laboratory, while the upper unit was placed in the laboratory, simulating the site's control room. A crack-free location is first selected for testing, which lasts for 3 hours.

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Table 1. Crack-Free Real-time monitoring results

0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00

Table 2. Cracked Real-time monitoring results

3.10	3.16	3.12	3.12
3.16	3.16	3.16	3.18
3.14	3.14	3.16	3.14
3.31	3.16	3.14	3.16
3.16	3.10	3.14	3.10
3.16	3.10	3.16	3.08

It can be seen from the above results that the system can obtain detection data in real time, and better realize the function of real-time monitoring. When there is no crack, the output voltage of the system is always 0 V, and the data is relatively stable; when there is a crack, the output voltage of the system is stable between 3.02 V and 3.31 V, and data storage and alarm functions are also realized.

Experiments show that the detection accuracy of the flaw detection system is high, and it can realize long-term online crack monitoring, which meets our design requirements.

6. Conclusion

In this paper, an eddy current flaw detection system for real-time monitoring of metallic structures is designed based on practical applications. The experimental results show that the system can monitor the cracks on the surface of metal specimens more accurately.

The system adopts a new differential bridge circuit, which effectively overcomes the interference of the pick-up effect and other factors, thus improving the detection accuracy of the system. Moreover, the wireless transmission communication mode makes the data transmission more convenient and simpler. At the same time, because the PC monitoring software developed under the WPF framework is applicable to all different versions of the current Windows operating system. Therefore, the system has greater practicality and better meets the needs of the field.

The system in this paper has only been tested in the laboratory and will need to be tested in the field in the future, especially for performance indicators such as sensitivity and stability of the system. In addition, the system can only analyze the crack information qualitatively at present, but it needs to be further optimized to realize the quantification and visualization of the crack information in the future.

The system also has potential applications for large metal structures in other industries, with appropriate adaptations.

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