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AC SOURCING CURRENT FREQUENCY INFLUENCE ON EDDY-CURRENT TESTING

ВЛИЯНИЕ ЧАСТОТЫ ТОКА ПИТАНИЯ НА РЕЗУЛЬТАТЫ ВТ КОНТРОЛЯ

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Abstract: *Nondestructive electromagnetic evaluation and testing are widely used for evaluating and testing of electro conductive and magneto conductive stuffs and details. Usually, this nondestructive technique, electromagnetic, works in harmonic continuous mode, and its analysis is based on a frequency analysis method. Lately, it is more often used pulsed electromagnetic mode of nondestructive evaluation and testing due to its multi-parameters features. This mode can be also analyzed with the help of frequency analysis method due to Fourier and Laplace methods. Thus, this article is dedicated to Eddy-Current sensor electrical parameters (resistance, inductance and capacitance) calculation as a function of AC sourcing current frequency with aallowance for influence of Testing Samples parameters. Analytical model was developed with the help of similitude method, which let to take into account "skin-effect" in a wire with round cross-section of sensors coil, curvature of its round wire and proximity effect of coil of the sensor and Testing Samples parameters.*

KEYWORDS: Electromagnetic control, Eddy-Current sensor, electric parameters of coil, "skin-effect", proximity effect, similitude method.

1. *Introduction*

Nondestructive electromagnetic evaluation and testing are widely used to evaluate and test the quality of electro (Eddy-Current Technique) and magneto (Inductive Technique) conductive stuffs and details, because of its simplicity in device development and usage [1 – 4]. This technique is widely used in crack detection, structure metering, mho metering, thickness metering and so on [2]. Electromagnetic gauges are usually working in Continues Harmonic mode, but lately, they are more often used in Pulsed mode, due to its multi parameters features [4]. For Example, non typical usage of Eddy-Current Technique is based on continuous harmonic scanning in certain frequency band of Testing Samples (TS) and analyzing measured data [5]. Lately, electromagnetic sensors are also complicated – multi-differential sensors [1], and they can be used either in continues harmonic mode, or in pulsed mode, or in combined mode (continues harmonic mode and pulsed mode) [6]. Usually, as a sensor, in electromagnetic evaluation and testing is used coil. Coil, depending on AC current frequency band, can be realized as a coiler (low AC sourcing current frequency band) or as a Printed Circuit Board (PCB) (high AC sourcing current frequency band) [2]. Coils realized as PCB are characterized by its stability, repeatability, reliability, availability and are cheap in realization. And coilers are more practical in the case of low AC sourcing current frequencies [2].

2. *Prepositions and means for resolving the problem*

The importance of Nondestructive Electromagnetic Evaluation and Testing and, as a result, gauges quality development is mentioned above. So, it is important to calculate accurately electromagnetic sensor of the gauge to decrease time of development and to develop a gauge with necessary measuring parameters, which determines quality by this testing. It is necessary to emphases, that independent of mode of gauge working (Continues Harmonic, Pulsed or Combined), gauge sensor can be calculated, if we determine its parameters (active and reactive impedances) as a function of AC sourcing current frequency with allowance for TS parameters, such as electric and magnetic conductivity of TS stuff, TS geometrical parameters, distance between electromagnetic sensor and TS, sensors displacement relatively figured TS symmetry axis and so on. For example, if we consider Pulse mode of gauge working, sensor active and reactive impedances in frequency domain are functions of AC sourcing current frequency and parameters of TS P and in time domain, due to Laplace or Fourier transform, are functions of time and parameters of TS P, and can be determined as [7 – 9]:

$$\dot{Z}_t\left(\tilde{t}_n,P\right)=IDLT\left(\dot{Z}_p\left(\tilde{p}_n,P\right)\right), \qquad (1)$$

where $\dot{Z}_t\left(\tilde{t}_n,P\right),\dot{Z}_p\left(\tilde{p}_n,P\right)$ – impedances as functions of normalized time $\tilde{t}_n$, and normalized complex frequency $\tilde{p}_n=\tilde{\sigma}_n+j\tilde{\omega}_n$, accordingly, and P – other parameters of TS; $IDLT\left(\bullet\right)$, – Inverse Discrete Laplace Transform. If $\tilde{\sigma}_n=0$, than (1) is transformed into Inverse Discrete Fourier Transform and can be computed with the help of widely used Inverse Fast Fourier Transform algorithm.

Thus, it is necessary to determine gauge electromagnetic sensor electrical parameters as a function of AC sourcing current frequency with allowance for parameters of TS. In this work we consider, that gauge electromagnetic sensor is sourcing by low AC sourcing current frequency, so we consider a coil of electromagnetic sensor as a cylindrical coiler, and it is used to evaluate and test TS, presented as cylindrical rods. It is well known, that main electrical parameters of sensor coil (resistivity, inductivity and capacitance) are not only TS parameters dependent during the testing, but also AC sourcing current frequency dependent due to "skin-effect" in wires of the coil, cylindrical coil wire curvature and proximity effect, which is becoming apparent due to neighboring coil wires electromagnetic field influence on AC sourcing current density distribution in wire of the coil. Thus, in this work, we propose an analytical model of cylindrical coil as a coiler, which wire has round cross-section. Approximate calculation of such coils can be found in [2] and is based on assumption, that wire is a filament and coil is infinitely long, "skin-effect" in wire of the coil, its curvature and proximity effect is neglected and its impedance can be presented as [2]:

$$\dot{Z}\left(\gamma_{TS},R_{TS}\right)=-j\pi\omega\mu_0 W_1^2\times\left(\begin{array}{l}R_1^2-R_{TS}^2+\dfrac{2\mu_{rTS}R_{TS}}{\sqrt{-j\omega\gamma_{TS}\mu_{rTS}\mu_0}}\times\\ \times\dfrac{I_1\left(R_{TS}\sqrt{-j\omega\gamma_{TS}\mu_{rTS}\mu_0}\right)}{I_0\left(R_{TS}\sqrt{-j\omega\gamma_{TS}\mu_{rTS}\mu_0}\right)}\end{array}\right),\qquad(2)$$

where $j=\sqrt{-1}$ – imaginary unit; $\omega=2\pi f$; f – AC current cyclic frequency; $\mu_0=4\pi 10^{-7}$, H/m ; W_1 – number of cylindrical coil wires; R_1, R_{TS} – radii of coiler and TS, accordingly; γ_{TS} – electro conductivity of TS; μ_{rTS} – relative permeability of TS; $I_0(\bullet), I_1(\bullet)$ – modified Bessel functions of 1st kind 0th and 1st orders, accordingly.

Thus, enhancing accuracy of testing results, requires improving accuracy of such coiler calculation, especially, when calculating Pulsed Eddy-Current mode of the sensor.

3. *Solution of the examined problem*

3.1. Function of Current Density Distribution

As a function of Current Density Distribution determines impedance of the coiler, let's determine it. To solve this problem we use similitude technique, based, in this case, on the solution of Helmholtz equation (3) for vector-potential of the "Eddy-Current Cylindrical Coiler – Cylindrical TS" system with an AC sourcing current flowing in $\mathbf{z}_0$ direction.

$$\Delta A_z=-\mu_r\mu_0 j_z(r),\qquad(3)$$

where $j_z(r)$ – current density distribution in $\mathbf{z}_0$ direction.

To determine impedance of the "Eddy-Current Cylindrical Coiler – Cylindrical TS" system as a function of AC sourcing current frequency, it is necessary to determine vector-potential of the "Eddy-Current Cylindrical Coiler – Cylindrical TS" system as a function of AC sourcing current frequency. This solution can be derived from well-known solution (2), based on assumption, that round coiler wires are presented as a filament, and a solution of vector-potential A_φ between cylindrical TS and cylindrical coiler, which can be presented as [2]:

$$A_\varphi(r)=\frac{\mu_0 H_0}{2}\times\left[r-\frac{1}{r}\left(\begin{array}{l}R_{TS}^2-\dfrac{2\mu_{rTS}R_{TS}}{\sqrt{-j\omega\gamma_{TS}\mu_{rTS}\mu_0}}\times\\ \times\dfrac{I_1\left(R_{TS}\sqrt{-j\omega\gamma_{TS}\mu_{rTS}\mu_0}\right)}{I_0\left(R_{TS}\sqrt{-j\omega\gamma_{TS}\mu_{rTS}\mu_0}\right)}\end{array}\right)\right],\qquad(4)$$

where H_0 – magnetic strength on TS surface.

Thus, to get vector-potential A_φ, as a function of AC sourcing current frequency, we should determine function of current density distribution in wire of coiler as a function of AC sourcing current frequency and in (4) we should determine H_0 as a function of AC sourcing current frequency and then, as (4) represents a Green function, it is necessary to integrate (4) over coiler wire cross-section.

To solve this problem, let's use similitude technique and consider round wire as an infinitely long straight cylindrical wire and determine a law of field distribution in a cylindrical wire, created by a cylindrical, infinitely thin cylinder with an AC sourcing current, flowing in z$_0$ direction. Cylindrical wire and cylinder with an AC current are placed symmetrically. In this case the solution of Helmholtz equation (3) for vector-potential A_z in a cylindrical wire is [10]:

$$A_z(r)=CI_0\left(r\sqrt{-j\omega\gamma_{TS}\mu_{rTS}\mu_0}\right),\qquad(5)$$

where C – constant value.

Then, function of AC sourcing current density distribution in round wire with round cross-section of coiler, accordingly to (5), if the center of coordinate system is placed in the center of round cross-section of the wire, can be written as [10 – 13]:

$$j_\varphi(r,\varphi)=I_{f0}C_\varphi\frac{I_0\left(\sqrt{-j\omega\gamma_{TS}\mu_{rTS}\mu_0}\,r\right)\left[1+G_p(r,\varphi)\right]}{\sqrt{\left(0.5\left(R_2-R_1\right)+r\cos(\varphi)\right)^2+r^2\sin^2(\varphi)}},\qquad(6)$$

where C_φ – constant value, which is determined from condition $\int j_\varphi(r,\varphi)\,r\,dr\,d\varphi=I_{f0}$; R_1, R_2 – inner and outer radii of wire; $G_p(r,\varphi)$ – proximity factor.

An example of AC Sourcing Current Density Distribution in a single wire is depicted on fig.1.

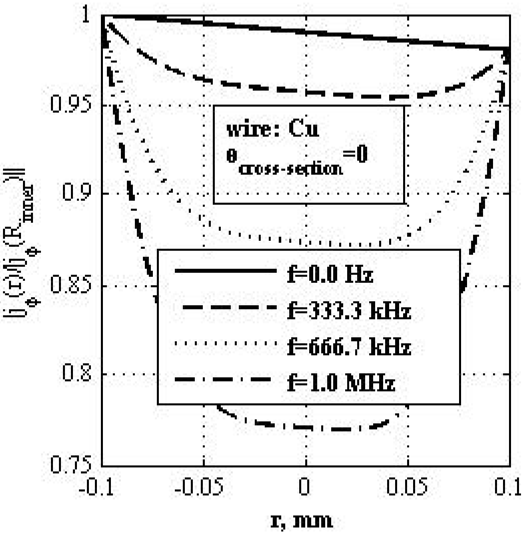

Fig. 1. Normalized Current Density Distribution in a single wire with round cross-section

Thus, we've got a function of current density distribution (6) in a round wire with round cross-section. It let to get a vector-potential of "Cylindrical Coil – cylindrical TS" system as a function of wire stuff parameters, AC sourcing current frequency and proximity effect.

3.2. Electric Parameters of Cylindrical Coil

There are three electrical parameters of coils: inductance, resistance and capacitance. Inductance of "Cylindrical Coiler –

Cylindrical TS" system can be determined due to Faradays Law, (4) and (6) as:

$$L(\omega)=\mu_0\frac{H_0(\omega)}{2l_0^2\eta}\times$$
$$\times\left[\begin{array}{l}\iint r^2 j_\varphi(r,\varphi)\,drd\varphi-\\ -\iint j_\varphi(r,\varphi)\,drd\varphi\left(\begin{array}{l}R_{TS}^2-\dfrac{2\mu_{rTS}R_{TS}}{\sqrt{-j\omega\gamma_{TS}\mu_{rTS}\mu_0}}\times\\ \times\dfrac{I_1\left(R_{TS}\sqrt{-j\omega\gamma_{TS}\mu_{rTS}\mu_0}\right)}{I_0\left(R_{TS}\sqrt{-j\omega\gamma_{TS}\mu_{rTS}\mu_0}\right)}\end{array}\right)\end{array}\right], \qquad (7)$$

Resistance of "Cylindrical Coiler – Cylindrical TS" system can be determined as:

$$R(\omega)=\frac{2\pi\sum_{i=1}^{N_w}R_{wi}}{\sigma_w S(\omega)}. \qquad (8)$$

Capacitance of "Cylindrical Coiler – Cylindrical TS" system depends on its coiler construction. If coiler is single layer its capacitance is determined by capacitance between two wires divided by a number of wires minus one and, hence, is usually small enough and can be neglected in most cases. In the case, if coiler has several layers of wires, its capacitance can be determined by capacitance between two wires multiplied by a number of wires minus one and divided by a number of layers of wires minus one. Thus, to determine the capacitance of "Cylindrical Coiler – Cylindrical TS" system, it is enough to determine capacitance between two neighbor wires and multiply it on the coefficient, which is determined by the number of wires, layers and their spatial distribution.

Capacitance of any system can be calculated from the next expression [13]:

$$\dot{C}=\frac{\dot{Q}}{\dot{U}}, \qquad (9)$$

where $\dot{Q}$ – full complex charge of the system; $\dot{U}$ – full complex voltage drop across the system. In general case (9) can be presented in complex form, designated the possibility of the system to store electric energy $\mathrm{Re}(\dot{C})$ and to dissipate it $\mathrm{Im}(\dot{C})$. Due to Gauss expression it is possible to determine full complex charge $\dot{Q}$ of the system, as [10]:

$$\dot{Q}=\varepsilon_0\oiint_S\dot{\varepsilon}(s)\,grad\,\varphi(s)\,ds-j\omega\varepsilon_0\oiint_S\dot{\varepsilon}(s)\bar{A}(s)\,d\bar{s},$$

where $\varepsilon_0=8.85\bullet10^{-12}$; $\dot{\varepsilon}(s)=\varepsilon'-j\varepsilon''$ – complex relative permittivity of the system; ε' – real relative permittivity, depict the capability of the system to store electric charge; ε'' – imaginary relative permittivity, depict the capability of the system to dissipate electric charge; s – surface, which envelop the system; $\varphi(s)$ – scalar electric potential of the system, depicts static state of the system; $\bar{A}(s)$ – electro dynamic vector potential of the system, depicts dynamic state of the system.

So, if mean value of voltage, which drops on the system, is equal to zero full complex capacitance is determined only by dynamic part of it and complex dynamic Capacitance of "Cylindrical Coiler – Cylindrical TS" system can be determined as:

$$C(\omega)+jG(\omega)=\frac{8\pi\dot{\varepsilon}_{iw}\varepsilon_0\varsigma R_w\left(dR_w+dR_{iw}\right)\omega\dot{A}\left(R_{ws},\omega\right)}{jI_0\left(R(\omega)+j\omega L(\omega)\right)}, \qquad (10)$$

where $C(\omega)$ – dynamic capacitance of the "Cylindrical Coiler – Cylindrical TS" system as a function of AC sourcing Current frequency; $G(\omega)$ – dynamic Leakance of the "Cylindrical Coiler – Cylindrical TS" system as a function of AC sourcing Current frequency

Thus, we determined all electrical parameters of coiler: inductance (7), resistance (8) and complex capacitance (10).

4. Modeling results and discussion

Consider Eddy-Current sensor as a coiler. Constructive characteristics of the coiler are: two layers of wires; inner diameter of coiler is 10 mm; number of wires is 198. To emphasis AC sourcing current frequency influence on coiler electrical parameters, it is considered a coiler without a TS..

On fig. 2 – 6 are presented dependences of electrical parameters (inductance, resistance, quality factor, capacitance and leakance) of coiler in free space as a function of AC sourcing current frequency.

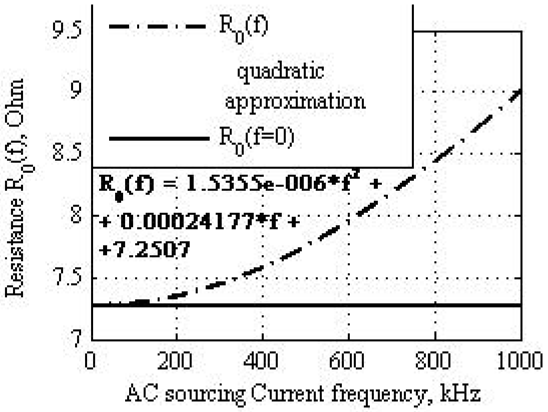

Fig. 2. Resistance of a coiler in free space as a function of AC sourcing current frequency

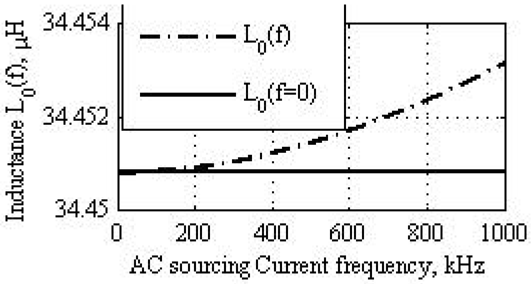

Fig. 3. Inductance of a coiler in free space as a function of AC sourcing Current frequency

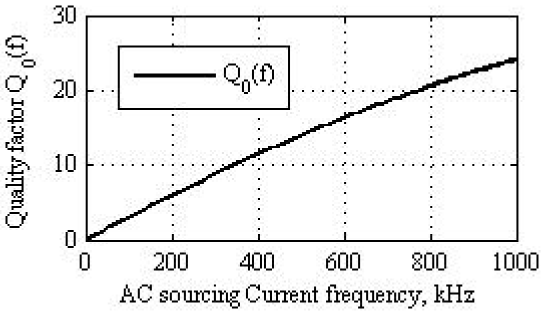

Fig. 4. Quality factor of a coiler in free space as a function of AC sourcing Current frequency

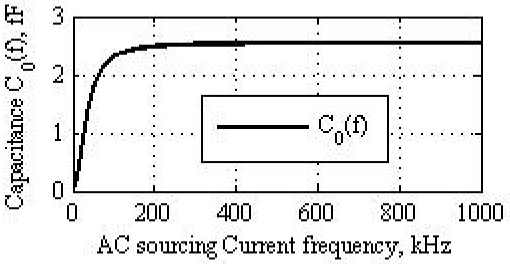

Fig. 5. Capacitance of a coiler in free space as a function of AC sourcing Current frequency

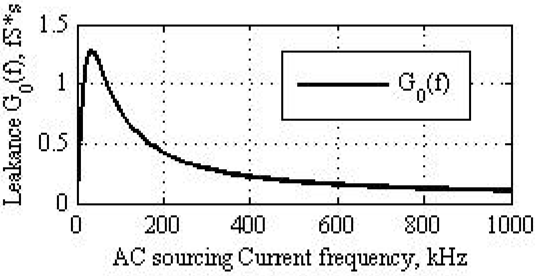

Fig. 6. Leakance of a coiler in free space as a function of AC sourcing Current frequency

So, Fig. 2 proves experimental expression for coiler resistance in free space as a function of AC sourcing Current frequency and can be presented as [14]:

$$R(f) = k_0 + k_1 f + k_2 f^2.$$

From fig. 3, it can be noticed, that AC sourcing Current frequency increasing leads to external magnetic flux of coiler increasing, due to inner magnetic flux of coiler wire increasing, and, as a result, surface AC sourcing Current of Coiler wire increasing. It is also known, that surface AC sourcing Current of Coiler wire determines external magnetic flux of Coiler, and, as a result, it leads to Coiler sensitivity on TS parameters increasing. Fig. 4 depicts the possibility of the Coiler to store magnetic energy and fig. 5 and 6 – to store and to dissipate electric energy of the coiler, accordingly.

Thus, modeling of electrical parameters of Cylindrical Coiler in free space, as a function of AC sourcing Current frequency, was carried out.

5. *Conclusion*

As a result of this paper we've got a mathematical model of "Cylindrical Coiler – Cylindrical TS" system, which let to calculate its main electrical parameters (resistance, inductance and capacitance) as a function of AC sourcing current frequency. To show AC sourcing current frequency influence on electrical parameters of the coiler, there were carried out its modeling in free space. This theoretical investigation shows the possibility of the coiler to store and to dissipate magnetic and electric energy as a function of AC sourcing current frequency. And it is important when analyzed coiler is oscillating, especially, when coiler is used in transient pulsed, as in work [4], pulsed or combined mode [6].

And, finally, it is necessary to emphasis, that TS reflected field, created by eddy-currents in TS, also influence on AC sourcing current density distribution in coiler wires and should be taken into account in future work.

6. *References*

1. *Учанин В.Н.* "Вихретоковые мультидифференциальные преобразователи и их применение," *Техническая диагностика и неразрушающий контроль.* no 3, c. 34- 41, 2006.
2. *Клюев В.В.* Неразрушающий контроль и диагностика: Справочник в 2 т. М.: Машиностроение, 2003. Т. 2: Вихретоковый контроль, с. 688, 2003.
3. *Закревський О. Ф.* "Вимірювання амплітуди механічних коливань ультразвукового частотного діапазону (Огляд)," *Електроніка та Зв'язок (ISSN 1811-4512)*, no 2(67), c. 41-50, 2012.
4. *Куц Ю.В., Лисенко Ю.Ю., Петрик В.Ф., Дугин А.Л.*, "Экспериментальное исследование вихретоковой системы контроля крупногабаритных изделий," *Научни известия на НТСМ (*ISSN 1310-3946*)*, no 2 (139), c. 72 – 74, 2013.
5. *Pinotti E. and Puppin E.* "Simple Lock-In Technique for Thickness Measurement of Metallic Plates," *IEEE Trans. Instrum. Measurement,* vol. 63, no 2, pp. 479 – 484, 2014.
6. *Vasic D., Bilas V., Ambrus D.,* "Pulsed eddy current nondestructive testing of ferromagnetic tubes," *Instrum. and Measurement Technology Conf., 2003. IMTC '03.* Proceedings of the 20th IEEE (Vol.2), pp. 1120 - 1125, 20-22 May 2003.
7. *Jozsef Pavo*, "Numerical Calculation Method for Pulsed Eddy-Current Testing," *IEEE Trans. Magn.,* vol. 38, no 2, pp. 1169 – 1172, 2002.
8. *Kumar P., Dharmasena and Haydn N., G. Wadley,* "Modeling multifrequency eddy current sensor interactions during vertical Bridgman growth of semiconductors," *Rev. Sci. Instrum.*, vol. 70, no 7, pp. 3125 – 3142, 1999.
9. *Reinhold Ludwig, Xiao-Wei Dai,* "Numerical and Analytical Modeling of Pulsed Eddy Currents in a Conducting Half-Space," *IEEE Trans. Magn.,* vol. 26, no 1, pp. 299 – 307, 1990.
10. *Пименов Ю. В., Вольман В. И., Муравцов А. Д.* Техническая электродинамика / под ред. *Ю. В. Пименова*: Учеб. Пособие для вуз. – М.: Радио и связь. 2000. – 536 с.
11. *Zakrevskyi O.F., Movchanuk A.V.* "The model of Eddy-Current Probe," *Scientific proceedings. "NDT Days 2012" (ISSN 1310-3946)*, no 1(133), pp. 252-254, 2012.
12. *Zeljko Pantic and Srdjan Lukic*, "Computationally-Efficient, Generalized Expressions for the Proximity-Effect in Multi-Layer, Multi-Turn Tubular Coils for Wireless Power Transfer Systems," *IEEE Trans. Magn.*, vol. 49, no. 11, pp. 5404-5416, Nov. 2013.
13. *Зернов Н. В.* Теория радиотехнических цепей. / Зернов Н. В., Карпов В. Г. //. Издание 2-е, переработ. и доп., – Л., «Энергия», 1972. – 816 с.
14. *Jakub Kral, RadislavSmid, Helena Maria Geirinhas Ramos, A. Lopes Ribeiro*, "The Lift-Off Effect in Eddy Currents on Thickness Modeling and Measurement," *IEEE Trans. Instrum.Measurement,* vol. 62, no7, pp. 2043 – 2049, 2013.