IDENTIFICATION AND DETECTION OF DEFECT IN METAL CASING
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Abstract- Based on the propagation rules of electromagnetic waves in metal conductors, this paper analyzes the characteristics of electric field and magnetic field of internal conductors. Then the complex power of electromagnetic wave is calculated. The impedance calculation formula of metal conductor is derived. Moreover, in order to identify and detect defects of metal casing, an alternating current impedance measuring method for the metal casing is proposed by changing the alternating current frequency. Furthermore, a three-dimensional metal casing model is built in COMSOL. Both the electric field and magnetic field are numerically calculated for non-defective and defective casing separately. Meanwhile, the influence of casing defects on the electric field and magnetic field is analyzed. Finally, simulation and measurement results show that: casing defects can be quantitatively detected and effectively located by measuring the alternating impedance of the metal casing.

Index terms: alternating-current impedance; defect detecting; metal casing detecting; skin effect.
I. INTRODUCTION

The basic functions of the casing of a well are to provide wellbore stability, zonal isolation and control of well fluids [1]. Casing integrity is vital to oil and gas production whether a well is a producer or an injector. A routine casing inspection program may not only be used as early warning indicators, but could also help in developing corrosion-preventative measures to increase the life of the well. Casing corrosion is a relentless process with electrochemical, chemical, or mechanical origins that is difficult to slow down [2-3]. It costs the oil and gas industry many billions of dollars each year [4]. Casing corrosion occurs in the form of either internal or external pitting, or general wall loss (thinning). Various methods have been developed to evaluate and monitor casing corrosion. They include: Multi-finger Calipers, Down-hole Video, Ultrasonic, Magnetic Flux Leakage (MFL), Eddy Current (EC) and Direct Current (DC) Impedance methods. Multi-Finger Calipers (MFC) tools take measurements of slight changes in tubular diameter when the fingers come in contact with its surface. These tools to operate in almost all fluids are found in wells including gas, heterogeneous mixtures and muds, and they are limited to defining internal corrosion and pits [5-8]. Down-hole Video systems can provide good qualitative internal information, but only if the well fluids are relatively clear; systems do not work in muds, areas with high percentages of oil or where the water is turbid [9-11]. Ultrasonic tools can accurately measure both the internal diameter and the wall thickness of the tubular but have difficulty locating small pits and holes; and need to be run in a liquid filled environment [12-13]. When metal casing is exposed to a magnetic field, the magnetic flux travels within the metal and when a defect is encountered, the flux capacity of the metal is reduced. In the presence of a defect, the flux is forced to leak into the surrounding medium. MFL tools can be run in both liquid or gas environments and are normally preferred for corrosion applications because of their ability to recognize small isolated pits and hole in the casing, even in the midst of general corrosion. In addition, they have the ability to differentiate between internal and external defects [14-15]. The physical fundamental of the EC tool is Faraday’s law of induction. When supplying current into the transmitting coil (or, call it excitation coil) of the tool, there will be time-varying induced electromotive force in its receiving coil (or pickup coil). If there is thickness variation, faults or flaws in pipe string, the induced EMF shall vary from its expected level in time domain. After data processing, one can diagnose defects such as holes, pitting and cracks in the pipe string and measure the pipe string...
thickness variation [16-17]. The physical fundamental of the DC impedance method is Ohm’s law. When a DC current is injected into the metal casing under test, its impedance can be measured. When there is a defect in the casing, the impedance is bigger than that of nondefective casing[18-19]. This method is easy in explanation and simple in imaging. But DC impedance method cannot locate defects in radial direction. In addition, the DC offset of amplifier may affect the useful DC signal.

This paper introduces a novel defect detection and location method based on AC impedance measurements. The skin effect [20-21] is utilized to detect casing defects. An alternating current is injected into the internal wall of metal casing. The AC equivalent impedance of the casing will change according to the variation of the AC frequency[22-23]. When we change exciting signal frequencies, current distributions on a metal pipe will change[24]. When there is an external defect on the defective casing, the higher the AC frequency, the smaller the difference between the AC equivalent impedance and that of non-defective casing is. When there is an internal defect on the defective casing, the AC equivalent impedance is always smaller than that of non-defective casing at high frequency. Therefore, we can locate defects in radial direction.

II. DEFECT-DETECTION THEORY

A. Electromagnetic field calculation

The oil casing is characterized by good electrical conductivity with high permeability $\mu$ and high conductivity $\sigma$. Electromagnetic wave power suffers from attenuation when waves are transmitting in metal conductors because of continual ohmic loss. Loss tangent $\tan \theta$ of metal conductor meets:

$$\tan \theta = \frac{\sigma}{(\omega \varepsilon')} \gg 1,$$

where $\sigma$ is the conductivity, $\omega$ is the angular frequency of electromagnetic waves, and $\varepsilon'$ is the dielectric constant.

The propagation constant [25] of electromagnetic waves in metal material is:

$$jk = j\omega\sqrt{\mu\varepsilon'} \sqrt{1 - j\frac{\sigma}{\omega\varepsilon'}},$$

where $\mu$ is magnetic permittivity. Combined with (1), (2) can be simplified as:
\[ jk \approx j\omega\sqrt{\mu\varepsilon}\left(j\frac{\sigma}{\omega\varepsilon} = j\sqrt{-j\omega\mu\sigma} = (1+j)\sqrt{\mu\varepsilon}\right) = \alpha + j\beta. \]  

(3)

Then here comes:

\[ \alpha = \beta = \sqrt{\mu\varepsilon}, \]

(4)

which shows that the attenuation coefficient \( \alpha \) is equal to the phase constant \( \beta \).

Consider a metal conductor whose width is \( a \) and length is \( b \). The current flows in the \( +x \) direction, as is shown in Figure 1. We suppose that \( z > 0 \) area is of good conductor, \( z < 0 \) area is of ideal dielectric, and that the transmitted electromagnetic wave along the direction \( +z \) has only electric field component \( E_x \), which is:

\[ E_x(z) = E_{x0}e^{-\alpha z}\cos(\omega t - \beta z), \]

(5)

where \( E_{x0} \) is the electric field amplitude of conductor surface.

![Figure 1. Metal conductor current distribution](image)

For a good conductor, conduction current density \( J_{\sigma}\) is much greater than displacement current density \( J_{ds} \), and \( J_{ds} \) is ignored. There is:

\[ J_x(z) \approx J_{\sigma}(z) = \sigma E_x(z) = \sigma E_{x0}e^{-\alpha z}\cos(\omega t - \beta z) = J_{x0}e^{-\alpha z}\cos(\omega t - \beta z), \]

(6)

where \( J_{x0} \) is current density of conductor surface. (5) and (6) show that: in a good conductor, the field intensity \( E_x \) and the current density \( J_x \) decrease exponentially as they penetrate into the conductor, which is called skin effect. The skin depth \( \delta \) is determined by material conductivity \( \sigma \), permeability \( \mu \), and electromagnetic waves working frequency \( f \). That is

\[ \delta = \frac{1}{\alpha}. \]  

(7)
In (5) and (7), the exponential factor is unity at \( z = 0 \) and decreases to \( e^{-1} \approx 0.368 \) when \( z = \delta \), and decrease to \( e^{-3} \approx 0.05 \) when \( z = 3\delta \). In practical engineering, we can say that electromagnetic waves attenuate to zero when \( z \geq 3\delta \). Using skin depth, we can rewrite (5) as:

\[
E_x(z) = E_{x0} e^{-\frac{z}{\delta}} \cos(\omega t - \frac{z}{\delta}).
\]  

The wave impedance [26] of magnetic field in dielectric, \( \eta \) is:

\[
\eta = \sqrt{\frac{j \omega \mu}{\sigma + j \omega \epsilon'}},
\]

and in good conductor, when \( \sigma >> \omega \epsilon' \), (9) can be written as:

\[
\eta \approx \sqrt{\frac{j \omega \mu}{\sigma}} = \frac{1}{\sigma \delta} = \frac{\sqrt{2}}{\sigma \delta} \angle -\frac{\pi}{4},
\]

therefore, field intensity \( H_y \) is:

\[
H_y(z) = \frac{\sigma \delta E_{x0}}{\sqrt{2}} e^{-i \delta t} \cos(\omega t - z / \delta - \frac{\pi}{4}).
\]

Comparing (8) with (11), we see that the maximum amplitude of magnetic field intensity occurs one-eighth of a cycle later than the maximum amplitude of the electric field intensity at every point.

B. Conductor impedance calculation

The sinusoidal electromagnetic wave can be expressed by phasor form, therefore (6), (8), and (11) can be rewritten as:

\[
J_x = J_{x0} e^{-\frac{z}{\delta}} e^{-j \frac{z}{\delta}},
\]

\[
E_{x} = E_{x0} e^{-\frac{z}{\delta}} e^{-j \frac{z}{\delta}},
\]
The complex poynting vector \( \mathbf{P}_z \) can be calculated by (15),

\[
\mathbf{P}_z = \frac{1}{2}(E_x \times \mathbf{H}_y^\ast),
\]

where \( \mathbf{H}_y^\ast \) is the conjugate phasor of \( \mathbf{H}_y \). We substitute (13) and (14) into (15), which results in:

\[
\mathbf{P}_z = \frac{1}{2} \left[ \frac{\sigma \delta E_{x0}}{\sqrt{2}} e^{-\frac{z}{\delta} e^{-j\frac{\delta}{4}}} \right]
\]

\[
= \frac{1}{2} \left[ \frac{\sigma \delta E_{x0}^2}{\sqrt{2}} e^{-\frac{2z}{\delta} e^{j\frac{\delta}{4}}} \right]
\]

\[
= \frac{1}{4} \sigma \delta E_{x0}^2 e^{-\frac{2z}{\delta}} + j \frac{1}{4} \sigma \delta E_{x0}^2 e^{\frac{2z}{\delta}}.
\]

In (16), the real part of the complex poynting vector is active power density, which describes the conductor resistance; the imaginary part is the reactive power density, which describes the conductor inductance.

As is shown in Figure 1, the complex power inside conductor, \( S^* \), can be obtained by solving the complex power of surface conductor, so there is:

\[
S^* = \int_0^h \int_0^a \mathbf{P}_z |_{z=0} dxdy = \int_0^h \int_0^a \left( \frac{1}{4} \sigma \delta E_{x0}^2 + j \frac{1}{4} \sigma \delta E_{x0}^2 \right) dxdy = \frac{1}{4} \sigma \delta ab E_{x0}^2 + j \frac{1}{4} \sigma \delta ab E_{x0}^2.
\]

We substitute \( J_{x0} = \sigma E_{x0} \) into (17), which results in:

\[
S^* = \frac{1}{4 \sigma} \delta ab J_{x0}^2 + j \frac{1}{4 \sigma} \delta ab J_{x0}^2 = P + jQ = I^2R + jlf^2X_L,
\]

where \( P \) is the average power, \( Q \) is the reactive power, \( I \) is the effective values of equivalent, \( R \) is the equivalent resistance, and \( X_L \) is the equivalent inductive reactance of conductor. Then the equivalent impedance \( Z \) can be written as:
\[ Z = R + jX_L . \]  \hspace{1cm} (19)\

To figure out the relationship between parameters of equivalent impedance and those of materials, \( I \) needs to be calculated. Combined with (12), the phasor \( I_s \) of equivalent current in a conductor of infinite thickness along the direction \( z \), is

\[ I_s = \int_{0}^{\infty} J_x dydz = \int_{0}^{\infty} J_x e^{-(1+j)\frac{z}{\delta}} dydz = \frac{J_{x0}a\delta}{1+j}. \]  \hspace{1cm} (20)\

\( I \) is the RMS value of \( I_s \):

\[ I = \frac{1}{2} J_{x0}a\delta. \]  \hspace{1cm} (21)\

Combined with (18) and (21), there are:

\[ P = I^2R = \left( \frac{1}{2} J_{x0}a\delta \right)^2 R = \frac{1}{4\sigma} \delta ab J_{x0}^2, \]  \hspace{1cm} (22)\
\[ Q = I^2X_L = \left( \frac{1}{2} J_{x0}a\delta \right)^2 X_L = \frac{1}{4\sigma} \delta ab J_{x0}^2. \]  \hspace{1cm} (23)\

Therefore we obtain:

\[ Z = R + jX_L = \frac{b}{\sigma a\delta} + j \frac{b}{\sigma a\delta} = \frac{b}{\sigma a\delta} (1 + j). \]  \hspace{1cm} (24)\

We substitute (7) and (4) into (24), resulting in:

\[ Z = \frac{b}{a} \sqrt{\frac{\pi f \mu}{\sigma}} (1 + j), \]  \hspace{1cm} (25)\

which presents: for a conductor of infinite thickness in the direction \( z \), the alternating current impedance is determined by the geometrical sizes \( (a \ and \ b) \), the electromagnetic parameters \( (\sigma \ and \ \mu) \) of the material, and the frequency of electromagnetic waves. From (25), we can further derive metal conductor resistance \( R \) and inductance \( L \):

\[ R = \frac{b}{a} \sqrt{\frac{\pi f \mu}{\sigma}}, \]  \hspace{1cm} (26)
\[ L = \frac{b}{2a} \sqrt{\frac{\mu}{\pi f \sigma}}. \]  

(27)

It is shown that when geometrical sizes and electromagnetic parameters are determined, conductor resistance \( R \) is proportional to the square root of electromagnetic wave frequency \( \sqrt{f} \), and the material inductance is inversely proportional to \( \sqrt{f} \).

C. Defect-detection principle

In practice, the metal conductor is always of finite thickness in \( +z \) direction. The attenuation of electromagnetic waves in the finite-size conductor is similar to that of waves in infinite-size conductor as in Figure 1. Because of skin effect, when conductor is much thicker than \( 3\delta \), we may use (25) to calculate the impedance. When the conductor thickness is close to skin depth \( \delta \), because of reflection and refraction of electromagnetic waves, the accurate derivation of impedance becomes relatively complex. Then we can replace it with direct current impedance of conductor. In general, some defects of metal conductor include cracks, holes and corrosions, etc. These defects can be equivalently described as the changing of material size, while electromagnetic parameters remain the same. Therefore, when there is a change, the impedance can be computed by (24) or (25).

Suppose that there is a defect in the metal conductor, we change the frequency of the electromagnetic wave, and the skin depth \( \delta \) is changed accordingly. At a frequency, the impedance of defective conductor is \( Z' \), that of non-defective conductor is \( Z \), and impedance variation rate \( \Delta Z \) is:

\[ \Delta Z = \frac{Z' - Z}{Z}. \]  

(28)

When the impedance change rate \( \Delta Z \) is smaller than a threshold, we consider conductor non-defective, otherwise defective. For the metal conductor, we can also find the defect and locate it. For the metal casing, its radius is much greater than its skin depth. The above impedance calculation formula can be approximately used for metal casing, which has high precision.
III. THREE-DIMENSIONAL METAL CASING MODEL

Consider that a non-defective metal casing is constructed of a material for \( \mu_r = 100, \varepsilon_r = 1 \) and \( \sigma = 4 \times 10^6 \text{ S/m} \). The two radii (\( r \) is the outer radius of casing and \( q \) is the inner radius) are 7cm and 9cm, the height \( h \) is 60 cm, as is shown in Figure 2. The height \( m \) of current or grounding circular band is 1cm, the height \( h_3 \) of testing part is 10cm, the height \( h_1 \) is 15cm, and the height \( h_2 \) is 30cm. To simplify the model, no media exists outside the casing, and the whole casing surface is in magnetic and electric insulations. The three-dimensional casing model is built in COMSOL software. The electric field and magnetic field are studied based on the steady state analysis. The current flows inward the internal casing wall through the low circular band, and the current is 1A. The grounding circular band is positioned at upper part of the casing. Mesh results of the casing model are shown as in figure 3.

![Figure 2. Nondefective casing model](image1)

![Figure 3. Mesh results of the casing model](image2)
IV. ELECTRIC FIELD OF NONDEFECTIVE CASING

A. Current line drawing
If there is a current $I_s$ applied to the internal wall of the casing, it will set up current $I_1$ and $I_0$ through the internal wall of the casing, as is shown in Figure 4. A part of current $I_0$ flows, from the injecting circular band along the internal casing wall, into grounding circular band; while the other part of current $I_1$ flows, from the injecting circular band along the internal casing wall, through external casing wall, back into grounding circular band. The current line of the casing is drawn in COMSOL software, as is shown in Figure 5, which shows that current distributions are consistent with the theoretical analysis in Figure 4.

![Figure 4. Current distribution of the casing](image)

![Figure 5. Simulation results of the current distribution of the casing](image)

B. Casing equivalent circuit
The equivalent circuit of the casing model is shown as in Figure 6. The equivalent impedance of internal wall between current circular band and grounding circular band is $Z_0$. The equivalent impedance of internal wall between current circular band and one end of the casing is $Z_1$. Because of symmetry, the equivalent impedance of internal wall between grounding circular band and the other end of the casing is also $Z_1$. The equivalent impedance of the section is $Z_2$, and the equivalent impedance of external wall is $Z_3$. Applying the circuit laws, the following relations hold

$$I_s = I_0 + I_1,$$  \hspace{1cm} (29)
\[ I_0 = \frac{2Z_1 + 2Z_2 + Z_3}{(2Z_1 + 2Z_2 + Z_3) + Z_0} I_S , \]  
(30)

\[ I_1 = \frac{Z_0}{(2Z_1 + 2Z_2 + Z_3) + Z_0} I_S . \]  
(31)

As is shown in Figure 2, when the distance \( h_z \) between the current circular band and the grounding circular band remains the same, and the casing height \( h \) is sufficient, hence the impedance \( Z_0 \ll (2Z_1 + 2Z_2 + Z_3) \) so that :

\[ I_0 \approx I_S . \]  
(32)

When the casing height \( h \) is finite, the current \( I_1 \) cannot be ignored. In production well, casing length is as long as thousands of miles, the condition is met.

![Casing equivalent circuit](image)

Figure 6. Casing equivalent circuit

C. Electric field of nondefective model

Through software simulation calculation, the electric field of the model in the \( xz \) plane is obtained as is shown in Figure 7. It is shown that the electric field in the internal wall between current circular band and grounding circular band is stronger than that of other parts, and the field energy mainly concentrates between them. Because of skin effect, the electric field concentrates around the internal wall zone in the \( xy \) plane as is shown in Figure 8.

![Electric field of non-defective model](image)

Figure 7. Electric field of non-defective model in the \( xz \) plane (\( y=0\)cm)
The electric field along the line is shown in Figure 9. Under the constant condition of the frequency, the electric field between current circular band and grounding circular band is steady. The higher the frequency is, the stronger the electric field is. There are very abrupt changes near the current circular band ($z=14\text{cm-15cm}$) and grounding circular band ($z=45\text{cm-46cm}$). The rest electric field is weaker.

Figure 10 shows the electric field along the line ($z=30\text{cm}$, $y=0\text{cm}$, $x=7-9\text{cm}$), the electric field decreases from external and internal wall to the inside of the casing. Becase the source is located on internal wall, the electric field of the internal wall is stronger that of the external wall. The higher the frequency is, the faster the change is.
V. ELECTRIC FIELD OF DEFECTIVE CASING

A. Uniform corrosion model

Consider that a defective metal casing is constructed of uniform corrosion of the internal wall, the thickness of the corrosion is 0.5cm, and the length $h_3$ of the corrosion is 10cm, as is shown in Figure 11. Figure 12 shows there is an external uniform corrosion in the metal casing, the thickness of the corrosion is 0.5cm, and the length $h_3$ of the corrosion is 10cm. The other parameters remain unchanged. The corrosion models are built in COMSOL software.
B. Electric field of uniform corrosion model

When there is an internal uniform corrosion in the metal casing, the electric field in the \( xz \) plane is shown as Figure 13. Figure 14 presents electric field distribution in the \( xz \) plane when there is an external uniform corrosion in the metal casing. Figure 15 and 16 show the electric field along line when there are uniform corrosion respectively. The electric fields of the corrosion range become weaker than that of non-corrosion range under all frequencies except for 1Hz frequency as is shown in Figure 15. Figure 16 shows the electric fields of the corrosion range have some changes under all frequencies. The significant change occur in lower frequencies especially in 1Hz. Hardly any change occurs at all in higher frequency especially in 100Hz.

![Figure 12. External uniform corrosion model](image)

![Figure 13. Electric field of the internal uniform corrosion model in the xz plane (y=0cm)](image)
Figure 14. Electric field of the external uniform corrosion model in the \(xz\) plane \((y=0\text{cm})\)

Figure 15. Electric field of the internal uniform corrosion model along the line \((x=7\text{cm}, y=0\text{cm}, z=20\text{cm}-40\text{cm})\)

Figure 16. Electric field of the external uniform corrosion model along the line \((x=7\text{cm}, y=0\text{cm}, z=20\text{cm}-40\text{cm})\)
C. Potential of Uniform corrosion model

Figure 17 and 18 present the potential along the line when there are uniform corrosions in metal casing respectively. Under the internal uniform corrosion range, the lower the frequency is, the bigger the slope change of the potential is as is shown in Figure 17. Figure 18 shows: the lower the frequency is, the bigger the slope change of the potential is. There is no change in higher frequencies, such as in 100Hz.

Figure 17. Potential of the internal uniform corrosion model
along the line (x=7cm, y=0cm, z=20cm-40cm)

Figure 18. Potential of the external uniform corrosion model
along the line (x=7cm, y=0cm, z=20cm-40cm)
VI. EXPERIMENT RESULTS

A. Relationship of skin depth and frequency

According to (7), the skin depth $\delta$ is a function of frequency $f$, permeability $\mu$, and conductor conductivity $\sigma$. The metal casing parameters described in III are chosen, and the skin depths under different frequencies are shown as in table 1.

<table>
<thead>
<tr>
<th>$f$ (Hz)</th>
<th>$\delta$ (mm)</th>
<th>$3\delta$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.15</td>
<td>75.45</td>
</tr>
<tr>
<td>10</td>
<td>7.95</td>
<td>23.86</td>
</tr>
<tr>
<td>20</td>
<td>5.62</td>
<td>16.87</td>
</tr>
<tr>
<td>30</td>
<td>4.59</td>
<td>13.78</td>
</tr>
<tr>
<td>40</td>
<td>3.98</td>
<td>11.93</td>
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<tr>
<td>50</td>
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<td>9.74</td>
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<td>70</td>
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<td>8.44</td>
</tr>
<tr>
<td>90</td>
<td>2.65</td>
<td>7.95</td>
</tr>
<tr>
<td>100</td>
<td>2.52</td>
<td>7.55</td>
</tr>
</tbody>
</table>

B. Simulation results of uniform corrosion model

The casing length is as long as thousands of miles in production well. However, due to the limitations of computer memory and calculation time, the COMSOL software can not simulate too big model. Therefore, we can only build the casing model of finite size. The uniform corrosion models(Figure 11 and Figure 12) are built in COMSOL software. The calculating impedance values of defective and nondefective casing are shown as in Table 2 and Table 3 respectively. In calculating casing model, the measurement range of the nondefective casing is $z = 20 - 25$ cm, the measurement range of the defective casing is $z = 27.5 - 32.5$ cm. The defects are detected and located through measuring the impedance of the casing.
In the condition of all frequencies, impedance differences exist between the internal wall corrosion part and the non-corrosion part, as is shown in Table 2. When the frequency is 1Hz and the skin depth is 25.15mm (see Table 1). The skin depth is greater than the thickness of the casing itself (the thickness is 20mm). Therefore, the even current distribution of the cross section of the casing is obtained when the frequency is 1Hz, the DC impedance is measured. The cross-sectional area of the corrosion part is reduced and the DC impedance increases. The operation frequency is increased, the useful cross-sectional area is increased, the AC impedance of the corrosion part is lower than that of the non-corrosion part. In Table 2, the impedance change rate reaches 36.7% when the frequency is 1Hz. The impedance change rate has range about -5.2% - -4.0% when the frequency is in the 10Hz-100Hz. Therefore, we can easily detect the internal wall defects according to the AC impedance.

Table 2. Simulation results of the internal uniform corrosion model

| $f$ (Hz) | $|Z|$(μΩ) | $|Z'|$(μΩ) | $\Delta Z$ |
|---------|-----------|-----------|----------|
| 1       | 1.20      | 1.64      | 36.7%    |
| 10      | 3.25      | 3.12      | -4.0%    |
| 20      | 4.77      | 4.54      | -4.8%    |
| 40      | 6.99      | 6.63      | -5.2%    |
| 60      | 8.65      | 8.25      | -4.6%    |
| 80      | 10.03     | 9.56      | -4.7%    |
| 100     | 11.24     | 10.70     | -4.8%    |

The smaller the impedance difference between the corrosion part and the non-corrosion part is, the higher the frequency is, as is shown in Table 3. When the frequency is 1Hz, the corrosion part impedance increases, the reason is the same as that in Table 2 above. As frequency increases, skin depth $\delta$ becomes smaller and the influence of the external wall corrosion on impedance gets weaker. The impedance change rate will be less than two-thousandths (2/1000) when the frequency is 60Hz, 80Hz or 100Hz, the impedance differences can be considered zero. Ultimately, we reach the conclusion that there is no defect within three times skin depths range (the range is 9.74mm when the frequency is 60Hz) calculated from the internal wall of the casing. The conclusion is consistent with that of the external wall corrosion (the external corrosion thicker is 5mm). The positioning
precision is improved by choosing parameters appropriately, the parameters include the frequency and the threshold of the impedance rate.

Table 3. Simulation results of the external uniform corrosion model

| \( f \) (Hz) | \( |Z| \) (μΩ) | \( |Z'| \) (μΩ) | ΔZ |
|------------|--------------|--------------|-----|
| 1          | 1.37         | 1.74         | 27.0% |
| 10         | 3.42         | 3.34         | -2.3%|
| 20         | 4.96         | 4.87         | -1.8%|
| 40         | 7.21         | 7.12         | -1.2%|
| 60         | 8.88         | 8.87         | -0.1%|
| 80         | 10.27        | 10.29        | 0.2% |
| 100        | 11.49        | 11.51        | 0.2% |

C. Experimental results

A steel casing acquired from an oil company is tested. The outer radius of the casing is 88.90mm, the inner radius of the casing is 80.85mm, and the length of the casing is 9m. The measurement system is made up of five parts. The five parts are casing, high power programmable signal source, electrode push-backing system, low noise amplifier and high accuracy data acquisition system of NI Company as shown in Figure 19. An external uniform corrosion is constructed. The corrosion thickness is 4mm and the length is 0.8m. The current electrodes, ground electrodes and measurement electrodes are contacted reliably through the electrode push-backing system. The distance between the current electrodes A and the ground electrodes B is 2m. The fixed distance between measuring electrodes C and D is 0.5m. The voltage signal of direct measurement passes through the low noise amplifier which performs such functions as amplification, attenuation, filtering, and signal conditioning. The data acquisition system shown in Figure 19 is a real-time system. With Digital Phase-Sensitive Detection (DPSD) technique, the amplitude and the phase of the useful signal are obtained. First, at the non-corrosion part, electrodes-measuring is applied to detect voltages under different frequency conditions; second, electrodes-measuring is moved to the corrosion part to test its voltage. Then, the data is processed and the impedance is obtained, and the results are shown in Table 4. The smaller the impedance difference between the corrosion part and the non-corrosion part is, the higher the frequency is, as is shown in Table 4. The changes follow the same trend as is shown in Table 3. It can be identified that there is the external corrosion in
testing part. If conductivity $\sigma$ and permeability $\mu$ of the casing can be obtained, a quantitative calculation of defect range at the direction of thickness can be conducted so as to realize the quantitative testing and location of defects.

![Defect detecting system diagram of casing](image)

**Figure 19 Defect detecting system diagram of casing**

**Table 4. Test results of the external uniform corrosion casing**

| $f$ (Hz) | $|Z|$ ($\mu\Omega$) | $|Z'|$ ($\mu\Omega$) | $\Delta Z$ |
|----------|------------------|------------------|---------|
| 1        | 23.79            | 30.92            | 30.0%   |
| 10       | 59.47            | 57.81            | -2.8%   |
| 20       | 86.58            | 85.02            | -1.8%   |
| 40       | 125.94           | 124.43           | -1.2%   |
| 60       | 154.25           | 153.01           | -0.8%   |
| 80       | 178.11           | 176.86           | -0.7%   |
| 100      | 199.13           | 198.13           | -0.5%   |

**VII. CONCLUSIONS**

The AC impedance of metal casing is determined by the geometrical sizes and the electromagnetic parameters of metal casing, and the frequency of electromagnetic waves. When a defect exists the changes in the sizes of the metal casing will occur. When the frequency is changed, the skin depth is changed accordingly. For a specific metal casing, by comparing the impedances of the non-defective casing and testing casing under different frequencies, whether the testing casing part is defective or not can be judged. If conductivity $\sigma$ and permeability $\mu$ of the casing can be obtained, according to the relation between the skin depth and the frequency, the defects in the thickness direction of the casing can be detected and located.
VIII. REFERENCES


