A Complex Parameter Measurement Method of Metal Pipeline Using Tilt Angle Intersection

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Abstract. This paper proposes an eddy current nondestructive measurement method for metal pipeline parameters, which can measure the pipeline thickness and conductivity simultaneously. In this paper, the tilt angle intersection of the relative impedance changes of the coil, which is little affected by the tilt angle, is used. Based on the analytic solution of eddy current field model of the pipeline excited by the coil placed arbitrarily outside the pipeline, the law of the tilt angle intersection with the change of the pipeline parameters is obtained and an inverse method is established which utilizes the relationship between the frequencies of two tilt angle intersection points and the pipeline parameters. It has been found that the method has high measurement accuracy and can avoid the error caused by the deflection of the coil in a small range.

Keywords: Tilt Angle Intersection; Eddy Current Testing; Pipeline Parameters; Inversion Model

1. INTRODUCTION

The industrial pipeline undertakes the transportation and connection function in chemical, energy and other applications. Nondestructive testing of pipelines in service is one guarantee of the safe operation in industry. The ultrasonic detection has higher measurement accuracy, but it requires coupling agent and contacts with the specimen [1]. Eddy current testing (ECT) is based on electromagnetic induction. Compared with others, ECT is commonly used for nondestructive testing of pipeline parameters due to its characteristics of non-contact, high sensitivity and high efficiency [2,3].

The analytical solution of the eddy current field corresponding to different pipeline models provides the theoretical basis for the measurement of specimen [4,5]. In conventional eddy current testing, the information of the specimen is obtained by analyzing the impedance signal of the probe. Mao et al. realized the inversion of multiple pipeline parameters and lift-off simultaneously using Levenberg-Marquardt algorithm based on the analytical expression of the relative impedance change of the vertical coil outside the pipeline [6]. Chen et al. proposed a non-contact pulsed eddy current testing method for measuring the relative thickness change of ferromagnetic pipelines, considering the coupling relationship of the electromagnetic parameters [7]. Sun et al. measured the pipeline thickness using remote field eddy current (RFEC) model and Quasi-Newton's method (QNM), which can effectively overcome the lift-off effect [8]. It has shown that the pulse signal is more suitable than the sinusoidal signal for measuring the thickness of large-diameter pipelines [9].

At present, extracting characteristic quantities from eddy current testing signals to measure parameters has attracted much interest, such as peak frequency of inductance changes [10], peak voltage and time-to-peak [11], lift-off point of intersection [12], zero-crossing time of induced voltage [13]. Yu et al. proposed an approach for detection the defect depth or width of the plate specimen to reduce lift-off noise by taking the slope of the curve of the differential peak voltage and the lift-off as the feature [14]. A frequency-band-selecting pulse eddy current testing (FSPECT) using the zero-crossing time has been proposed for the detection of local wall thinning defects when the range of the thickness defect is known [15]. For large-diameter ferromagnetic pipelines, the thinning of inner or outer wall of pipelines is evaluated by the linear relationship between the coil voltage attenuation rate and the pipeline thickness [16].

Coils are not restricted by installation and are ideal for in-service inspection of pipelines [17]. However, in practice, the deflection of the coil will seriously affect the result of pipeline testing and reduce the detection accuracy. The analytic solution of eddy current field model of the pipeline excited by the coil placed arbitrarily outside the pipeline has been obtained [18]. When the other parameters are fixed, the frequency sweep curve of the relative impedance change of the probe coil corresponding to different tilt angles θ_s are shown in **Fig. 1**. The three curves intersect in a small region, defined as tilt angle intersection domain [19]. The relative impedance change of the coil in the domain is little affected by the tilt angle, which avoids the deflection noise of the coil. Consequently, the tilt angle intersection point, that is, the intersection point within the tilt angle intersection domain, can be used as the characteristic signal for ECT to reduce the adverse effect of coil deflection.

In this paper, the tilt angle intersection (imaginary part) is studied based on the analytical solution of the eddy current field. And the law of the tilt angle intersection on the pipeline thickness and conductivity is analyzed. In order to measure the pipeline thickness and conductivity simultaneously, an inversion method is proposed using two equal-frequency curves of the tilt angle intersection with the pipeline thickness and conductivity. Simulation verifies that the method has high measurement accuracy and feasibility. In addition, the influence of the deflection of the coil is evaluated. The results show that the relative error of the actual measurement is maintained in an acceptable range when the tilt angle has a small error in the operation. The discovery and application of the tilt angle intersection provide a new direction for eddy current nondestructive testing.

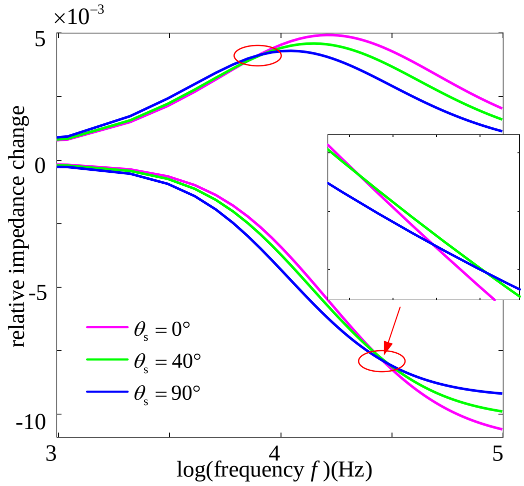
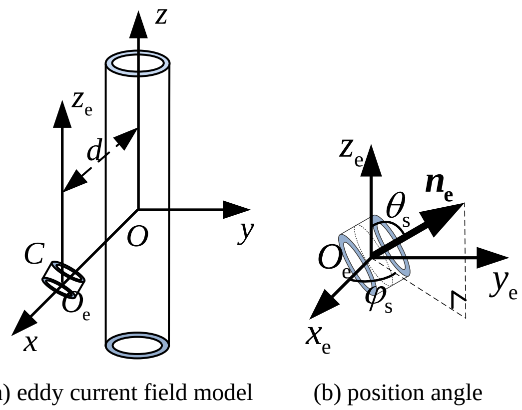


Fig. 1 Definition of the tilt angle intersection.

2. ANALYTICAL MODEL

A coil C is placed outside of an infinite length pipeline arbitrarily. The inner radius of the pipeline is r_i, the outer radius is r_o, the conductivity is σ, and the relative permeability is μ_r. The air permeability is μ_0. The number of turns of the coil is N, the inner radius is r_{ei}, the outer radius is r_{eo} and the height is h. An alternating current with an amplitude I and an angle frequency ω is communicated in the coil.



(a) eddy current field model (b) position angle

Fig. 2 Schematic diagram of arbitrarily placed coil.

The coordinate system $Oxyz$ is established with the central axis of the pipeline as the z axis, wherein the x axis passes through the center O_e of the coil. The local coordinate system $O_e x_e y_e z_e$ is established with the coil center as the origin, in which the direction of the x_e axis is the same as that of x axis, and the direction of the z_e axis is the same as that of z axis. The vertical distance from the center of the coil to the central axis of the pipeline is d, as shown in **Fig. 2(a)**. Two position angles are introduced to indicate the relative position of the coil and the pipeline, as shown in **Fig. 2(b)**. The unit normal vector of the cross section of the cylinder center of the coil is $\boldsymbol{n}_e$. The horizontal angle φ_s is the included angle between the x_e axis and the projection of $\boldsymbol{n}_e$ in the $O_e x_e y_e$ plane. The tilt angle θ_s is the included angle between the vector $\boldsymbol{n}_e$ and the z_e axis.

Based on the analysis of the eddy current field of the coil placed outside the pipeline, the coil coefficient C_{sm} is expressed as

$$G_n = \int_{r_{ei}}^{r_{eo}} \int_{-\frac{h}{2}}^{\frac{h}{2}} \sin\theta_0 r_0^{n+1} \mathrm{P}_n^1\left(\cos\theta_0\right) \mathrm{d}x_0 \mathrm{d}z_0 , \tag{1}$$

$$\begin{aligned} C_{sm} = & \frac{\mathrm{j}\mu_0 i_0}{2} \sum_{n=1}^{\infty} \frac{G_n \alpha^{n-1}}{n+1} \sum_{v=-n}^{n} \left[\operatorname{sgn}(\alpha)\right]^v \times \\ & \frac{(-\mathrm{j})^{n-v}}{\pi(n+v)!} \mathrm{P}_n^v\left(\cos\theta_s\right) \mathrm{e}^{-\mathrm{j}v\varphi_s} \mathrm{K}_{m-v}\left(|\alpha| d\right) \end{aligned} , \tag{2}$$

where G_n is the integral of the region where the coil is located; $n_0 = N / h\ (r_{eo} - r_{ei})$ is the coil turn density; I_m and K_m represent modified Bessel function of the first and the second kind of order m, respectively; $\sin\theta_0 = x_0 / r_0$; $r_0 = \mathrm{sqrt}\ (x_0^2 + z_0^2)$.

By substituting the coil coefficient C_{sm} and the correlation coefficient D_{ecm} into

$$\begin{aligned} \Delta Z\left(\theta_s, \varphi_s\right) = & -\frac{4\mathrm{j}\omega\pi^2}{\mu_0 I^2} \int_{-\infty}^{\infty} \sum_{m=-\infty}^{\infty} \alpha^2 C_{sm}\left(\theta_s, \varphi_s\right) \times \\ & D_{ecm}\left(\theta_s, \varphi_s\right) \mathrm{d}\alpha \end{aligned} , \tag{3}$$

the complete expression of the impedance change of the coil can be obtained. The specific relationship between C_{sm} and D_{ecm} is shown in [20]. The self-inductance ωL_0 of the coil in the air is taken as the normalization factor to normalize the coil impedance change, that is, $\Delta Z / \omega L_0$, to obtain the relative impedance change of the coil.

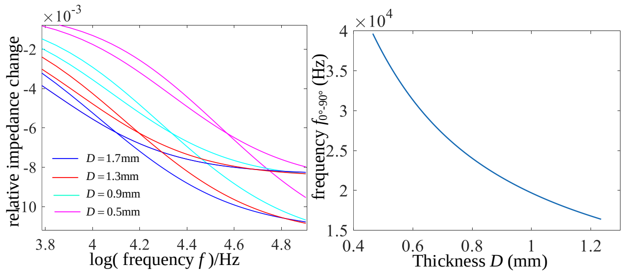
3. INFLUENCES OF PIPELINE PARAMETERS

The tilt angle intersection is determined by the pipeline parameters, coil parameters and position parameters. In this chapter, the influence of the pipeline parameters on the tilt angle intersection is analyzed through simulation. The outer radius r_o of the pipeline is 25.5 mm, the inner radius r_i is 24.5 mm, the conductivity σ is 1.46 MS/m, the relative permeability μ_r is 1. The probe is a single-layer and multi-turn coil, and the radius R is 20 mm, the number of turns N is 14, and the height h is 2.5 mm. Take the tilt angles 0°, 90° as an example and the frequency of the tilt angle intersection point of 0°, 90° is $f_{0°\text{-}90°}$.

3.1. Pipeline Thickness

In case d = 50 mm and the outer radius of the pipeline is constant, (3) is used to calculate the relative impedance change under different pipeline thicknesses D and the frequency of the tilt angle intersection point is obtained.

The results of the relative impedance change are shown in **Fig. 3(a)**. Overall, the amplitude of the tilt angle intersection point is almost not affected by the change of pipeline thickness. But the tilt angle intersection point shift to left when D increases. The curve of the frequency $f_{0°\text{-}90°}$ varying with D is shown in **Fig. 3(b)**. It is found that $f_{0°\text{-}90°}$ decreases as the increase of D monotonously. And the frequency of the tilt angle intersection point is more sensitive to the small thickness.

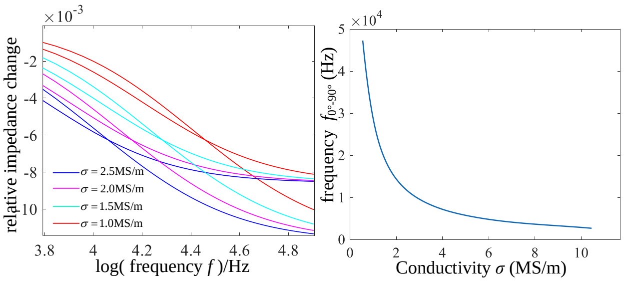


(a) relative impedance change (b) relation curve

Fig. 3 Curve of the tilt angle intersection with the change of the pipeline thickness D.

3.2. Conductivity

The strength of eddy current is influenced by material conductivity. The change of pipeline conductivity will lead to the change of the tilt angle intersection point, as shown in **Fig. 4(a)**. The increase of conductivity can make the tilt angle intersection point shift to left, i.e., the frequency of the intersection decreases. The curve of the frequency $f_{0°\text{-}90°}$ varies with the conductivity is shown in **Fig. 4(b)**. The frequency decreases monotonically with the increase of σ. When the conductivity is less than 2 MS/m, the frequency decreases rapidly with the increase of the conductivity. Otherwise, the sensitivity of the frequency to the conductivity decreases significantly. Large conductivity has little effect on the frequency.



(a) relative impedance change (b) relation curve

Fig. 4 Curve of the tilt angle intersection point with the change of the pipeline conductivity σ.

3.3. Complex Parameters

It is shown that the frequency of the tilt angle intersection point decreases monotonously as the increase of pipe thickness. Also, the law of that as the conductivity is monotone. Comprehensively, the 3-D relationship curve of them is shown in **Fig. 5**. The frequency $f_{0°\text{-}90°}$ is sensitive to the small thickness and small conductivity. It is found that the frequency $f_{0°\text{-}90°}$ corresponds to the thickness and conductivity of pipelines one to one. As shown in **Fig. 6**, the equal-frequency curves of different frequencies have no intersection.

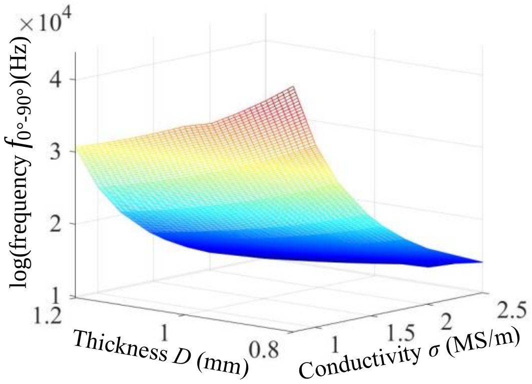


Fig. 5 The relationship between the frequency $f_{0°\text{-}90°}$, the pipeline thickness D and conductivity σ.

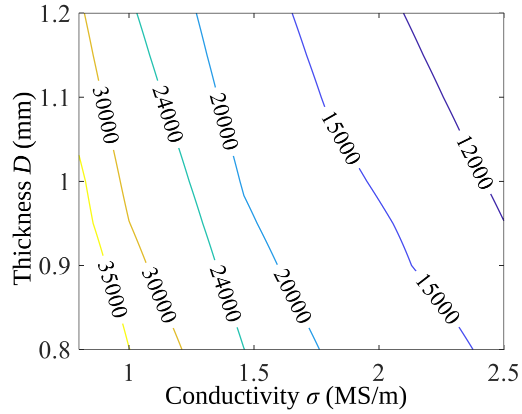


Fig. 6 The equal-frequency curve of the pipeline thickness D and conductivity σ.

4. Method of Measurement

The tilt angle intersection is closely related to the pipeline parameters. Thus, the tilt angle intersection point can be used as the characteristic signal to invert pipeline parameters. When the frequency $f_{0°\text{-}90°}$ is known, an equal-frequency curve of the pipeline thickness and conductivity can be obtained. There must be a point in the curve that corresponds to the actual pipeline thickness and conductivity. In order to measure the thickness and conductivity simultaneously, another equal-frequency curve is needed. The tilt angle intersection frequency of other tilt angles has the same rule as that of 0°and 90°, such as 40° and 90°, as shown in **Fig. 7**. Therefore, the equal-frequency curve of another set of tilt angles can be selected as the second. The intersection point of the two curves is the result of the pipeline parameters to be tested. In conclusion, an inversion model is proposed to measure the pipeline thickness and conductivity simultaneously.

Fig. 8 shows the flow chart of the inversion method for the complex parameters of the pipeline. First, determine the vertical distance d and two sets of tilt angles θ_1, θ_2, θ_3 and θ_4. Put the relevant parameters into the analytical solution of the coil impedance change. Then, the relative impedance change of the coil is calculated, and the relationship curve between the pipeline thickness, conductivity and the frequency of the tilt angle intersection point is obtained. The actual measured frequency of the tilt angle intersection point of the pipeline to be tested is substituted into the curve obtained by simulation, and its equal-frequency curve is fitted. That is, the relationship curve of the two parameters under the practical frequency of the tilt angle intersection point. There must be a point in the curve that corresponds to the actual parameters of the pipeline. Therefore, through changing the tilt angle and repeating the above steps, the second equal-frequency curve of the parameters can be obtained. The intersection point of the two curves is the inversion result of the pipeline parameters.

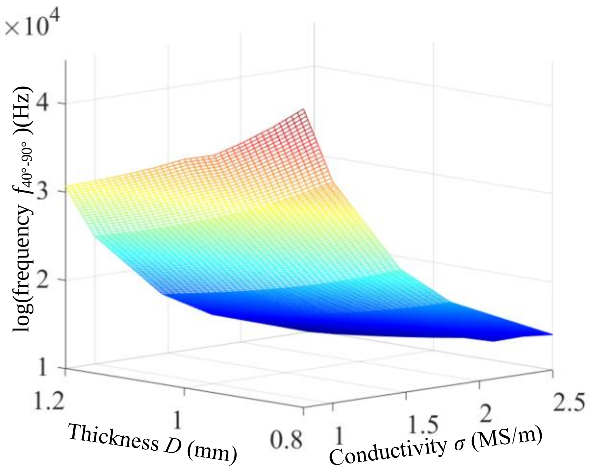


Fig. 7 The relationship between the frequency $f_{40°\text{-}90°}$, the pipeline thickness D and conductivity σ.

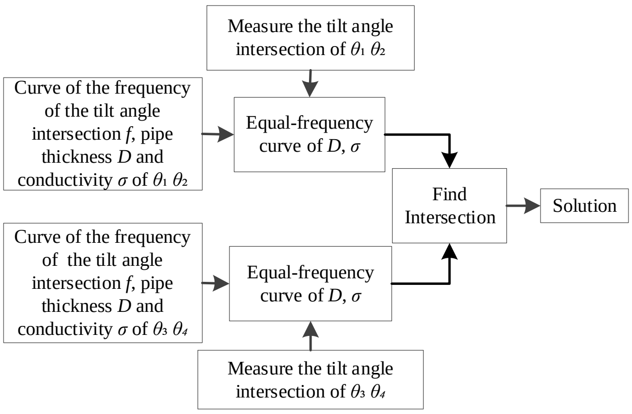
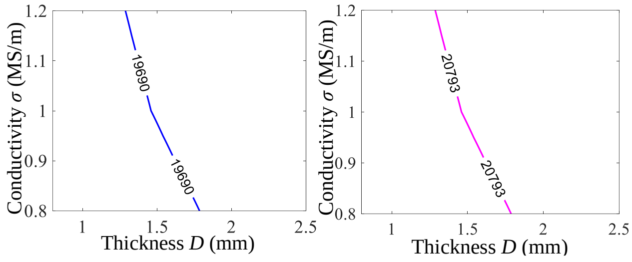


Fig. 8 The flow chart of the measurement method.

5. Verification of the Method

In order to verify the correctness of the method, we carried out relevant simulation and analyzed the result. The parameters of the pipeline and coil are the same as those in Chapter 3. The four tilt angles are selected as $\theta_1 = 0°$, $\theta_2 = 90°$, $\theta_3 = 40°$, and $\theta_4 = 90°$.

Set d = 50 mm and substitute the pipeline, coil and angle parameters into the analytic expression, then calculate the frequency $f_{0°\text{-}90°}$ and $f_{40°\text{-}90°}$. The relation curve of the frequency on the pipeline thickness and conductivity is drawn. The two frequencies of the tilt angle intersection point are 19690 Hz and 20793 Hz, respectively. The equal-frequency curves of the pipe thickness and conductivity are shown in **Fig. 9**. The intersection point of the two curves is (1.4652, 0.9980). This means that the inversion result of pipeline thickness is 0.9980 mm and the conductivity is 1.4652 MS/m. The relative errors are 0.2%, 0.36%, respectively. This indicates the correctness of the method.



(a) θ_1, θ_2 (b) θ_3, θ_4

Fig. 9 The equal-frequency curve of pipe thickness and conductivity.

The frequency of the tilt angle intersection point is almost not affected by the tilt angle, so this method can reduce the error caused by the coil deflection to a certain extent. The influence of coil deflection on the measurement error is evaluated when the angle deviation is 5°. **Table. 1** shows the results of pipeline thickness and conductivity under four different angle deflection cases. The calculation results show that the measurement error caused by angle deflection is less than 8%. When the actual operating error of the tilt angle is 5°, the error of the pipe thickness and conductivity inversion results is in an acceptable range, which indicates that the method can reduce the error caused by the coil deflection to a certain extent.

Table. 1 Results of coil deflection on measurement.

Tilt angle θ_1, θ_2(°)	0, 90	0, 85(90)	5(0), 90	5(0), 85(90)
Tilt angle θ_3, θ_4(°)	40, 85(90)[a]	40, 85(90)	45(40), 85(90)	45(40), 85(90)
Conductivity (MS/m)	1.5156	1.5689	1.4331	1.4402
Relative error (%)	3.81	7.46	1.84	1.37
Thickness (mm)	0.927	0.9243	1.0290	1.0210
Relative error (%)	7.30	7.57	2.90	2.1

a. The angle in brackets is the specified standard angle and the rest is the same.

6. Conclusion

Based on the analytic solution of eddy current field model of the pipeline excited by the coil placed arbitrarily outside the pipeline, this paper analyzes the law of the tilt angle intersection with the change of pipeline parameters. The frequency of the tilt angle intersection point decreases with the increase of the pipe thickness. The greater the conductivity of the pipe is, the smaller the tilt angle intersection frequency will be. In order to measure the pipeline thickness and conductivity simultaneously, an inversion method is proposed. This method uses the relation between the tilt angle intersection frequencies of two sets of tilt angles and pipe parameters. It has been found that the method has high measurement accuracy.

Besides, the method can reduce the influence of the deflection of coil on the measured results.

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