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An Experimental Study of Nondestructive Testing System to measure Dimension of Cylindrical Rod using Solenoid Eddy Current Coil

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Abstract

An experimental study of an eddy current nondestructive testing system to measure dimensions of cylindrical metallic rods, such as cross-sectional area or diameter, is presented.

Impedance characteristics of a solenoid sensor, which are generally based on Maxwell's equations in electromagnetic field, are briefly discussed for inspecting geometrical parameters of the coil sensor and testing materials. A measurement system for detecting the diameter of the metallic rod is implemented. This instrument has capabilities for detecting the sensor output signals and estimating demensions of the testing material, continuously. As a result, it was shown that the eddy current sensor with an encircling coil could estimate the diameter of metallic rod. The implemented measurement system gives accurate information for inspecting the dimension of conducting rod with good sensitivity.

Ⅰ. Introduction

Eddy current method which sensor head is implemented by using a probe coil or an encircling coil has been widely applied in nondestructive test(NDT) of conductive materials.[1~3] Thus many instruments have been developed and used in various industrial fields. Eddy current testing could be possible for all conductive materials and then includes the inspection of the dimension of the test materials, the measurement of the thickness of metallic plates or non-metallic coating, and the assessment corrosion, deterioration or other metallic properties. An important advantage of eddy current testing compared with other testing methods is that there is no need for physical contact with the surface of the object under testing, and its measurement speed is rapid.

However, there still exist some difficulties in designing eddy current instruments because of various and complex phenomena of the magnetic properties. Since magnetic flux generated by an exciting coil may be distributed in free space as well as all materials near the coil, its intensity affected on the test material may not be easily analyzed or measured.[4,5] Therefore it is necessary for test apparatus to be designed carefully. In most instruments with solenoid coils, their structures and exciting frequencies are determined by some experimental methods for every testing object, such as electrical and magnetic performances and geometrical aspects.

In this study, we show several properties for designing an eddy current sensor to detect the diameter of cylindrical materials. Through the examination of impedance for a solenoid coil without any searching coil, the diameter variation of conductive object could be readily quantified by using the sensor output for impedance variation.

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A measurement system with a small length coil and a driving motor is implemented and tested for several materials. Sensor response is directly read by a computer and then, a linear function in order to estimate diameter of test samples is derived and measurement sensitivity is also discussed.

II. Impedance Properties of Eddy Current Sensor

2.1 Magnetic Flux Density and Normalized Impedance

As shown in Fig. 2.1, a solenoid having a conducting material at the longitudinal axis is excited by an alternating current. It is assumed that there is no search coil or probe to detect dimension of the testing material. In this sensor, thus, the electromagnetic performances of the material would appear as the impedance variation of the coil itself.

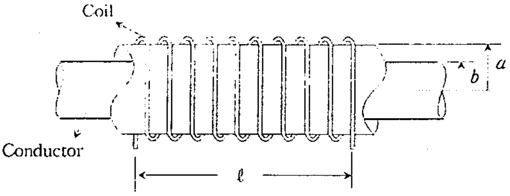


Fig. 2.1 Schematic diagram of solenoid eddy current sensor

The solenoid coil has a finite length ℓ and its effective radius is a . It is assumed that the test material is an electrically conducting cylindrical rod having a radius b, and a homogeneous structure for the simplicity of analysis. Its conductivity and relative permeability are defined as σ and μ_r, respectively.

When an alternating current, $i(t) = i_o e^{j\omega t}$ is applied to the solenoid sensor, there is the induction of an alternating magnetic field H_0 , with the same frequency. Then the mag $B_0 = \mu_0 H_0$ netic flux density inside the coil is given by , where μ_o denotes the permeability of free space. With a conductive material inserted into the coil, the magnetic flux density at a given position in the rod becomes $B = \mu_o \mu_r H$. For the exciting current with $e^{-j\omega t}$, in general, the magnetic flux density can be given as follows

$$\nabla^2 B = \mu\sigma \frac{\partial B}{\partial t} \tag{2.1}$$

Therefore, we can have $\nabla^2 B = j\omega\mu_r\mu_o\sigma B = -k^2 B$ for all values of time t, where $k^2 = -j|k|^2$ and $|k| = \sqrt{\omega\mu\sigma} = \sqrt{2}/\delta$. Here δ denotes the standard penetration depth of magnetic flux.[6]

The mean magnetic flux density $\overline{B}$ for the magnetic flux Φ through the cross section of the rod satisfies the following relation

$$\overline{B} = \frac{2\mu_r B_o}{kb} \frac{J_1(kb)}{J_0(kb)} \tag{2.2}$$

where J_o and J_1 are the first kind Bessel's functions with zeroth and first order, respectively. For the simplicity, the proof of Eq. (2.2) is omitted here because it is shown in Reference [7].

Since magnetic flux does not attenuate in air, eddy current could not be generated in air-cored coil and then, sensor impedance is given as follows

$$\dot{Z}_0 = R_0 + j\omega L_0 \tag{2.3}$$

where R_0 and L_0 denote the resistance and the self inductance of the coil, respectively.

Let the sensor impedance in the presence of the rod inside the sensor be

$$\dot{Z} = R + j\omega L \tag{2.4}$$

Resistance R includes both the coil resistance and the resistive components determined by current source or hysterisis loss. And the inductance L also represents both the self inductance of the coil and the inductive components obtained by magnetic skin effect, which is dependent on the geometrical aspects of the coil and material.

From Fig. 2.1, letting Φ_G and Φ be the flux in air gap and that in the conductor, respectively, the total flux, $\Phi_T = \Phi + \Phi_G$ which is generated in the cross sectional area of sensor is given by

$$\Phi_T = \pi b^2 \overline{B} + \pi(a^2 - b^2)B_0 \tag{2.5}$$

If $\overline{B_T}$ denotes the mean flux density corresponding to Φ_T, the total flux can be written as $\Phi_T = \pi a^2 \overline{B_T}$. Dividing Eq. (2.5) by that of air-cored coil, B_0 and letting the fill factor be $\eta = (b/a)^2$, we can get

$$\widehat{\mu_T} = \eta\hat{\mu} + 1 - \eta \tag{2.6}$$

where $\widehat{\mu_T} = \overline{B_T}/B_0$ and $\hat{\mu} = \overline{B}/B_0$.

Since kb in Eq. (2.2) is a complex variable and $\hat{\mu} = \overline{B}/B_0$, letting $\hat{\mu} \equiv \widehat{\mu_R} - j\widehat{\mu_I}$ and substituting it into Eq. (2.6) becomes

$$\widehat{\mu_T} = \eta\widehat{\mu_R} + 1 - \eta - j\eta\widehat{\mu_I} \tag{2.7}$$

Assuming that the amplitude of exciting current is constant, the coil impedance is proportional to the magnetic flux linkage.

Using Eqs. (2.3) and (2.4), the impedance ratio of sensor with the rod can be obtained as

$$\widehat{\mu_T} \fallingdotseq \frac{\omega L}{\omega L_0} - j\frac{R}{\omega L_0} \tag{2.8}$$

when R_0 in Eq. (2.3) is assumed to be negligible. This equation is so called as the nomalized impedance with demensionless[3]. Consequently, from Eqs. (2.7) and (2.8), the real and imaginary part is readily given by

$$\omega L/\omega L_0 = \eta\widehat{\mu_R} + 1 - \eta \tag{2.9}$$

$$R/\omega L_0 = \eta\widehat{\mu_I} \tag{2.10}$$

It is noted that the equations for the normalized impedance is closely related to the fill factor. Therefore, the cross sectional area, diameter, conductivity or permeability of the material could be estimated by Eqs. (2.9) and (2.10). Most of NDT apparatus with such a solenoid coil to measure some performances of metallic conductors are virtually utilized by these relations.

2.2 Numerical Analysis

As shown in Eqs. (2.9) and (2.10), we can know that the geometric variation of test rod would change the impedance of the sensor and its change may be brought by the variation of impedance and phase. Therefore, the correct measurement for these two variables could give a precise value for the diameter's variation. However, it may be possible to inspect the diameter variation to some degree, through only the impedance change is detected by a suitable mesurement system. To examine analytic properties obtained in the previous section for measuring demensions of metallic rods, some numerical results are examined.

Fig. 2.2 shows sensor impedance for frequency range, 0~100[㎑], for a non-ferromagnetic rod when varying the fill factor as 25, 50, 75 and 100[%]. The testing rod is assumed to be an aluminum rod with conductivity, σ =35[MS/m], and a solenoid sensor having an effective radius, a =13.25[㎜] and the inductance at $f=0$ [㎐], L_0 =74.7[μH].

It is obvious in Fig. 2.2 that the fill factor of the sample is closely correlated to the impedance for most frequency range. In fact, the correlation coefficient between the impedance and the fill factor is nearly equal to -1. This implies that the diameter of material could be correctly detected by using the estimate function. Although all the frequencies may be available to estimate the fill factor, the higher frequency gives a precise result

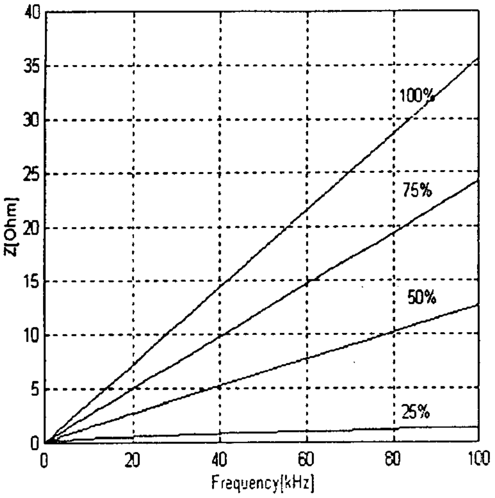


Fig 2.2 Impedance for a non-ferromagnetic conductor.

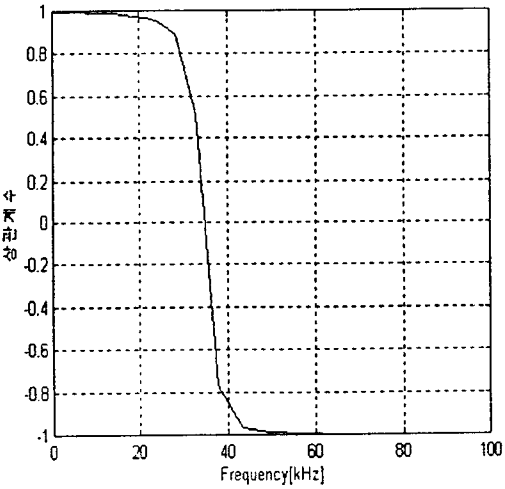


Fig. 2.3 Correlation coefficient for a ferromagnetic conductor.

because the measurement value is more sensitive and includes less mesurement noise. Consequently, the fill factor would be determined by using linear regression which is obtained from such the characteristic as Fig. 2.2. Procedures to obtain a linear estimate function will be discussed in Chap. Ⅲ.

For a ferromagnetic material with μ_r =100 and σ = 5[MS/m], Fig. 2.3 demonstrates the correlation coefficient property to predict a linear regression relation between fill factors and impedances. However, the correlation is not the same as that of the previous non-ferromagnetic rod because of the relative permeability. As shown in Fig 2.3, it is easily known that there exists uncorrelated region but such two parameters are very closely correlated in the lower or higher band. Therefore, the exciting frequency of sensor inspecting fill factor should be carefully chosen. It is also noted that such the frequency may be dependent on electrical and magnetic characteristics of metal as well as the geometrical aspects of sensor and testing rod. Consequently, in detecting fill factor of metallic rod with a solenoid coil, it should give a careful attention to use these performances.

Ⅲ. Implementation and Experimental Study

3.1 Implementation of Measurement system

In order to verify an effectiveness for detecting fill factor of metallic rod, a measurement system is designed as shown in Fig. 3.1. A constant current source with variable frequency is implemented to have a capability of controlling current amplitude from 0 to max. 100[㎃] and then the sensor response could be precisely adjusted to obtain a measurable range and have a high resolution.

As shown in Chap. Ⅱ, a cylindrical rod to be tested and a solenoid coil are assumed to be a infinite length and then it was proven that dimensions of the rod could be directly detected by sensor output. Although a sensor with long

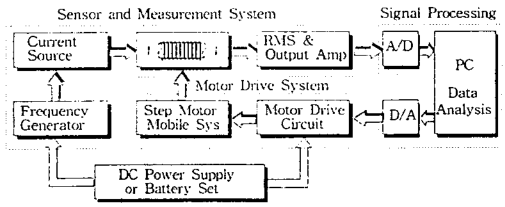


Fig. 3.1 An implemented measurement system

length would give response with good sensitivity, its output demonstrates the mean value of fill factor for the test material inside the coil. Therefore, such a sensor could not be measured any diameter variation for a short length. Hence it is necessary to design a shorter sensor such that fill factor of a short length could be detected precisely. If a solenoid coil length is finite, it would be seemed that the analytic result as given in Chap. II may not be satisfied any more when inspecting the fill factor. Considering the effectiveness for impedance on bobbin length change, it is, however, easily seen that even a sensor with finite length holds the same property for inspecting the fill factor of the rod.

A solenoid coil having ℓ =9[㎜] length and mean diameter, a =29[㎜] is implemented. Since the response of the sensor appears an alternating signal with the exciting frequency, it is converted to a root-mean-squares value by an rms chip and then, its output is amplified to have a suitable level. At that time, the output data is transferred to the memory by using a 16-bit AD converter.

To obtain continuous measurements, a step motor and its driver circuit are designed. The motor is operated by computer and then, distance data can be homogeneously recorded into memory. This system can transports the sensor head with constant speed to any direction, while the testing rod is fixed.

3.2 Samples and Estimation Function

To show one of methods for inspecting the fill factor of conducting rod, a cylindrical rod with length 800[㎜] and diameter d =16.1[㎜], which is a hard-drawn aluminum rod is prepared. This rod is assumed to be a reference sample to obtain an estimation function of fill factor. Fig. 3.2 illustrates schematic diagram for the reference rod and Table 3.1 shows diameters and corresponding fill factors, where d_r and η_r denote the diameter and fill factor for the sample, respectively.

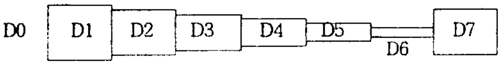


Fig. 3.2 Structure of reference rod.

Table 3.1 Diameter and fill factor for the reference sample.

Sample		D0	D1	D2	D3
Aluminum	d_r[㎜]	0.0	16.1	13.7	12.5
	η_r[%]	0.0	30.82	22.32	18.58
Sample		D4	D5	D6	D7
Aluminum	d_r[㎜]	10.25	8.15	6.1	13.25
	η_r[%]	12.49	7.90	4.42	20.87

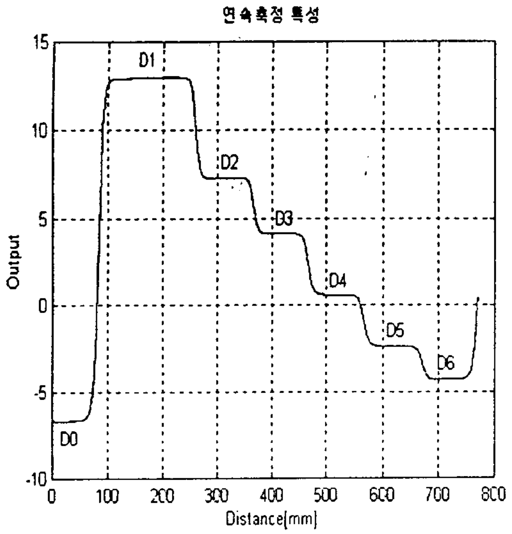
Fig. 3.3 shows sensor ouput for the reference sample when the exciting frequency and current amplitude are adjusted to 50[㎑] and 10[㎃], respectively. In Fig. 3.3(a), the output of the sensor demonstrates as constant values in the diameters without change while it shows a smooth curve in the slope part.

Fig. 3.3(b) demonstrates the relation between fill factors given in Table 3.1 and average outputs of diameters, D0~D6 as shown in Fig. 3.3(a). Furthermore, an estimate function by linear regression analysis for these parameters also gives in Fig. 3.3(b). Letting V be the output and $\hat{\eta}_r$ in percent be the fill factor estimates of the reference sample, then it can readily obtain the following equation through a curve fitting

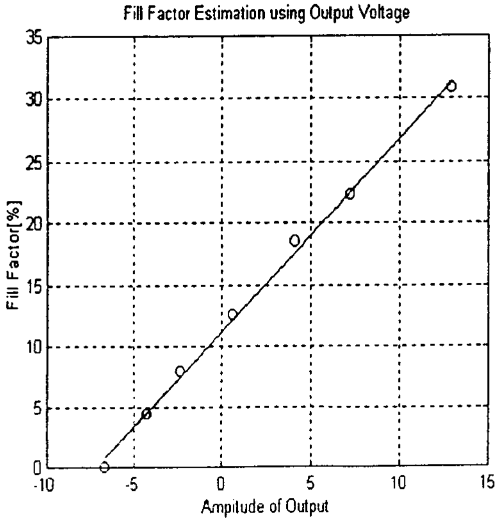
$$\hat{\eta}_r = 1.5602V + 11.1764 \qquad (3.1)$$

where the correlation coefficient was nearly one.

To verify effectiveness for the impemented detection system, an arbitrary sample with length 500[㎜] and diameters given in Table 3.2 is tested. This is also a hard-drawn aluminum rod similar to the reference sample. Fig. 3.4 shows the fill factor property estimated by using sensor



(a) sensor output



(b) estimated fill factor

Fig. 3.3 Sensor output property and correlation between fill factor and sensor output for the reference aluminum rod.

Table 3.2 Diameter and fill factor for a sample.

Sample		A0	A1	A2	A3	A4
Aluminum	d_a[㎜]	0.0	11.35	9.55	7.0	6.05
	η_a[%]	0.0	15.32	10.84	5.83	4.35
	$\widehat{\eta_a}$[%]	0.1	15.48	10.80	5.79	4.30

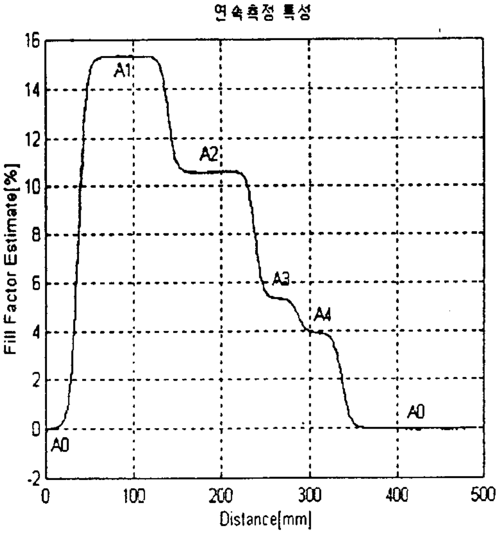


Fig. 3.4 Property for estimated fill factor for an aluminum rod.

outputs and Eq. (3.1). In Table 3.2, η_a and $\widehat{\eta_a}$ are calculated fill factors for the sensor diameter a=29[㎜] and estimated fill factors for the flat parts of Fig. 3.4, respectively. From these results, it is known that the estimated fill factors of the rod have good accuracy.

In this testing, the correlation coefficient between the output of sensor and the fill factor was nearly one. This fact represents that the fill factor of rod could be correctly estimated by the sensor output. Finally, it is obvious that, after measuring the output of the rod, the fill factor could be determined by using Eq. (3.1) and the results would have good reliability.

The performances for inspecting such local flaws or partial corrosions may be dependent on coil length. From Fig. 3.3(a), it can be readily shown that the sensor with a shorter length would make an accurate measurement for any local position. Furthermore, the output for the slope gives also good information for the variation of diameter or gradient.

Fig. 3.5 demonstrates properties for the slopes after considering the given coil length. In this

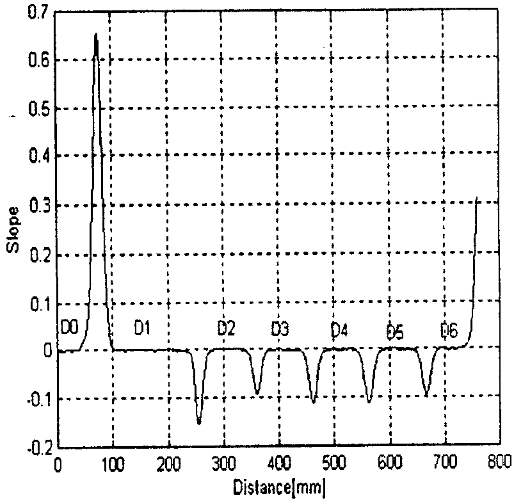


Fig. 3.5 Properties of slopes.

figure, positive peaks represents positive slopes but negative ones shows negative slopes. Moreover, it may also predict such features as fill factor variations, i.e., diameter changes. As a result, assuming that a suitable algorithm to estimate them from the peak values would be given, a measurement of width or slope structure could be also available.

As shown in Sec. 2.2, the impedance and fill factor property for any ferromagnetic rod is slightly different to that for a non-ferromagnetic one. However, a process to estimate fill factor is the same to that of non- ferromagnetic rod and then some details are omitted here.

Although the NDT method suggested above shows good sensitivity and reliability for estimating the fill factor of conducting metallic rods, it has some limitations to use in practice. First, it is always required standard or reference samples in order to calibrate the apparatus before use, because this measurement unit adapts a comparison measurement technique. Thus, this sensor would be available to use only in such a case. Second, it could not be applied to inspect dimensions, wear or surface flaws of wire ropes in service.[8,9] Finally, since solenoid sensor may be very sensitive for environments such as temperature or any other magnetic field, it is necessary to give attention to design or use such instruments.

IV. Conclusions

An experimental properties for inspecting dimensions of metallic rods are discussed in this study. Assuming that the testing material is a cylindrical rod, some analytic performances between the impedance of a solenoid eddy current sensor and the fill factor of the rod are presented. As a result, it was shown that the fill factor is closely correlated to the impedance of the sensor.

A testing measurement system is implemented for having the capability to detect impedance variation of the rod continuously. For a reference sample, a process to determine an estimation function and a method to inspect fill factor are examined. Through some experimental results, it is shown that the designed measurement system using such an NDT method gives accurate information for estimating the fill factor of the metallic rod and has also good sensitivity.

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