Research on the detection of curved ferromagnetic materials by flexible eddy current array sensor based on ldc1614

Li Cao¹, Weipeng Zhang*, Qi Zhang¹, Rui Chen¹, Wenqiang Ma¹
¹ Jiangsu Automation Research Institute, Lianyungang, Jiangsu, 222006, China
*Corresponding author’s e-mail: zwp782870361@163.com

Abstract: Flexible eddy current array nondestructive testing technology has the advantages of large single scanning area and fast scanning speed in the defect detection of conductive materials, so it becomes a common research hotspot of sensor and nondestructive testing technology. The performance of the array probe on the sensor is an important factor to determine the performance of the sensor, and the detection circuit and excitation mode are another important factor. In this paper, the array coils with different parameters are simulated and analyzed, and the resonant detection circuit based on ldc1614c digital inductance conversion chip is used to detect the high permeability materials on curved surface. Through the digital imaging technology, the defect image of the tested material is obtained to verify the selection of the probe coil and the reliability of the detection circuit.

1. Introduction
Eddy current testing is a nondestructive testing method using electromagnetic induction[1]. The eddy current sensor can be used to measure the shape, conductivity and thickness of defects of metal objects in a non-contact way. The final output of the sensor needs to give accurate defect evaluation results. The array detection of probe can greatly improve the detection speed and efficiency[2].

Eddy current sensor is usually composed of detecting probe (coil), tested object (conductor), signal processing circuit and other parts. The signal processing circuit includes signal extraction, signal separation and signal conversion. The flow chart of eddy current sensor detection is shown in figure 1.

![Figure 1 Schematic diagram of the eddy current sensor detection process](image)

In practical application, the FECA sensor has the following problems to be studied in the surface defect detection of curved materials with high permeability.

1. Because of the coupling of magnetoresistance effect and eddy current effect, the selection of detection signal characteristics is a key.

2. Because the surface of the object to be measured is a curved surface with different curvature, it is necessary to design an array sensor with flexible substrate to complete the detection. The common flexible sensors have the disadvantages of high cost and low inductance, which lead to the lack of sensitivity or coverage area.

3. The array probe is arranged in a compact way. Because the probe is usually a detection coil, the mutual inductance between the coils will greatly weaken the sensitivity of the sensor and cause the
distortion of the detection signal.

In order to solve the above problems, the FECA sensor is designed in this paper: the cylindrical coil is selected as the detection coil, and the ferrite core is added; the resonance method detection circuit is selected, and the inductance is output as the signal feature, and the time-sharing oscillation method is used to solve the mutual inductance effect on the array probe. The interference of mutual inductance effect is reduced from the aspects of structure design and excitation mode. And the sensor is applied to the actual detection experiment. The experimental results show that the sensor can detect the surface defects of high permeability materials.

2. Signal characteristics and probe structure

Eddy current testing is use to the principle of eddy current effect to detect the change of permeability or conductivity of the surface or near surface of the conductor due to the change of mechanical or chemical or physical properties such as material, shape, deformation, defect[3]. The change of magnetic field is detected by detecting probe. For the detection probe using coil, because the interaction of alternating original excitation magnetic field and induced eddy current magnetic field will reflect the impedance change of the detection coil, and also the inductance and resistance of the detection coil will change. Eddy current effect as shown in figure 1.

![Figure 1: Eddy current effect](image1)

2.1. selection of signal characteristics

In the process of eddy current effect, the inductance value of the coil will decrease because the induced magnetic field hinders the change of the original magnetic field. At the same time, due to the thermal effect of the induced current, according to the conservation of energy, the eddy current in the conductor will consume energy, so the equivalent resistance of the coil will increase. When the AC oscillation current of a certain frequency enters into the coil, the alternating magnetic field will be generated in the detection coil of the probe. In the no-load state, all the energy will be lost on the equivalent resistance of the coil. When the conductor is close to the magnetic field, the induced current is generated on the surface and near the surface of the conductor. The change of the resistivity \( \rho \), the permeability \( \mu \), the discontinuity of the surface shape, or the distance \( X \) between the probe and the target, as well as the change of the excitation current frequency \( f \), will change the eddy current distribution on the surface of the test piece, resulting in the change of the impedance \( Z \) of the test coil. As shown in formula (1):

\[
Z = f(\rho, \mu, x, f)
\]  

(1)

For the coupling relationship between the detection coil and the target, the transformer model theory is proposed to explain the eddy interaction[4]. As shown in figure. 3 (a):

![Figure 3: Eddy current effect](image2)
The detection coil representing eddy current sensor can be equivalent to a series of resistance and inductance, and the detection coil of eddy current sensor can be regarded as a series of variable resistance and inductance. At the same time, there are parasitic capacitances between the detection coil and the interface. In practice, the value of the parasitic capacitances is always the same. Figure 3 (b) shows the eddy current effect between the probe and the target. The detection coil is the primary part of the transformer model, and the tested object is the secondary part of the model. The detection coil can be reduced to the series connection of inductance and resistance ideally. According to Kirchhoff’s law, it can be obtained that:

\[
\begin{align*}
R_c I_1 + j\omega L_c I_1 - j\omega M I_2 &= U \\
R I_2 + j\omega L I_2 - j\omega M I_1 &= U
\end{align*}
\]

(2)

By solving the equation, we can get:

\[
I = \frac{U}{R_c + \frac{\omega^2 M^2}{R_c^2 + (\omega L_c)^2} R_c + j\omega L_c - \frac{\omega^2 M^2}{R_c^2 + (\omega L_c)^2} L_c}
\]

(3)

Therefore, the equivalent impedance of eddy current sensor (input impedance of transformer) is

\[
Z = \frac{U}{I} = R_c + \frac{\omega^2 M^2}{R_c^2 + (\omega L_c)^2} R_c + j\omega L_c - \frac{\omega^2 M^2}{R_c^2 + (\omega L_c)^2} L_c
\]

(4)

The part of inductance and resistance can be divided into the following forms:

\[
\begin{align*}
R &= R_c + \frac{\omega^2 M^2}{R_c^2 + (\omega L_c)^2} R_c \\
L &= L_c - \frac{\omega^2 M^2}{R_c^2 + (\omega L_c)^2} L_c
\end{align*}
\]

(5)

In the above formula, \(\omega=2\pi f\) is the angular frequency, and \(M\) is the mutual inductance between the coil and the measured target, which can be written as follows:

\[
M = k \sqrt{L_c L} \quad (0 < k < 1)
\]

(6)

In the above formula, \(K\) is the coupling coefficient of primary and secondary in the theoretical model of the transformer. The value of \(K\) is between 0 and 1. When the sensor is close to the target, the electromagnetic characteristics of the target remain unchanged when the frequency of the sensor is constant, and \(f\), \(\mu\), \(\rho\) are constants. Thus, the equivalent impedance of the eddy current sensor can be simplified.

Substituting equation 2 into equation 6, the impedance calculation expression of eddy current sensor coil can be obtained.
Due to the effect of eddy current, the coil impedance changes from original to $Z$. The comparison shows that the eddy current makes the coil resistance increase and the inductive reactance decrease, and the coil quality factor $Q$ decreases because of the heat generated by the eddy current in the measured body. The quality factor $Q$ of the coil can be obtained by simplifying formula (7) as follows[5]:

$$Q = \frac{2\pi f L}{R} = 2\pi f \frac{L - \frac{(2\pi f)^2 M^2}{L_2}}{R_1 + \frac{(2\pi f)^2 M^2}{R_2}} = Q_0 \frac{1 - \frac{L_2 (2\pi f)^2 M^2}{Z_2^2}}{1 + \frac{R_2 (2\pi f)^2 M^2}{Z_2^2}}$$

(8)

Where, $Q_0$ is the quality factor of the detector coil under no-load state, and $Z$ is the impedance of the eddy current ring generated in the measured body.

According to the above derivation, with the change of detection distance, the coil impedance, resistance, inductance and quality factor will change with the mutual inductance between the coil and the tested body. According to different detection purposes and conditions, different conversion circuits will be used to convert the above parameters into electrical signal output.

According to the above equation, the inductance and quality factor of the coil can be expressed as a function of the impedance.

$$Z, L, Q = f(x, \mu, \rho, f)$$

(9)

In summary, the basic output of eddy current sensor includes impedance, inductance and $Q$ value. Therefore, the inductance value can directly reflect the change of magnetic field caused by eddy current effect between the probe and the object to be measured, which can be extracted, amplified and output as signal characteristics.

2.2. Parameter optimization of probe coil based on COMSOL

The parameters of the detecting coil have a great influence on the properties of the FECA sensor. After the sinusoidal alternating current is connected, the impedance, inductance and $Q$ value of the detection coil will change. In this chapter, COMSOL multiphysics, a finite element analysis software for multi physical field modeling and simulation, is used to simulate the shape, wire diameter, wire distance and turns of the coil, and obtain the magnetic field distribution, impedance and $Q$-value curve of quality factor. Through the simulation analysis of the coil parameters, the more appropriate parameters of the detection coil are selected.

To realize high resolution coil, it is necessary to ensure large inductance and high $Q$ value. The shape of the coil also has a great influence on the performance of the probe. In this paper, the magnetic field distribution of rectangular coil and cylindrical coil is considered to be more complex by numerical calculation. In this paper, COMSOL finite element analysis software will be used to simulate the performance of two kinds of coils. In this paper, its ad / DC module is used. Before the finite element analysis, the finite element model of rectangular coil is established by SolidWorks. To facilitate the description of model size, this paper will show one-half of the model, as shown in figure 4:
Table 1 shows the relevant parameter settings of the simulation model.

| PROJECT                  | PARAMETER                     | VALUE         |
|--------------------------|-------------------------------|---------------|
| Boundary material:       | relative permeability        | 1             |
| Air                      | relative dielectric constant  | 1             |
|                          | conductivity (S/m)           | 0             |
| Material of coil:        | relative permeability        | 1             |
| Copper                   | relative dielectric constant  | 1             |
|                          | conductivity (S/m)           | 5.998e^-7     |
| Material of lsbst:       | relative permeability        | 4000          |
| Martensitic stainless    | relative dielectric constant  | 1             |
| steel                    | conductivity (MS/m)          | 1.74          |
| Material of core:        | relative permeability        | 5000          |
| Ferrite                  | relative dielectric constant  | 1             |
|                          | conductivity (MS/m)          | 1e^-12        |
| Sensor                   | Excitation frequency (MHz)   | 0.7-1.4       |
|                          | Voltage of coil (V)          | 0.05          |
|                          | Maximum unit size (mm)       | 8             |
|                          | Minimum unit size (mm)       | 0.1           |
| Mesh                     | Maximum unit growth rate     | 1.45          |
|                          | Curvature factor             | 0.5           |
|                          | Narrow area scale            | 0.06          |

Through the finite element analysis, the magnetic field distribution of rectangular coil and cylindrical coil is obtained, as shown in figure 5. It can be seen from the results that the magnetic induction intensity and concentration degree in the cylinder coil are greater than that in the rectangular coil.
In order to fully explore the difference of coil sensitivity between the two shapes, this paper changes the lift height of the model, records and generates the curve of resistance and inductive reactance changing with the detection distance. Through the analysis of the changes of coil resistance and inductive reactance with the detection distance, it is found that in the same measurement range, the relative changes of impedance resistance and inductive reactance of rectangular column coil are large. As shown in figure 6:

![figure 6](image)

Figure 6. Relationship between cylindrical and rectangular coil resistance and inductive reactance and detection distance

Based on the above analysis of the two shapes of the coil, the advantages and disadvantages of the two shapes of the coil and the machining difficulty are considered comprehensively. This paper considers that the concentration of the magnetic field strength is conducive to the design of array probe array shape, so the cylindrical coil is adopted in this paper.

In order to further improve the Q value as much as possible, and ensure a higher self resonance frequency as much as possible, consider increasing the inductance value of the detection coil, so as to increase the sensitivity of the sensor. Due to the limited coil space, its outer diameter and turns often can't use larger parameters, because the existing sensors use hollow coils, which reduces the difficulty of processing and leads to the loss of magnetic field energy, so that the magnetic field energy can't be maximized, thus affecting the performance of the sensor. The quality of the probe can be improved by adding the magnetic core to the detection coil.

![figure 7](image)

Figure 7. Cylindrical coil with ferrite core

When the core is introduced, the eddy current loss caused by the core will appear. At present, eddy current loss has been widely studied at home and abroad. The eddy current loss caused by the magnetization of cylindrical magnetic materials in alternating magnetic field is as follows:

\[ We = \left(\pi B_s R^2\right) \sigma \cdot 4 \cdot 10^{-16} W/cm^3 \]  

(10)

In formula,
- \( f \) —— excitation frequency,
- \( B \) —— saturation magnetic induction intensity,
- \( R \) —— radius of cylinder,
- \( \sigma \) —— material conductivity

It can be seen from equation 10 that the eddy current loss is inversely proportional to the conductivity of the core material, that is, the smaller the conductivity is, the smaller the eddy current loss is. Therefore, in order to reduce the eddy current loss caused by the core, the material with small conductivity must be selected. Ferrite is easy to be magnetized as a soft magnetic material. When the external magnetic field disappears completely, the residual flux density is very small. In addition, ferrite materials have much lower conductivity than metal materials, which can restrain eddy current and reduce eddy current loss. Therefore, ferrite is widely used as core material.
Using the design parameter parameters in Table 1, use the cylindrical coil axisymmetric model and add the ferrite model to the finite element model. The flux density pattern obtained from the finite element analysis of ferrite core and hollow sensor is shown in figure 8.

![Figure 8 Comparison of ferrite core finite element models](image)

As can be seen from figure 8, the distribution of the magnetic field lines of the coil containing the ferrite core is centralized, which reduces the flux leakage and makes the magnetic field energy more concentrated. The main reason is that the ferrite core enhances the main field in the coil, and the secondary field caused by the main field in the measurement body increases correspondingly. Although the main field and the secondary field are opposite in direction, the resistance and inductance of the coil increase significantly at the same elevation through the increase of the total magnetic flux of the coil.

3. Detection circuit

The resonant detection circuit is used in the FECA sensor detection system. The resonant circuit is a constant amplitude frequency modulation circuit, which is characterized by taking the detection coil as the inductance component of LC oscillator. For example, when the distance between the sensor coil and the measured conductor changes, the inductance or impedance of the sensor coil changes, so that the frequency of the oscillator changes. In this process, the voltage of the excitation frequency output pin is clamped, and the frequency value can be used to express the value of the measured parameter. The detected frequency signal can be converted into inductive signal output. In this paper, the inductance digital conversion chip LDC1614 of TI company is used. As shown in figure 9.

![Figure 9. FECA sensor detection inductance physical map](image)
The simple principle of the resonance detection circuit is shown in figure 10.

Figure 10. Detection principle

\( f_{\text{sensor}} \) is the resonance signal of LC parallel resonant circuit, which enters into the internal inductance measurement module after conditioning. \( f_{\text{sensor}} \)'s first passes through the internal frequency multiplier, the frequency becomes three times of the original; then it enters the frequency divider, the frequency division coefficient is the response time in the register; finally, it enters the 24 bit timer through the frequency division signal, \( f_{\text{ext}} \) is the timer clock, provided by the external crystal or MCU, the timer measures the period of the signal after the frequency division, so as to realize the measurement of \( f_{\text{sensor}} \)'s frequency.

A functional block diagram of a detection chip is shown in figure 11. The sensor is connected to channels in1a / in1b to in4a / in4b. A high frequency reference clock can be connected to the CLKIN pin or use an internal reference oscillator. This reference clock (\( f_{\text{REF}} \)) is used to measure the sensor frequency (\( f_{\text{sensor}} \)). The front end of the detection circuit used in this paper is used to drive the resonant circuit, followed by a multiplexer, which can connect the active channels to the kernel module in turn, and measure and digitize the frequency of the sensor. The core uses a reference frequency to measure the frequency of the sensor. \( f_{\text{REF}} \) comes from an internal reference clock (oscillator), or an external supplied clock. The digital output of each channel is the proportion of \( f_{\text{sensor}} / f_{\text{REF}} \). I2C interface is used for device configuration and digital frequency value transmission to host processor.

Figure 11. Schematic diagram of the LDC1614 clock signal

In figure 11, the key clock is \( f_{\text{IN}}, f_{\text{REF}}, f_{\text{CLK}}, f_{\text{CLK}} \) comes from internal clock source or external clock source (CLKIN). The reference clock for frequency measurement, \( f_{\text{REF}} \), comes from the clock source fclk. The external master clock is used in high-precision application, and the stability and accuracy requirements provided can meet the application. Internal oscillators can be used in applications that require low cost and do not require high accuracy. The \( f_{\text{IN}}X \) clock comes from the sensor frequency \( f_{\text{sensor}} \) X of channel X. \( f_{REF}X \) and \( f_{\text{IN}}X \) must meet the requirements listed in the table below, depending on whether the master clock (\( f_{\text{CLK}} \)) is an internal or external clock.
The register is used to control the sensor drive current so that the sensor signal amplitude is in the best range of 1.2V to 1.8V (outside the sensor). The device can still convert to sensors less than 0.6V, but the conversion noise will increase. Below 0.6V, the sensor may be unstable or may stop completely, and the conversion chip will stop the conversion. If the current drive causes the oscillation amplitude greater than 1.8V, the internal echo circuit will become active. This may cause the sensor frequency to shift so that the output no longer represents a valid system state. Figure 12 is a schematic of the sensor driver. Each channel has an independent setting of iDrive current for setting the oscillation amplitude of the sensor.

![Figure 12. Chip conversion drive current indication](image)

For the sampling process of the resonant circuit of the probe, there is a high-frequency oscillator inside the chip, which continuously outputs the sweep signal. When the external LC network resonates, the impedance of the LC resonant circuit is the largest, and the voltage at the output pin is the largest at this time. By maintaining the output pin at a certain maximum voltage value, the LC network is always in the resonant state. Eddy current array testing requires multiple channels to sample a single channel, which is optional. The process of oscillation and channel conversion is shown in figure 13:

![Figure 13. Schematic diagram of the start-up and sampling process of the conversion chip](image)

Each chip has four channels to detect the probe signal, and the chip will sample each channel successively in multi-channel mode. The excitation mode can avoid mutual inductance interference between the detection coils, keep high quality factor and avoid signal distortion.
As shown in figure 14, the communication between the chip and the host is based on I2C interface, and ldc1614 uses an extended start sequence to access registers. The maximum speed of I2C interface is 400kbit / s. The data sequence starts with the 7-bit slave address of standard I2C communication, followed by an 8bit pointer register byte to set the register address. When the addr pin of the device is set low, the I2C address of ldc1614 is 0x2a; when the address pin is set high, the I2C address of LDC is 0x2b.

The analog signal of the frequency collected by the detection coil through the oscillation circuit is converted into digital signal through ldc1614 and uploaded to the register of MSP430 host computer for storage, which can be called and displayed by the host computer in real time. As shown in figure 15, after the frequency signal change between the test piece and the FECA probe due to the eddy current effect is collected by the detection circuit, the voltage signal is converted into the inductance digital signal by ldc1614 and uploaded to the register of MSP430 of the host computer, then the inductance signal is collected by the computer, and the real-time detection curve is output by the host computer software, at the same time, the experiment data of the inductance signal will generate the L-form in Excel, through the MATLAB software to process the defect signal, lay the foundation for the defect imaging. Figure.15 shown the schematic diagram of the detection process of the FECA sensor.
After the detection coil is sealed, it is sealed with the parallel capacitor and welded on the flexible substrate. The flexible substrate is made of flexible printed circuit board technology. As a result, the FECA sensor probe was successfully prepared, as shown in figure 16.

In this paper, a FECA sensor detection system test bench is built, as shown in figure 17. The experimental platform consists of a desktop three-axis mechanical arm, a detection chip, a computer display, a flexible array probe and a specimen clamp. The table top three-axis mechanical arm is driven by 42 step motor to transmit the moment by the lead screw. It adopts the linear bearing, which has high precision, small resistance and small moving and stable vibration.
4. Experiment

4.1. Coil parameter
Using the flexible vortex array sensor detection system, we tested the detection coils with different outer diameters. The excitation frequency of the coil is adjusted by changing the size of the shunt capacitor. The no-load impedance of the coil with different outer diameter is measured by calculating the Q value and using the impedance meter when the frequency increases. The curve of Q value and impedance is also measured.

Table 2. Self-resonant frequency of different outer diameter coils

| Coil outer diameter (mm) | 3    | 4    | 6    | 8    | 13   | 29   |
|-------------------------|------|------|------|------|------|------|
| Self resonance frequency (MHz) | 27.5 | 22.1 | 14.8 | 11.6 | 9.3  | 0.7  |

Figure 18 shows that before reaching the resonance frequency, the quality factor of the coil increases with the increase of the outer diameter, and the Q value decreases after reaching the resonance frequency. The impedance curve increases with the increase of frequency. At the same frequency, the larger the outer diameter, the higher the coil quality factor and the higher the impedance.

Table 3 below lists the self resonance frequencies of coils with different turns when the outer diameter of coil model is 3mm.
| Coil outer diameter (mm) | 10 | 80 | 160 |
|-------------------------|----|----|-----|
| Self resonance frequency (MHz) | >10 | 3.7 | 0.7 |

Figure 19. Q value and resonance impedance curve of different outer diameter coils

Figure 19 shows that the coil with more turns has higher Q value and impedance before reaching resonance frequency. At the same time, combining with the two images, we can see that before the detection coil reaches the resonance frequency, its quality factor and impedance increase with the increase of the excitation frequency. Under the same excitation frequency, the quality factor and impedance increase with the increase of the coil outer diameter and turns. Through the experiment, the characteristic curve of probe coil parameters with frequency is verified.

4.2. Natural defect detection

In this paper, a typical curved surface high permeability material, turbine last stage blade, is selected, as shown in the figure. In the figure 20, the upper part is turbine blade with natural defects, and the lower part is turbine blade without defects.

![Figure 20. Turbine Blades](image)

The key components of steam turbine are rotor, blade or classifier, casing and casing. In low pressure environment, fatigue, creep and brittle fracture are the main problems of turbine components[6]. When working in creep state, the possibility of brittle fracture of blade at lower temperature is more concerned than creep change. In the turbine blade, especially in the last stage, corrosion fatigue and stress corrosion are serious[7]. Figure 21 shows the micro image of the surface defect of the last stage blade of the steam turbine.
In this paper, the turbine blades are clamped on the three grasp chuck to scan the blade body, as shown in figure 22, and the inductance parameters including the absence of the blade body are collected, as shown in figure 23.
The test results after filtering and probe zero compensation are as shown in the figure 24.

![Figure 24. Experimental data processed](image1)

According to the experimental data of the above eight channels, the two-dimensional image of the curve is obtained in this paper. As shown in figure 25, the defect position information can be obtained from the two-dimensional image of the defect.

![Figure 25. Defect Digital Image](image2)

It can be seen from the figure that the detection results reflect the distribution of blade body defects more closely. In the surface defect detection of curved surface detection object with high permeability, it can better reflect the location, type and shape of defects. This is of great significance to improve the work efficiency of technicians engaged in testing this type of materials.

5. Conclusions

According to the principle of eddy current testing technology, this paper designs a flexible eddy current array sensor, studies the selection of testing coil and the simulation model of ferrite core, and prepares the flexible array probe welded on the flexible substrate. The impedance characteristic and Q value curve of the coil with different outer diameter and turns are studied. The detection experiment is designed, the last stage blade with surface defects is selected as the research object, the scanning detection is carried out, the inductance signal curve including the defect characteristics is obtained, and the digital image is obtained by signal processing. The research content of this paper will provide a reference for the detection probe and detection circuit of the surface defect detection instrument of curved ferromagnetic materials.
Acknowledgements
This work is financially supported by National Key R&D Program of China (2017YFC0805800).

References
[1] Ding S. B, Liu F. J. New NDT technology and application [M]. Beijing: Higher Education Press, 2012: 3-7.
[2] C G Pascaud, B Lorecki, M Pierantoni. Eddy current array probe development for non-destructive testing[C]. 16th World Conference on NDT, Montreal, Canada, 2004: 1-8.1.
[3] Chady T, Kowalczyk J. Multifrequency. Eddy current evaluation of heat exchangers structures[C]. Review of Progress in Quantitative NDE Evaluation: Proceedings of the 35th Annual Review of Progress in Quantitative Nondestructive Evaluation, AIP Publishing, 2009, 1096(1): 363-370.
[4] Yating Y, Pingan D. Research on the correlation between measured material properties and output of eddy current sensor[C]// IEEE International Conference on Industrial Technology. IEEE, 2006.
[5] Yating Y, Pingan D, Zhenwei W. Study on the electromagnetic properties of eddy current sensor[C]// Mechatronics & Automation, IEEE International Conference. IEEE, 2005.
[6] Mazur Z, Garcia-illescas R, Aguirre-romano J, et al. Steam Turbine Blade Failure Analysis[J]. Engineering Failure Analysis, 2008, 15(1):129-141.
[7] Mohamed E M, Nicolas S, Olivier D, et al. Effect of Corrosion on the Low-cycle Fatigue Strength of Steels used in Frequent Start-up Power Generation Steam Turbine[J]. Elsevier Ltd, 2015, 133: 528-534.