

NEW CALCULUS METHOD OF THE PLANE-SPIRAL COILS SELF INDUCTANCE FOR HIGH ENERGY RATE FORMING

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ABSTRACT

The paper deals with the self-inductance calculus of the plane-spiral coils made by rectangular-section conductor, which equip the installations for plastic strain in electromagnetic field.

KEYWORDS: self-inductance, plane-spiral coil, rectangular conductor, plastic strain.

1. INTRODUCTION

The plastic strain in electromagnetic field is one of the electrotechnological procedures that are denominated as "high energy strain" or "high energy rate forming".

The method's principle is discharge of a condenser battery (charged in a previous phase) through a coil and the processed piece can be placed inner or outer of this coil. In the case of the cylindrical coils there are enough precise relation for the inductance calculation.

In order to form metallic pieces with plane and thin walls, in the last years the plane coils are preferred. These can have various shapes but the most used are the plane-spiral coils. Knowing the coil inductance value is very important because it determines the values of the maxim discharge current, the discharge oscillation frequency, the maxim magnetic field intensity, the developed electromagnetic forces, so it controls practically the forming regime.

In the literature, the inductance calculus of the plane-spiral coils is not enough developed. There are some relations for plate coils in the particular case when the field lines close only through air [2]. But, for the plastic strain in electromagnetic field, the plane coils are laid on the processed piece characterised by the magnetic permeability $\mu > \mu_0$. Moreover, for the coils stiffening, these are included in an organic or inorganic resistant material, which has the electromagnetic proprieties different from the air.

The paper [1] deals with self-inductance calculus of the plane-spiral coils made by circular cross-section conductor. In practice, the plane-spiral coils made by rectangular cross-section conductor seems to be preferred. The advantages come from the technological simplicity, the large typodimensional range and the increased "lying" surface of the coil.

2. THE SELF-INDUCTANCE CALCULATION FOR THE PLANE COILS MADE BY RECTANGULAR CROSS-SECTION CONDUCTOR

One considers a plane-spiral coil with circular shape (Fig. 2), having n turns and the exterior radius R_1 , made by rectangular cross-section conductor and placed in the environment with the magnetic permeability μ_0 .

The ideal coil shape respect the *Archimedian spiral*.

The two dimensions of the cross-section are noted with b and c (Fig. 1).

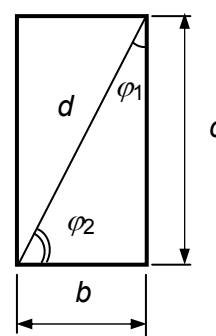


Fig. 1. The conductor cross-section.

Similar to the previous studied case [1], we consider that two half-turns with different curvatures composes every turn, and so the plane-spiral shape involves the same condition for the constant distance between the turns m (Fig. 2):

$$b < m \leq \frac{R_1}{n} \quad (1)$$

In the particular case $m = R_1/n$, one end of the n turns is exactly in the centre of the centre of the circle of radius R_1 .

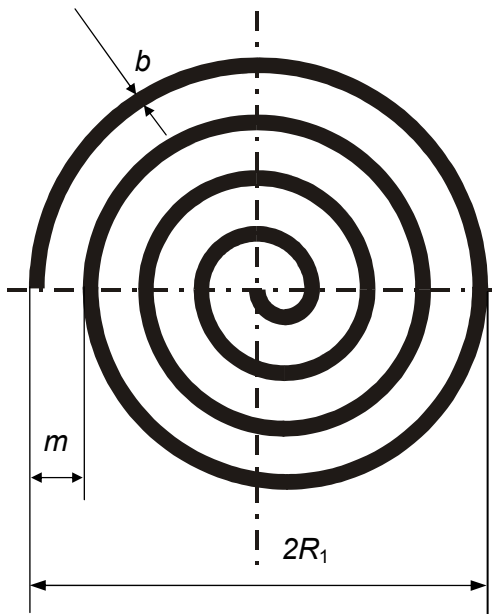


Fig. 2. Coil shape

Also, let note with R_i and R'_i the different two radius of the two half-turns that compose the turn i (Fig. 3).

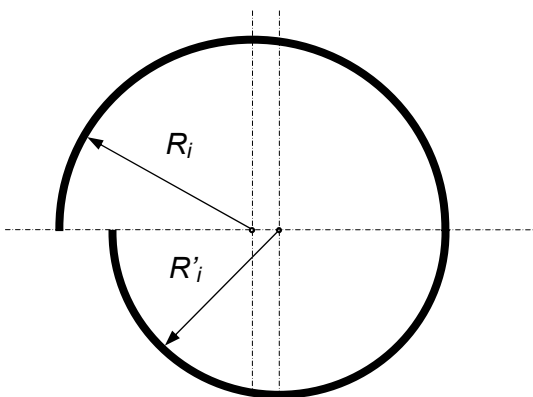


Fig. 3. The different radius for the two half-turns

In [1] is shown that the distance between the centres of the two half-turns is $m/2$ and the following relations are respected:

$$R_i = R_1 - (i - 1) \cdot m \quad (2)$$

$$R'_i = R_1 - \frac{2 \cdot i - 1}{2} \cdot m \quad (3)$$

where R_1 is the largest half-turn radius. Taking into account the influences of the high operation frequency ranged between 10 and 25 kHz, we have established the expression of the inductance of one half-turn having the radius R and built by rectangular cross-section conductor:

$$L = \frac{\mu_0 R}{2} \left[\ln \frac{8R}{g} - 2 \right] \quad (4)$$

In (4), g represents the proper medium geometrical distance of the conductor cross-section perimeter, which can be calculated with [2]:

$$\ln g = \frac{b^2 \cdot \ln b + c^2 \cdot \ln c + 2bc \cdot \ln d}{(b + c)^2} + \frac{c \cdot \varphi_1 + b \cdot \varphi_2}{b + c} - \frac{3}{2} \quad (5)$$

where the variables b , c , d , φ_1 and φ_2 are defined in figure 1.

The effect superposition principle can be applied again, so the coil self inductance is:

$$L = \sum_{i=1}^n L_i + \sum_{i=1}^n L'_i + \sum_{k=1}^n \sum_{i=1}^n M_{ki} + \sum_{k=1}^n \sum_{i=1}^n M'_{ki} + \sum_{k=1}^n \sum_{i=1}^n M''_{ki} \quad (6)$$

where the sum of the self-inductances of the upper half-turns is:

$$\sum_{i=1}^n L_i = \sum_{i=1}^n \frac{\mu_0 R_i}{2} \left(\ln \frac{8R_i}{g} - 2 \right) = \mu_0 \cdot n \cdot \left(\frac{n-1}{2} m - R_1 \right) + \quad (7)$$

$$+ \frac{\mu_0}{2} \sum_{i=1}^n [R_1 - (i-1)m] \cdot \ln \frac{8[R_1 - (i-1)m]}{g}$$

and the sum of the self-inductances of the lower half-turns is:

$$\begin{aligned} \sum_{i=1}^n L'_i &= \sum_{i=1}^n \frac{\mu_0 R'_i}{2} \left(\ln \frac{8R'_i}{g} - 2 \right) = \\ &= \mu_0 \cdot n \cdot \left(\frac{n}{2} m - R_1 \right) + \\ &+ \frac{\mu_0}{4} \sum_{i=1}^n [2R_1 - (2i - 1)m] \cdot \ln \frac{4}{g} [2R_1 - (2i - 1)m] \end{aligned} \quad (8)$$

The other terms in the second member of (6) can be calculated with the relation (9), where R_k and R_i ($1 \leq k, i \leq n, k \neq i$) are given in (2), relation (10), where R'_k and R'_i ($1 \leq k, i \leq n, k \neq i$) are given in (3), relation (11), $1 \leq k, i \leq n$, including $k = i$, and represent successive the sum of the mutual inductances of the upper half-turns ($k \neq i$), the sum of the mutual inductances of the lower half-turns ($k \neq i$) and the sum of the mutual inductances between the upper and lower half-turns.

$$M_{ki} = \frac{\mu_0}{4\pi} \int_0^\pi d\theta_k \int_0^\pi \frac{R_k R_i \cos(\theta_k - \theta_i) d\theta_i}{\sqrt{(R_k \cdot \cos \theta_k - R_i \cdot \cos \theta_i)^2 + (R_k \cdot \sin \theta_k - R_i \cdot \sin \theta_i)^2}} \quad (9)$$

$$M'_{ki} = \frac{\mu_0}{4\pi} \int_0^\pi d\theta_k \int_0^\pi \frac{R'_k R'_i \cos(\theta_k - \theta_i) d\theta_i}{\sqrt{(R'_k \cdot \cos \theta_k - R'_i \cdot \cos \theta_i)^2 + (R'_k \cdot \sin \theta_k - R'_i \cdot \sin \theta_i)^2}} \quad (10)$$

$$M''_{ki} = -\frac{\mu_0}{4\pi} \int_0^\pi d\theta_k \int_0^\pi \frac{R_k R'_i \cos(\theta_k - \theta_i) d\theta_i}{\sqrt{\left(R_k \cdot \cos \theta_k + \frac{m}{2} + R'_i \cdot \cos \theta_i \right)^2 + (R_k \cdot \sin \theta_k + R'_i \cdot \sin \theta_i)^2}} \quad (11)$$

Thus, all the terms in (6) are specified. The integration of (6) can be easier performed by numerical integration.

If the plane-spiral coil is placed on the plane surface of a body with the magnetic permeability μ_b the inductance value becomes [2]:

$$L_b = L \frac{2\mu_b}{\mu_0 + \mu_b} \quad (12)$$

In the case of the high-energy-rate forming process the last relation must be applied only if the piece wall is thick and the magnetic saturation is not achieved during the process.

3. EXPERIMENTAL VALIDATION

A number of four plane-spiral coils were built using rectangular cross-section conductor (1,2 x 10,1) mm² and having different number of turns, $n = 3, 5, 7$ and 9 . All the coils are built with an identical exterior half-turn radius $R_1 = 0,039$ m.

Table 1 presents the measured and calculated values of the coils inductances, as well as the percentage differences between these. A numerical program built in Mathcad was used to perform the integration of (6), supposing an operating frequency $f = 10$ kHz and the magnetic permeability of the stiffening environment $\mu = \mu_0$.

Table 1 Experimental results

Coil number	Conductor	Turn number	Measured value	Calculated value	Error %
1	Rectangular	3	0.33 μ H	0.31 μ H	6
2	Rectangular	5	0.73 μ H	0.73 μ H	0
3	Rectangular	7	1.37 μ H	1.38 μ H	0.7
4	Rectangular	9	2.18 μ H	2.22 μ H	2

4. THE PARAMETERS INFLUENCE ON THE INDUCTANCE VALUE

The inductance value of the plane-spiral coil depends on the turn number, the exterior radius and the conductor cross-section dimensions. A graphical representation of these dependencies is exemplified in Fig. 3. These diagrams can be used to a quickly determination of the necessary parameters for a desired value of the coil inductance.

For example, in Fig. 3 the inductance values of the plane-spiral coil with $r = 0.0025$ m are given. The variable parameters are the turn number (comprised between 3 and 9) and the external radius (I – $R_1=0.08$ m; II – $R_1 = 0.07$ m; III – $R_1 = 0.06$ m, IV – $R_1 = 0.05$ m; V – $R_1 = 0.04$ m). So, if we need to build an inductance with $L = 2$ μ H, we can choose the number of turns $n = 7$ and the exterior radius $R_1 = 0.05$ m.

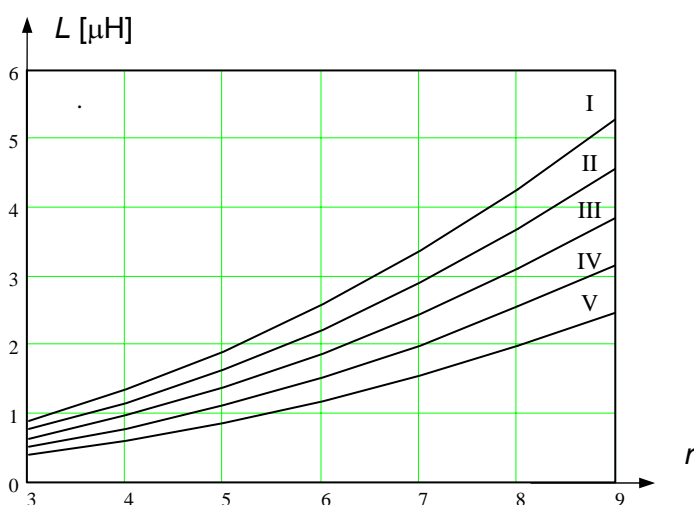


Fig. 3. The inductance dependence on turn number and exterior radius.

5. CONCLUSION

The proposed calculation method is special adapted for the self-inductance value calculation of the plane-spiral coils built with rectangular cross-section conductor, at a higher operation frequency. The experimental precision measurements show very low calculation errors.

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