A Study of the Frequency Characteristics of Low-frequency Eddy Current Detection for a Vibrating Screen Beam with a Cladding Layer

Fu Sheng¹, Xu Xiao-Dong*, Liu Yi¹, Xu Yong-Gang¹ and Chen Tao¹

¹Machinery Industry Key Laboratory of Precision Measurement and Control Technology and Instrument, Beijing University of Technology, Beijing, 100124, China.

ABSTRACT

A low-frequency eddy current detection method to detect cracks in a vibrating screen beam equipped with a cladding layer is proposed in this paper. The simulation research shows that the optimal detection frequency is from 10 Hz to 100 Hz. The experimental study determined the relationship between the testing frequency for different sizes of cracks and the amplitude and phase beneath a 7-mm-thick cladding layer. Finally, the optimum detection frequency has been determined to be from 150 Hz to 200 Hz using phase identification and has been determined to be from 300 Hz to 400 Hz using the magnitude.

*Corresponding author: E-mail: liuyihefei@126.com;
Keywords: Vibrating screen beam; crack; cladding layer; low-frequency eddy current; frequency characteristic.

1. INTRODUCTION

Coal has been an important energy resource for a long period of time. Currently, there are many problems in the process of coal exploitation and utilization, such as waste of resources, environmental pollution, and inefficient transportation. The principal method used to reduce direct burning of raw coal and to improve transportation is to wash coal on the spot, which can improve the coal quality and availability while reducing environmental pollution.

A vibrating screen is a critical piece of equipment used in the coal washing process. The vibrating screen directly affects the safety and reliability of the washing process. The crossbeam is one of the most important structural components of the vibrating screen and is fixed to the interior of the screen box, as shown in Figs. 1a and b. Additionally, the crossbeam plays a role in connecting and supporting the screen, and it is common for fatigue cracks to emerge due to the complex forces, which include gravity, the static forces of the equipment itself, moving stress, and alternating stress. To reduce degradation due to the adverse working conditions, the crossbeam exterior is covered by a 7-mm-thick anti-corrosive coating, which makes detection of the crossbeam difficult, as shown in Fig. 1c. This difficulty in detection is the reason that there is so little research with respect to crossbeam crack detection. Researchers have proposed a method using magnetic memory and eddy current testing [1], but the study was not performed thoroughly, the ratio of the magnetic memory was not determined [2-4], and a determination of a method to assure that the eddy current penetrates the coating has not been achieved [5-7]. Therefore, crossbeam field detection has always been a problem. Low-frequency eddy current detection depth can reach a dozen millimeters because the skin effect is relatively small [8-10]. Low-frequency eddy current inspection technology was applied to a vibrating screen that is covered by a layer of coating, and the screen’s frequency characteristics were studied in this paper. The results provide important guidance for on-site low-frequency eddy current inspection of vibrating screens.

Fig. 1. Diagram and photo of the object whose elements were detected
2. THEORETICAL BASIS OF THE ANALYSIS

Based on the electromagnetic induction principle, when a detection coil carrying an alternating current approaches a conductive specimen the alternating current in the coil produces an alternating magnetic field, which induces eddy currents in the specimen, as shown in Fig. 2. The size, phase and flow pattern of the eddy current are affected by the conductivity of the specimen, and the reaction current field of the eddy current changes the impedance of the detection coil. Therefore, by measuring the change in the impedance of the detection coil, some conclusions about defects can be drawn if the conductivity of the tested specimen differs [11].

When there is an alternating current moving through a wire, the changing magnetic field around the wire will induce a current in the conductor, so the current distribution along the cross-sectional area of the conductor is not uniform. The current density on the surface is greater, and the current density at the center is less and decays following a negative exponential rule. If the penetration depth is defined as when the eddy current density decays to a value on the surface of 1/e, the standard penetration depth of the eddy current is the following [12]:

\[ \delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \]  

(1)

where \( i \) (H/m) is the magnetic permeability of the material, \( \sigma \) (S/m) is conductivity of the material, and \( f \) (Hz) is the alternating current frequency.

For a semi-infinite plane conductor and using Maxwell electromagnetic theory, the eddy current density at depth \( x \) from the surface of the conductor can be written as the following [13]:

\[ I_x = I_o e^{-\sqrt{\pi f \mu \sigma} x} \]  

(2)

where \( I_o \) is the eddy current density of the semi-infinite conductor surface.

Equations (1) and (2) imply that the detection frequency is fundamental to eddy current testing although the frequency cannot be reduced by adjusting the frequency parameter \( f \) without restriction when detecting a metal component as the material constant is a constant value. Therefore, metal components can be detected through a coating layer with a certain thickness when detecting metal component defects. For crack detection in the vibrating screen beam, low-frequency eddy current technology can be used to detect the beam cracks through the coating layer.

Low-frequency eddy current testing has a corresponding effect with respect to the instrument and sensor. In low-frequency eddy current testing, surface factors can cause large eddy current changes, so attention should be paid to the influence of the surface disturbance factors on the test results. Because the interference signal has little influence on the phase of the response signal, low-frequency eddy current instruments should display plane impedance to conveniently provide phase information [8]. At the same time to improve the detection sensitivity, the pumping power and gain should be greater. For the sensor probe, to increase the detection depth, the sensor diameter is generally larger because the penetration depth of the magnetic field generated by the sensor is approximately one-quarter of the diameter of the sensor [9].

Based on the theoretical analysis above, a low-frequency eddy current technique is feasible for crack detection in a vibrating screen beam with a cladding layer. However, currently, low-frequency eddy current frequency characteristic for the beam of a vibrating screen with a cladding layer does not have any relevant research. Specifically the specific thickness of a vibrating screen beam, the thickness of the cladding layer of the material and a suitable detection frequency for the bulk material need to be determined. In this paper, through theoretical analysis and experimental research, to achieve a solution of the corresponding problems, rapid, accurate and quantitative field tests on a beam from a vibrating screen with a cladding layer are performed.

3. SIMULATION STUDY

The choice of the excitation frequency is the most important parameter in low-frequency eddy current detection and is based on the alternating electromagnetic field theory. When using low-frequency eddy currents on a vibrating screen beam, we simplify the computations using the model in Fig. 3 because the fault information needs to be extracted
through the cladding layer, and the eddy current strength in the z direction is more important compared with that in the x and y directions; therefore, by only considering the eddy current strength along z direction and according to eddy current field theory given by the Maxwell equation and Bessel functions, the limit frequency \( f_g \) is derived as the following [14]:

\[
f_g = \frac{5066}{u \sigma d^2} = \frac{5066}{u \sigma (0.276886 \rho_0)^2}
\]  

(3)

where \( \sigma \) (S/m) is the electrical conductivity, \( \rho_0 \) (m) is the outer radius of the excitation coil, and \( i_c \) (H/m) is the relative magnetic permeability.

According to the related parameters of the vibrating screen beam, we selected \( i_c = 100, \ \sigma = 1.37 \times 10^6 \ \text{S/m}, \ \rho_0 = 30 \ \text{mm} \). When used in the formula, we obtain \( f_g = 0.536 \ \text{Hz} \). To further determine the trend of the eddy current strength with a change in the frequency, COMSOL software was used to analyze the detection model. Because the rubber cladding layer is not an electrical conductor, a height of 7 mm was used to replace the cladding. After assigning material properties, defining the boundary conditions, meshing, applying the load, and analyzing the results, the results were obtained and are shown in Fig. 4. The red arrow is the current flow direction in the coil, and each color represents the strength of the eddy current density on the beam. A deeper color (red) indicates a stronger eddy current density, and a lighter color (blue) indicates a weaker eddy current density.

Through the analysis of the simulation results, we can observe that with an increase in the detection frequency, the penetration depth of the eddy current is reduced and with an increase in the eddy current frequency, the skin effect becomes more obvious. When detecting a 10-mm-thick beam through a 7-mm cladding layer, the optimal detection frequency was between 0.1 and 1 Hz. However, the actual operating frequency was much greater than the value of the theoretical analysis. This result is due to the actual testing, as the magnetic flux of the coil will be less than the theoretical calculated value, and a portion of the magnetic flux was not involved in the detection process. To compensate for the loss of magnetic flux, an increase in the detection frequency is required. Therefore, further experimental studies are needed to obtain the actual and optimal detection frequency. Subsequently, by taking the detection frequency that is based on the theoretical analysis as the reference, the corresponding experimental research is carried out.

4. EXPERIMENTAL STUDIES FOR THE FREQUENCY CHARACTERISTICS

Based on the theoretical analysis above and the simulation results over the detection frequencies from 0.1 to 1 Hz, which is used as a reference frequency band, the following experimental studies further determine the actual optimum detection frequency. It is well known that the signal amplitude and the phase are the two most important characteristic indicators for low-frequency eddy current inspection [15]. These characteristics are an indirect expression of the defect parameters in addition to determining the direct basis for the defect. In actual testing, the selection of an optimum detection frequency such that at the excitation frequency, the impedance changes related to the defects and other factors affecting the coil impedance can have the greatest distinction. The impact of the defects on the coil impedance can be interpreted as a result of the combined effect of the electrical conductivity and the geometry of a defect. A crack in a beam is detected during the test performed to determine a specific frequency. Additionally, the impedance change of the conductivity and the coil defect cause a large change in the phase difference, i.e., the phase difference is 90 degrees. Therefore, the maximum amplitude and phase corresponding to a 90-degree shift in the frequency is the most appropriate frequency. An investigation of the relationship between the frequency and the amplitude and phase was performed using the following experiment.

The testing principle of a clad beam using a low-frequency eddy current is shown in Fig. 5a. The experimental system is shown in Fig. 5b. The experimental device consists of a dedicated low-frequency eddy current detector with a special low-frequency eddy current probe. The body material of the specimen is selected to be 16 Mn steel, which is the same material with girders. The coating layer is a 7-mm rubber wear layer, as shown in Fig. 5b, which can be divided into two types: Smooth and rough. Additionally, the testing requirements for the shaker beam in the actual site require simulation of cracks of different sizes, so the cracks were measured with wires of different sizes, as shown in Table 1. The pre-assay parameters were the following: 20 dB;
From the analysis and presented in Figs. 6 and 8, as the frequency increases when measuring the smooth cladding layer, the amplitude of different crack depths first increased then decreased, and there is a turning point frequency such that the amplitude was at a maximum. A comparison also demonstrated that the crack detection signal amplitude was greater when the cladding layer was rough. The variation in the eddy current signal variation, which was caused by the surface roughness, was very large in amplitude and had a disorganized detection signal. An analysis of Figs. 7 and 9 shows a smooth coating layer. A lower frequency results in a smaller phase angle, and as the frequency increases, the phase angle increases. However, the phase values are basically the same for different crack depths. The crack depth cannot be distinguished. When the coating layer is rough, the results with a smooth coating layer are similar except for the addition of some volatility in the phase.

**Fig. 2. Principle diagram of the eddy current testing**

**Fig. 3. Detection model diagram**
5. DISCUSSION OF THE EXPERIMENTAL RESULTS

5.1 Phase Angle Latency Issues

Further analysis of the experimental results from the phase map shows that the signal phase has a lag phenomenon as the signal frequency increases, and a greater detection frequency results in a more significant phase lag signal. Because the beam is a ferromagnetic material, detection methods for ferromagnetic components must be used. According electromagnetic theory, the signal penetration distance is $x$ from the exterior to the inside of the components, and the phase lag angle is the following:

$$
\theta_x = x \sqrt{\frac{\pi f \mu \sigma}{\rho}}
$$

where $x$ (m) is the penetration distance, $f$ (Hz) is detection frequency, $\rho$ (S / m) is the electrical conductivity, and $\mu$ is the magnetic permeability.

From equation (4), the phase angle $\theta_x$ of the signal is a function of the detection frequency $f$ and penetration distance $x$. An increase in $x$ results in a greater phase lag. To study the relationship between the changes in the detection frequency $f$ and changes in phase angle $\theta_x$, we assume $x$ is 1 mm. The theoretical value and the actual value of the lag phase angle are shown below.

Fig. 4. Simulation result of different frequency
Fig. 5. Experimental set up for low-frequency eddy current detect crack with cladding layer

Fig. 6. The relationship between frequency and amplitude of smooth cladding layer
Fig. 7. The relationship between frequency and phase of smooth cladding layer

Irregular

Effective frequency range

Fig. 8. The relationship between frequency and amplitude of rough cladding layer
Fig. 9. The relationship between frequency and phase of rough cladding layer

Fig. 10. Smooth cladding layer phase lag
As seen in Figs. 10 and 11, the actual value of the phase lag is less than the theoretical value, and therefore, the phase lag test results are within the theoretical error. The experimental results of the phase lag are reasonable. Therefore, the use of the phase angle to determine the best detection frequency is feasible.

![Graph showing phase lag and frequency](image1)

**Fig. 11. Rough cladding layer phase lag**

![Graph showing amplitude and frequency](image2)

**Fig. 12. Optional frequency translation of the amplitude**
5.2 Optimal Frequency Amplitude Problems

Further analysis of the experimental results of the amplitude diagram show that the signal amplitude has a problem such that there is an optimum frequency variation as the frequency increases. As shown in Fig. 12, the amplitude of the crack depth, which varies from 1 mm to 9 mm, corresponds to an optimum frequency, which ranges from 400 Hz to 300 Hz. An increase in the crack depth is indicated when the optimal frequency is reduced. This change is due to the low-frequency eddy current testing, which has drawbacks when determining links between factors of the test object, such as the physical properties, geometry and defect, and the parameter variation within the detection coil. Because the beam of a shaker is a metal conductor and the relaxation time of a charge in a metal conductor is very short, the density of the free charge can be assumed to be zero. In this case, the wave equation, which is derived from the Maxwell equations of an electromagnetic field, of the time-harmonic changes can be derived as follows [15]:

\[
\nabla^2 H = j\omega\mu(\sigma + j\omega\varepsilon)H
\]

\[(5)\]

where \(H\) \((A/m)\) is the strength of the magnetic field, \(\sigma\) \((S/m)\) is the electrical conductivity, \(\omega\) \((r/s)\) is the angular frequency, \(\mu\) \((H/m)\) is the magnetic permeability, and \(\varepsilon\) \((F/m)\) is the permittivity.

Table 1. Experimental material parameters

| Experimental material         | 16 Mn |
|-----------------------------|-------|
| Crack width/mm               | 0.5   |
| Crack depth/mm               | 1     |

If one assumes that the displacement current of a metal conductor is very small (for metal this displacement is approximately \(10^7 \text{/(V}\cdot\text{m})\) and \(\dot{\varepsilon}=8.85\times10^{-12} \text{ F/m}\) and if \(\dot{\varepsilon}\) is \(10^7 \text{/(V}\cdot\text{s})\), \(\dot{\varepsilon}\) and \(\dot{\varepsilon}\) are approximately \(10^9\) in magnitude. Therefore, \(\dot{\varepsilon}\), \(\dot{\varepsilon}\) and \(\dot{\varepsilon}\) are comparably negligible, equation (5) can be simplified to the following:

\[
\nabla^2 H = j\omega\mu\sigma H
\]

\[(6)\]

For the beam detection, according to the model in Fig. 3, we only care about the magnetic field strength along the z-axis. The field strength can be obtained after derivation, and the solution is the following:

\[
H_z = H_{0z} e^{-(j\omega_z)\sqrt{\mu\sigma}}
\]

\[(7)\]

where \(H_{0z}\) is the intensity of the magnetic field at \(x = 0\), \(x\) \((m)\) is the depth of detection, and \(j\) is the imaginary unit volume.

From (7) we can see that the magnetic field of the conductor is composed of two components: the real part and the imaginary part. The analysis of real part shows that the intensity of the magnetic field \((Hz)\) decreases when the detection depth \((x)\) increases; \(Hz\) increases when the frequency of the test \((f)\) decreases. Specifically, the intensity of magnetic field decreases when the electromagnetic field increases the depth of the internal conductor, and the intensity of the magnetic field increases when the testing frequency \((f)\) decreases. Therefore, as the transmission for the depth of the crack increases, the magnetic field strength is further reduced. An increase in the magnetic field strength is necessary to reduce the testing. The detection frequency decreases when the crack depth becomes deeper. Therefore, the change in the optimum frequency is reasonable in the detection result. The use of the amplitude to determine the optimum frequency is feasible.

5.3 The Problem Associated with the Optimal Frequency

According to the analysis of the phase lag and the optimal frequency of the amplitude change above, the use of the amplitude and the phase to determine the best detection frequency is feasible. From the perspective of phase, because the surface disturbance factor has little effect on the phase information during the low-frequency eddy current inspection and regardless of whether the cladding layer is smooth or not, a change in the detection frequency results in essentially the same phase, and the optimal frequency was determined to be between 150 Hz and 200 Hz. From the perspective of magnitude, the surface disturbance factor has a large effect on the magnitude, so in the smooth coating layer, a variation in the detection frequency causes the amplitude to change, and the optimal frequency was determined to be between 300 Hz and 400 Hz. However, in the rough coating layer, the
detect amplitude information is disorganized and not regular. Considering the characteristics when field testing the cladding layer and according to the different detection environments, the idea of using different detection frequencies has been adopted. For the smooth cladding layer, the optimal detection frequency at which the amplitude can be determined was between 300 Hz and 400 Hz. For the rough cladding layer, the optimal frequency at which the phase can be determined was between 150 Hz and 200 Hz.

6. CONCLUSIONS

In this paper, a low-frequency eddy current technique has been applied to crossbeam crack detection. This method successfully overcame the thick coating of the covering layer, and a theoretical analysis was proposed and an experimental study was performed.

Through experimental research and according to the specific materials and coating thickness, the optimum test frequency was proposed in this paper to be between 150 Hz and 200 Hz identified by the phase, and the optimum detection frequency determined by the magnitude was between 300 Hz and 400 Hz.

For different on-site detection environments, different detection frequencies should be used. When on-site factors have little influence on the low-frequency eddy, the optimum detection frequency using amplitude detection can be used. Conversely, the optimum detection frequency determined from the phase detection should be used for testing.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Guang-hui XUE, Guo-rui ZHAO, Shi-Gang ZHU, et al. Express detection method on the crack flaw of large vibrating screen lower beam based on metal magnetic memory testing and eddy current testing [J]. Journal of China Coal Society. 2010; 35(7):1215-1218.
2. Ling-li CUI, Chen-hui KANG, Jian-yu ZHANG, et al. Application of metal magnetic memory in gear early micro cracks testing [J]. Journal of Beijing University of Technology. 2012;38(10): 1442-1445.
3. Ming-xiu XU, Da-bo WU, Min-qiang XU, et al. The MMM detection of rotating bending fatigue damage for 45Q steel [J]. Advanced Science Letters. 2011;4(1–6): 1–6.
4. Doubov AA. The method of metal magnetic memory-the new trend in engineering diagnostics [J]. Welding in the World. 2005;49(9):314-319.
5. Zilberstein V. Walrath K, Grundy D, et al. MWM eddy-current arrays for crack initiation and growth monitoring [J]. Int. J. Fatigue. 2003;25:1147-1155.
6. Blodgett MP, Ukpabi CV, Nagy PB. Surface roughness influence on eddy current electrical conductivity measurements [J]. Mater. Eval. 2003;61:765-772.
7. Kunpeng LIU, Zihua ZHAO, Zheng ZHANG, et al. Characterization of early fatigue microstructure in AISI 321 steel using eddy current non-destructive methodology [J]. Journal of Wuhan University of Technology (Materials Science Edition). 2013;28(6): 1201-1206.
8. REN Hai-yan, Ke-qin DING. Simulation of low-frequency excitation frequency eddy current testing selected [J]. Nondestructive Testing. 2009;33(3):18-20.
9. Xu Wan-zhong. Application of low-frequency eddy current technique [J]. Nondestructive Testing. 1996;16(8):227-230.
10. Yu-hua ZHANG, Fei-lu LUO, Hui-xian SUN. Suppressing probe-coil’s lift-off effect on inspection of aircraft wheel hub using eddy current technique [J]. Chinese Journal of Scientific Instrument. 2009;30(4):787-790.
11. Hong-chun SUN, Yong-fa XIA, Yu CUI. Experimental study on the best testing parameters in eddy current testing method for small crack of steel bar [J]. Journal of Northeastern University (Natural Science). 2012;33(1):108-110.
12. Kai SONG, Yi-hua KANG, Lu-gen ZHANG, et al. Simulation of the effects of magnetic properties of steel pipes on ECT signals [J]. Journal of Huazhong University of Science and Technology (Natural Science Edition). 2011;39(10):11-13.
13. Guo-hou LI, Ping-jie HUANG, Pei-hua CHEN, et al. Application of eddy current testing in the quantitative evaluation of the rail cracks [J]. Journal of Zhejiang University (Engineering Science). 2011; 45(11):2038-2042.
14. Ze-bo SHAO, Xing-de LIU. Nondestructive testing [M]. Beijing: Chemical Industry Press. 2011; 19-143.
15. Ji-lin REN, Jun-ming LIN. Electromagnetic nondestructive testing [M]. Beijing: Science Press. 2008; 67-125.