

## Study on Defect Detecting and Locating Method of Tubular Cylindrical Conductor

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### Abstract

*This paper is to present a defect detecting and locating method of tubular cylindrical conductor based on alternating current impedance measurement theory. A defect estimation can be made through the impedance measurement of some distance on the inner and the outer surfaces of the tubular cylindrical conductor. A defect in the thickness direction can be located by the skin effect influence on impedance and the frequency change in exciting current. The results show that: this method can effectively identify and locate a defect, and therefore should be promoted in the defect detecting of metal materials in other shapes.*

**Keywords:** impedance measurement, defect detecting, defect locating, skin effect

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### 1. Introduction

The metal cylindrical tube is widely used in industry. In manufacturing process, due to negative factors such as poor condition control, it may have the hole defect, if the quantitative detection is not made to the tube, which may bring about serious consequences [1-2]. After a metal tube is used for a period of time, a defect detection of erosion and cracks etc. need to be made to dynamically evaluate the tube application with convenience. Currently, the nondestructive electrical detecting methods of metal material, such as the magnetic flux leakage method [3], the eddy current method [4-5] and the DC impedance method [6-7] are commonly used. The magnetic flux leakage method uses high magnetic field to magnetize a tube. When a metal material has any defect, the magnetic-field distribution will change. Then the defect can be detected by using Hall effects to measure magnetic flux density and its change in the material. The eddy current testing method is based on the electromagnetic induction principle, using the electromagnetic field coming from alternating current by transmitting coil to produce eddy current inside a material. When a material has any defect, the current distribution will change. Then a defect of the material can be detected by measuring the secondary induction electromotive and phase shift in the far end of receiving coil. The magnetic flux leakage method can detect a defect location in the thickness direction by using sensor array. The eddy current method uses the received response signal of array which launches a variety of frequency signals to locate a defect in thickness direction. They both, however, are relatively complicated in instruments design and results explanation. The DC impedance method estimates the average defect in a measured section after injecting a DC current, computing its impedance quantitatively by the ohm theorem. Testing results are easy to explain and image forming is simple. But this method cannot decide a location in the thickness direction, and signals from the actual instrument DC drift and testing are all DC signals with similar order of magnitude, which will influence the subsequent signal detection. This paper is to present a defect detecting and locating method based on AC impedance measurement theory. By using the skin effect, an alternating current is injected into the inner and the outer surfaces. When changing the exciting signal frequency, the current distributions on a metal section will change. Then through detecting the voltage on the inner and the outer surfaces at the same axial position of the tube, the inside and the outside AC impedance in a detected section can be estimated so as to locate a defect in the thickness direction. The actual instrument detection signal is AC signal which can be conveniently distinguished from DC drift signal.

## 2. AC Impedance Calculating Formula

### 2.1. Skin Effect

When a current transmits in a metal conductor, with an increase in frequency, the current density (or the electric field intensity) tends to flow towards the conductor surface, and then the skin effect appears [8]. Meanwhile, the current density begins to decay in the exponent function, as its penetration depth increases. The common variable  $\delta$  (called the skin depth) stands for the decay speed whose calculating formula [9] is presented here:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \quad (\text{m}) \quad (1)$$

Where  $\mu = \mu_0 \mu_r$ .

Where  $f$  is the current frequency in Hz,  $\mu$  is the conductor permeability in H/m,  $\mu_r$  is the conductor relative permeability,  $\mu_0$  ( $\mu_0 = 4\pi \times 10^{-7}$  H/m) is the conductor permeability of free space,  $\sigma$  is the conductor conductivity in S/m. As shown in Figure 1,  $x$  is supposed as a current direction in a good conductor,  $z$  is the penetration direction. As  $z$  increases,  $J_x(z)$  will decay in its  $e^{-z/\delta}$  time, (here  $J_x(0)$  is the conductor surface current density when  $z = 0$ ). In theory, when  $z$  tends to infinite,  $J_x(z)$  will go to zero. In an actual project, when  $z$  is  $3\delta \sim 5\delta$ , the current density  $J_x(z)$  will be  $4.98\%J_x(0) \sim 0.674\%J_x(0)$ , which can be considered approximating zero.  $\delta$  can influence the decay speed of current density. The smaller  $\delta$  is, the faster the decay will be. The bigger  $\delta$  is, the slower the decay will be. Therefore, based on formula (1), through changing the frequency and controlling the current density decay speed, the current density can exert in a certain thickness range (the thickness rang is  $3\delta$  in this paper). At this time, the equivalent impedance is within  $3\delta$  thickness range. When the equivalent impedance of  $3\delta$  thickness range needs to be detected, the current frequency can be computed by formula (1).

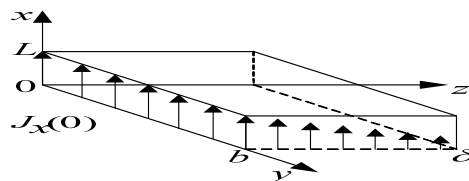


Figure 1. The Current Density Distribution in Conductor

### 2.2. AC Impedance Theoretical Formula

A defect-free metal tubular cylindrical conductor is chosen, shown as in Figure 2, where  $r$  and  $q$  are the outside and the inside radii respectively. There are two methods of a current injecting into a metal tube, one being from its outer surface, the other being from its inner surface. When a current flowing through a cylinder is DC, no matter it is injected into the inner surface or the outer surface, the current density on a conductor section is uniform distribution, and the DC impedance is:

$$R_{dc}(\sigma, r, q) = \frac{1}{\pi\sigma(r^2 - q^2)} \quad (\Omega/\text{m}) \quad (2)$$

Where  $r$  and  $q$  are the outside and the inside radii respectively. When an AC current is injected into the outer surface, its outer AC impedance [10] is:

$$Z_{ac-out}(\sigma, \mu, \omega, r, q) = \frac{j\omega\mu}{2\pi r\sigma} \times \frac{[\text{ber}(mr) + j\text{bei}(mr)] - \lambda[\text{ker}(mr) + j\text{kei}(mr)]}{[\text{ber}'(mr) + j\text{bei}'(mr)] - \lambda[\text{ker}'(mr) + j\text{kei}'(mr)]} \quad \Omega/\text{m} \quad (3)$$

Where  $\lambda = \frac{ber'(mq) + jbei'(mq)}{ker'(mq) + jkei'(mq)}$ ,  $m = \sqrt{\omega\mu\sigma} = \frac{\sqrt{2}}{\delta}$ .

Where  $ber$ ,  $ber'$ ,  $bei$ ,  $bei'$  are Bessel functions,  $ker$ ,  $ker'$ ,  $kei$ ,  $kei'$  are Kelvin functions[11]. When an AC current is injected into the inner surface, its inner AC impedance [10] is:

$$Z_{ac-in}(\sigma, \mu, \omega, r, q) = \frac{jm}{2\pi q\sigma} \times \frac{[ber(mq) + jbei(mq)] - \eta[ker(mq) + jkei(mq)]}{-[ber'(mq) + jbei'(mq)] + \eta[ker'(mq) + jkei'(mq)]} \quad (\Omega/m) \quad (4)$$

Where  $\eta = \frac{ber'(mr) + jbei'(mr)}{ker'(mr) + jkei'(mr)}$ .

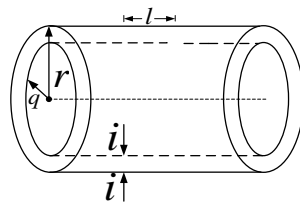


Figure 2. The Defect-free Tubular Cylindrical Conductor

For the convenience of testing the effectiveness of theoretical calculating methods, the supposed defects below are of uniform corrosion. Single surface uniform corrosions include the inner surface corrosion whose inside radius  $q$  is changed larger into  $q'$  as shown by Figure 3, the outer surface corrosion, whose outside radius  $r$  is changed smaller into  $r'$  as shown by Figure 4.

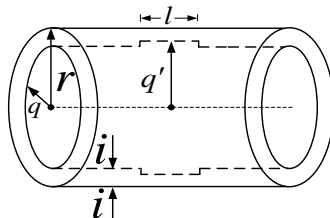


Figure 3. The Tubular Cylindrical Conductor with Inner Surface Uniform Corrosion

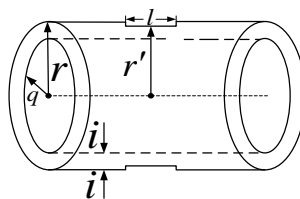


Figure 4. The Tubular Cylindrical Conductor with Outer Surface Uniform Corrosion

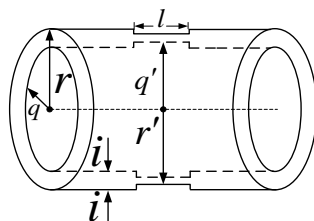


Figure 5. The Tubular Cylindrical Conductor with Inner and Outer Surface Uniform Corrosion

Inner and outer surface uniform corrosions are shown by Figure 5, in which the inside radius  $q$  is changed larger into  $q'$  and the outside radius  $r$  is changed smaller into  $r'$ . Because parameters of inside and outside radii are all included in formula (2), (3) and (4), and defects such as corrosion and cracks of a cylinder can all be considered changes in inside and outside radii (the equivalent section), the impedance of a measured section will change accordingly.

### 3. Defect Detecting and Locating

There are four steps to take when making a defect detection and location. First, obtain the correlation between a skin depth and a signal frequency according to parameters of a material, and achieve resolutions of defecting and locating after deciding the material thickness. Second, choose the low frequency, where the skin depth is larger than tubular cylinder thickness. An AC current is injected into the inner (or the outer) surface of the tubular cylinder. Then the current density will distribute over the whole section shown by the shadow in Figure 6. Detecting the whole impedance of the target range, if the difference between the detected impedance module and the theoretical value are smaller than the allowed value, the tubular cylinder will be regarded as defect-free. Otherwise, the defect detection needs to be made.

And then, according to what has been presented in 2.1, the current density of AC signal distributing among the  $3\delta$  depth range (as shown by shadows in Figure 7), decide the current frequency (the high frequency) and inject the high frequency current  $i_1$  into the inner and the outer surfaces separately, measure the voltage of the target section in both the inner and the outer surfaces separately, and then detect its impedance, if the difference between the detected impedance module value and the theoretical value is larger than the allowed value. Here, it can be confirmed that the defect is at a range of  $3\delta$  from the surface. Otherwise, a further defect detection needs to be made.

At last, decrease the current frequency gradually, increase the skin depth, i.e., increase the current density action range, inject the definite frequency current into the inner and the outer surfaces separately to detect the defect until it is located.

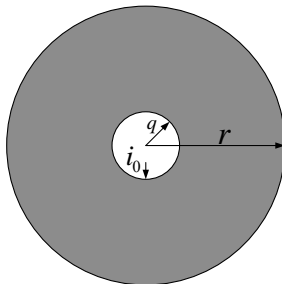


Figure 6. The Ultra Low Frequency Current Density Distribution

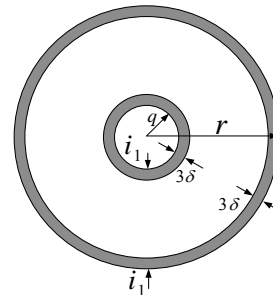


Figure 7. The High Frequency Current Density Distribution

## 4. Simulation Experiment Results and Analysis

### 4.1. Tubular Cylindrical Conductor Impedance Calculating

Suppose in Figure 2 that the conductivity  $\sigma$  is  $4 \times 10^6$  S/m, its relative magnetic conductivity  $\mu_r$  is 180, the length  $l$  is 1000 mm, its outside radius  $r$  is 88.9mm, its inside radius  $q$  is 80.85mm, and its thickness  $t$  ( $t = r - q$ ) is 8.05 mm, then DC impedance ( $R_{dc} = 58.2351 \mu\Omega$ ) can be calculated according to formula (2), and its inner and outer AC impedance can be calculated according to formula (3) and (4) respectively. Figure 8 presents the correlation between the impedance module and the frequency. Figure 8 shows that with an increase in signal frequency, both the inner and the outer impedance module will increase. As the frequency decreases, the impedance tends to be the DC impedance  $R_{dc}$ . When the frequency is the same, its inner impedance will be larger than its outer one.

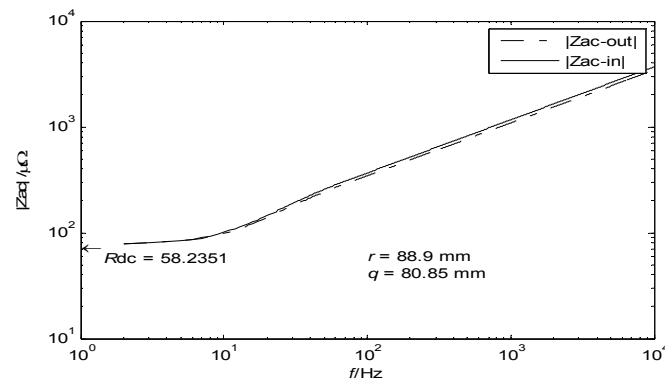
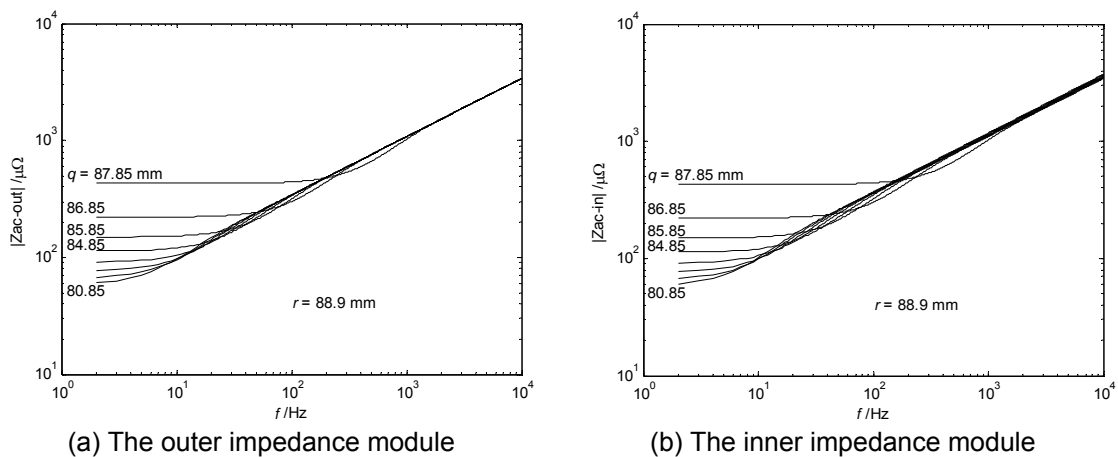


Figure 8. The correlation between impedance module and frequency

When the outside radius  $r$  remains the same, as shown in Figure 3, the inside radius  $q$  becomes larger, the impedance will change as is shown by Figure 9. Figure 9(a) presents the changing situation in which the outer impedance module changes with the frequency. In high frequency band, the outer impedance curves almost coincide (at high frequency, the outer impedance is unaffected by change in inside radius  $q$ ). In low frequency band, the outer impedance curves are discrete (when the frequency is low, change in inside radius  $q$  will have great effects on outer impedance). In low frequency band, with the same frequency, the larger the inside radius is, the bigger the outer impedance will be. Figure 9(b) is the changing situation in which the inner impedance module changes with the frequency. The overall changing tendency in curves is the same as that in Figure 9(a). The difference lies in that high frequency curves are separated (when the frequency is high, change in inside radius  $q$  will have an influence on the inner impedance).



(a) The outer impedance module

(b) The inner impedance module

Figure 9. The Impedance Module in a Different Inside Radius

When the inside radius does not change, and the outside radius becomes smaller, as is shown in Figure 4, the impedance will change as is shown by Figure 10. Figure 10(a) is the changing situation in which the outer impedance module changes with the frequency. Figure 10(b) is the changing situation in which the inner impedance module changes with the frequency. In high frequency band, the curves of Figure 10(a) are separated (when the frequency is high, change in the outside radius will have great influences on outer impedance). In high frequency band, the inner impedance curves of Figure 10(b) almost coincide with each other (at high frequency, the inner impedance is unaffected by the outside radius).

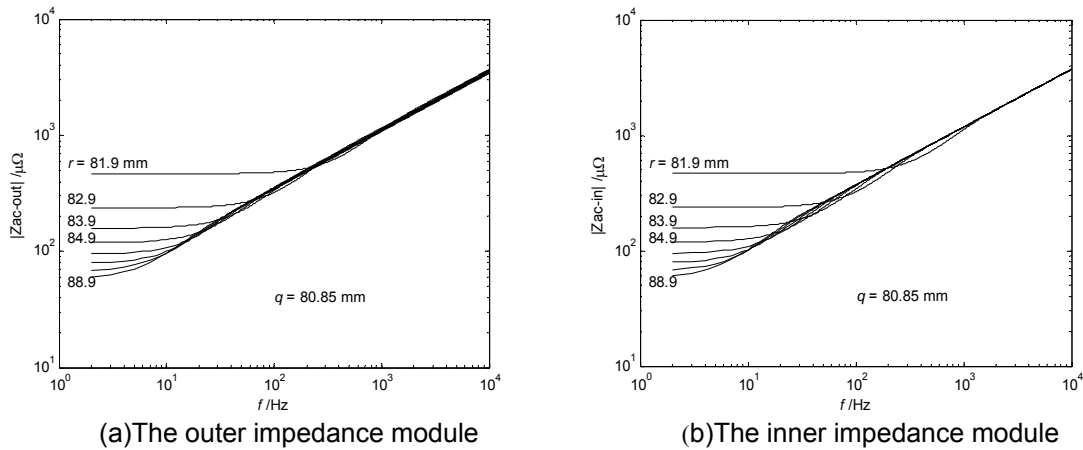


Figure 10. The Impedance Module in a Different Outside Radius

**4.2. Defect-free Tubular Cylindrical Conductor Detecting**

In a simulation experiment, a defect-free tubular cylindrical conductor is chosen, shown as in Figure 2, parameters are the same as those in 4.1 ( $\delta = 4 \times 10^6$  S/m,  $\mu_r = 180$ ,  $r = 88.9$  mm,  $q = 80.85$  mm). The impedance of a target length ( $l = 500$  mm) will be detected, which can be used as theoretical experimental data of a defect-free tubular cylindrical conductor. Simulation data are shown as in the Table 1. The frequencies are 2Hz, 100 Hz, 1000Hz and 10000Hz, then calculate the current action depth  $3\delta$ , choose different current injecting methods to detect the impedance in depth range, and the specific impedance value is shown in Table1.

Table 1. The impedance of defect-free tubular cylindrical conductor

f(Hz)	$3\delta$ (mm)	Zac-in ( $\mu\Omega$ )	Zac-out ( $\mu\Omega$ )	conclusion
2	39.7887	30.4164	-	no defect
$10^2$	5.6271	$1.8441 \times 10^2$	-	no defect
$10^2$	5.6271	-	$1.6958 \times 10^2$	no defect
$10^3$	1.7793	$5.8562 \times 10^2$	-	no defect
$10^3$	1.7793	-	$5.3446 \times 10^2$	no defect
$10^4$	0.5628	$1.8542 \times 10^3$	-	no defect
$10^4$	0.5628	-	$1.6882 \times 10^3$	no defect

**4.3. Single Surface Uniform Corrosion Detecting**

For the convenience of testing the effectiveness of theoretical calculating methods, the supposed defects below are of uniform corrosion. Single surface uniform corrosions include the inner surface corrosion and the outer surface corrosion, shown as in Figure 3 and in Figure 4 respectively. The following will take outer surface uniform corrosion for instance to illustrate the defect detecting and locating method. It is shown as in Figure 4, the target segment length  $l$  is 500mm, the outer uniform corrosion is 1mm, so the outside radius  $r'$  is changed into 87.9mm, and other parameters remain the same. The following steps are to make the defect detection and location. Simulation data are shown in Table 2.

First, when choosing the frequency 2Hz, measure the target segment impedance of tubular cylindrical conductor, inject a current from the inner surface, and then the detected impedance of the inner surface is  $34.3233\mu\Omega$ , which is the impedance of the whole tubular cylinder impedance. This value is different from that in Table 1: the impedance being  $30.4164\mu\Omega$ , the frequency being 2Hz, being defect-free. Therefore, it can be decided that there is a defect in the target segment. Second, when choosing a frequency  $10^4$  Hz, measure the target segment, inject a current from the inner surface, whose impedance is  $1.8542 \times 10^3\mu\Omega$ , which is the impedance when detection depth  $3\delta$  is 0.5628mm. This value is the same as the impedance value when  $f$  is  $10^4$  Hz and the cylinder is defect-free. Here, it can be ensured that

the target segment is defect-free (normal) at a range of 0.5628mm from the inner surface. When the current is injected from the outer surface, the impedance value is  $1.7074 \times 10^3 \mu\Omega$ , which is the impedance when detection depth is 0.5628mm, and which is different from the outer surface impedance value when the tubular cylinder is defect-free and the frequency is  $10^4 \text{Hz}$ , therefore it can be concluded that the target segment has defect in the depth range of 0.5628mm off the outer surface. After deciding that there's defect in the outer surface, the current can only be injected from the inner surface when taking the subsequent steps.

And then, when choosing a frequency  $10^3 \text{Hz}$ , measure the impedance of a target segment, inject a current from the inner surface, whose impedance is  $5.8562 \times 10^2 \mu\Omega$ , which is the impedance when detection depth is 1.7793mm, which is the same as the impedance value in Table 1, when choosing the frequency  $10^3 \text{Hz}$ , therefore it can be decided that the target segment is defect-free (normal) in the 1.7793mm depth range off the inner surface, and then decrease the frequency and make further detection.

At last, when choosing a frequency  $10^2 \text{Hz}$ , measure the impedance of a target segment, inject a current from the inner surface, whose impedance is  $1.8452 \times 10^2 \mu\Omega$ , which is the impedance when detection depth is 5.6271mm, which is slightly different from the impedance in Table 1 when the frequency is  $10^2 \text{Hz}$ , and this frequency is the critical point. Hence, it can be decided that the target segment is defect-free (normal) in the 5.6271mm depth range off the inner surface.

From the above steps, the following conclusions can be drawn: there is a defect in the measured target segment, the 5.6271mm depth range off the inner surface is defect-free, and the defect should be located beyond 5.6271mm depth range off the inner surface. This conclusion is the same as that when the supposed outer surface uniform corrosion is 1mm. A suitable frequency can be certainly chosen to obtain smaller depth resolution and to locate a defect more accurately. The above steps can be referred to when detecting and locating a defect with other single uniform corrosions.

Table 2. The impedance of tubular cylindrical conductor

f(Hz)	$3\delta(\text{mm})$	Zac-in ( $\mu\Omega$ )	Zac-out ( $\mu\Omega$ )	conclusion
2	39.7887	34.3233	-	defect
$10^4$	0.5628	$1.8542 \times 10^3$	-	no defect
$10^4$	0.5628	-	$1.7074 \times 10^3$	defect
$10^3$	1.7793	$5.8562 \times 10^2$	-	no defect
$10^2$	5.6271	$1.8452 \times 10^2$	-	criticality

#### 4.4. Inner and Outer Surface Uniform Corrosion Detecting

As is shown in Figure 5, the target segment is 500mm with 1mm inner and outer surface uniform corrosion, the inside radius  $q'$  becomes 81.85mm, the outside radius  $r'$  is 87.9mm, other parameters being the same. The following steps are to detect and locate its defect. Simulation data are shown in Table 3.

First, when the frequency  $f$  is 2Hz, measure the impedance of a target segment, inject a current from the inner surface whose impedance is  $39.2933 \mu\Omega$  which is the impedance of the whole tubular cylinder. This value is different from the value in Table 1 when the frequency is 2Hz, the measured impedance is  $30.4164 \mu\Omega$ . Therefore, it can be decided that there's defect in the target segment.

Second, when the frequency  $f$  is  $10^4 \text{Hz}$ , measure the impedance of a target segment, inject a current from the inner surface, whose impedance is  $1.8316 \times 10^3 \mu\Omega$  (the impedance becoming smaller), which is the impedance when detection depth is 0.5628mm, which is different from the value in Table 1: when the frequency is  $10^4 \text{Hz}$ , it is defect-free. Therefore, it can be decided that there is a defect in 0.5628mm depth range off the inner surface. When injecting the current from the outer surface, its impedance is  $1.7074 \times 10^3 \mu\Omega$  (the impedance becoming larger), which is the impedance when detection depth is 0.5628mm which is different from the impedance value in Table 1, when  $f$  is  $10^4 \text{Hz}$ . Hence, it can be decided that there is a defect in the 0.5628mm depth range off the outer surface of a target segment.

From the above steps, the following conclusion can be drawn: there is a defect in a target segment in the 0.5628mm depth range off the inner surface and in the 0.5628mm depth

off the outer surface. This is the same as the result when the supposed inner and outer uniform corrosion is 1mm.

Table 3. The impedance of tubular cylindrical conductor

f(Hz)	$3\delta$ (mm)	Zac-in ( $\mu\Omega$ )	Zac-out ( $\mu\Omega$ )	conclusion
2	39.7887	39.2933	-	defect
$10^4$	0.5628	$1.8316 \times 10^3$	-	defect
$10^4$	0.5628	-	$1.7074 \times 10^3$	defect

#### 4. Conclusion

This study put forward a defect detecting and locating method of a tubular cylindrical conductor based on the metal alternating current impedance measurement theory. It can be decided whether there's a defect in a target segment through choosing an ultra-low frequency, detecting AC impedance in certain distance, comparing measuring AC impedance with theoretical values. And it can be decided whether there's a defect in a target segment  $3\delta$  by certain depth ( $3\delta$ ) resolution, ensuring a high frequency, injecting a current from both the inner and the outer surfaces, comparing measured AC impedance with theoretical values. Simulation experiment results show that: by applying AC impedance detecting theory, a defect in tubular cylindrical conductor can effectively identified and located, and this method can be promoted to defect detecting of a metal material in other shapes. In an actual project, material defects are of non uniform, so it is relatively difficult to make theoretical calculations. Then finite element model analysis can be used to make further study on defect detection and location, on detection and explanation methods of impedance within smaller distance.

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