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The Second Structure of Constant Current

Annotation

Here we explore the structure of DC and the flow of electromagnetic energy in a wire. We show that the flow of electromagnetic energy is spreading inside the wire along a spiral. For a constant current value the density of spiral trajectory decreases with decreasing remaining load resistivity.

Contents

1. Introduction

In [1-3] was shown that DC in the wire has a complex structure, and the flow of electromagnetic energy is spreading inside the wire. Also the electromagnetic flow

- directed along the wire axis,
- spreads along the wire axis,
- spreads inside the wire,
- compensates the heat losses of the axis component of the current.

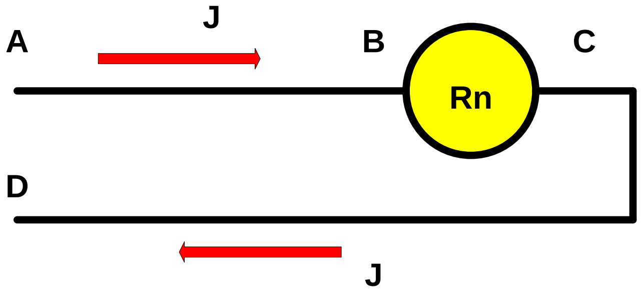

Fig. 1.

In [1-3] a mathematical model of the current and the flow has been. The model was built exclusively on base of Maxwell equations. Only one question remained unclear. The electric current **J** ток and the flow of electromagnetic energy **S** are spreading inside the wire **ABCD** and it is passing through the load **Rn**. In this load a certain amount of strength P is spent. Therefore the energy flow on the segment **AB** should be larger than the energy flow on the segment **CD**. More accurate, **Sab=Scd+P.** But the current strength after passing the load did not change. сила тока после прохождения нагрузки не изменилась. How must the current structure change so that ehe electromagnetic energy decreased correspondingly?

Below we shall consider a mathematical model more general than the model (compared to [1-3]) and allowing to clear also this question. This mathematical model is also built solely on the base of Maxwell equations. In [4] describes an experiment which was carried out in 2008. In [5] it is shown that this experiment can be explained on the basis of non-linear structure of constant current in the wire and can serve as an experimental proof of the existence of such a structure.

2. Mathematical Model

In building this model we shall be using the cylindrical coordinates $r, \ \varphi, \ z$ considering

- the main current J_o,
- the additional currents $J_r, \ J_\varphi, \ J_z$,
- magnetic intensities $H_r, \ H_\varphi, \ H_z$,
- electrical intensities E,
- electrical resistivity ρ.

The current in the wire is usually considered as average electrons flow. The mechanical interactions of electrons with the atoms are considered equivalent to electrical resistivity. Evidently,

$$E = \rho \cdot J \ . \tag{1}$$

The main current of density J_o creates additional currents with densities $J_r, \ J_\varphi, \ J_z$ and magnetic fields with intensities $H_r, \ H_\varphi, \ H_z$. They must satisfy the Maxwell equations. These equations for magnetic intensities and currents in a stationary magnetic field are as follows;

$$\operatorname{div}(H) = 0 , \tag{2}$$

$$\operatorname{rot}(\mathrm{H}) = J , \tag{3}$$

Besides that, the currents must satisfy the continuity condition

$$\mathrm{div}(J) = 0. \tag{4}$$

The equations (2-4) for cylindrical coordinates have the following form:

$$\frac{H_r}{r} + \frac{\partial H_r}{\partial r} + \frac{1}{r} \cdot \frac{\partial H_\varphi}{\partial \varphi} + \frac{\partial H_z}{\partial z} = 0, \tag{5}$$

$$\frac{1}{r} \cdot \frac{\partial H_z}{\partial \varphi} - \frac{\partial H_\varphi}{\partial z} = J_r, \tag{6}$$

$$\frac{\partial H_r}{\partial z} - \frac{\partial H_z}{\partial r} = J_\varphi, \tag{7}$$

$$\frac{H_\varphi}{r} + \frac{\partial H_\varphi}{\partial r} - \frac{1}{r} \cdot \frac{\partial H_r}{\partial \varphi} = J_z + J_o, \tag{8}$$

$$\frac{J_r}{r} + \frac{\partial J_r}{\partial r} + \frac{1}{r} \cdot \frac{\partial J_\varphi}{\partial \varphi} + \frac{\partial J_z}{\partial z} = 0. \tag{9}$$

For the sake of brevity further we shall use the following notations:

$$co = -\cos(\alpha\varphi + \chi z), \tag{10}$$

$$si = \sin(\alpha\varphi + \chi z), \tag{11}$$

where $\alpha, \ \chi$ – are certain constants. In the Appendix 1 it is shown that there exists a solution of the following form:

$$J_r. = j_r(r) co, \tag{12}$$

$$J_\varphi. = j_\varphi(r) si, \tag{13}$$

$$J_z. = j_z(r) si, \tag{14}$$

$$H_r. = h_r(r) co, \tag{15}$$

$$H_\varphi. = h_\varphi(r) si + J_o r/2, \tag{16}$$

$$H_z. = h_z(r) si, \tag{17}$$

where $j(r), \ h(r)$ - certain function of the coordinate r.

It can be assumed that the average speed of electrical charges doesn't depend on the current direction. In particular, for a fixed radius the way passed by the charge around a circle and the way passed by it along a vertical will be equal. Consequently, for a fixed radius it can be assumed that $\Delta\varphi \equiv \Delta z$. Based on this assumption we can build the trajectory of the charge motion according to the functions (10, 11).

The figure 2 shows three spiral lines for $\Delta\varphi = \Delta z$, described by functions (10, 11) of the current: the thick line for $\alpha = 2, \ \chi = 0.8$, the average line for $\alpha = 0.5, \ \chi = 2$ and a thin line for линия $\alpha = 2, \ \chi = 1.6$.

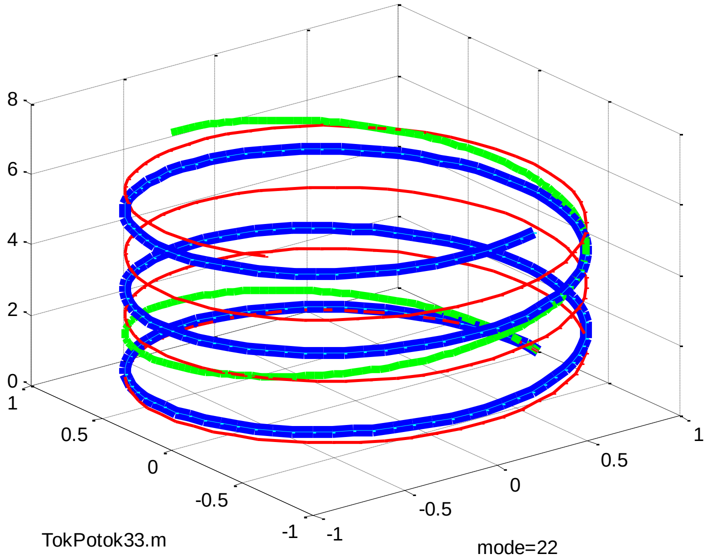

Рис. 2.

In Appendix 1 it is shown that the functions satisfy the following equations:

$$h_z(r) \equiv 0, \tag{20}$$

$$\frac{h_r(r)}{r} + h_r'(r) + \frac{h_\varphi(r)}{r}\alpha = 0, \tag{21}$$

$$-h_\varphi(r)\chi = j_r(r), \tag{22}$$

$$-h_r(r)\chi = j_\varphi(r), \tag{23}$$

$$\frac{h_\varphi(r)}{r} + h_\varphi'(r) + \frac{1}{r}\cdot h_r(r)\alpha = j_z(r). \tag{24}$$

This equations system is underdetermined – there are 4 equations (21-24) for 5 variables j_r, j_φ, j_z, h_r, h_φ. It is important to note that $h_z(r) \equiv 0$. If one of the variables is known, then the remaining ones are determined by differentiating this equations system. For example, for a known function $h_\varphi(r)$ we can find:

$$h_r'(r) = -\frac{h_r(r)}{r} - \frac{h_\varphi(r)}{r}\alpha, \tag{25}$$

$$j_r(r) = -h_\varphi(r)\chi, \tag{26}$$

$$j_\varphi(r) = -h_r(r)\chi,, \tag{27}$$

$$j_z(r) = \frac{h_\varphi(r)}{r} + h'_\varphi(r) + \frac{1}{r} \cdot h_r(r)\alpha.. \qquad (28)$$

Example 1. Let, for example, be $h_\varphi(r) = 10 \cdot \left(e^{11000r} - 1\right)$. Fig. 3 shows the graphs of functions $j_r(r),\ j_\varphi(r),\ j_z(r),\ h_r(r),\ h_\varphi(r),\ h_z(r)$. These functions are calculated for $\alpha = 0.1,\ \chi = -4 \cdot 10^{11}$, the wire radius $R = 0.001$ and initial condition $j_r(0) = 0$. The first column shows the functions $j_r(r),\ j_\varphi(r),\ j_z(r)$, the second column shows functions $h_r(r),\ h_\varphi(r),\ h_z(r)$, and the functions shown in the third column will be considered further. Here and further all numerical data is shown in CI system. The x-axis shows the values $(1000r)$.

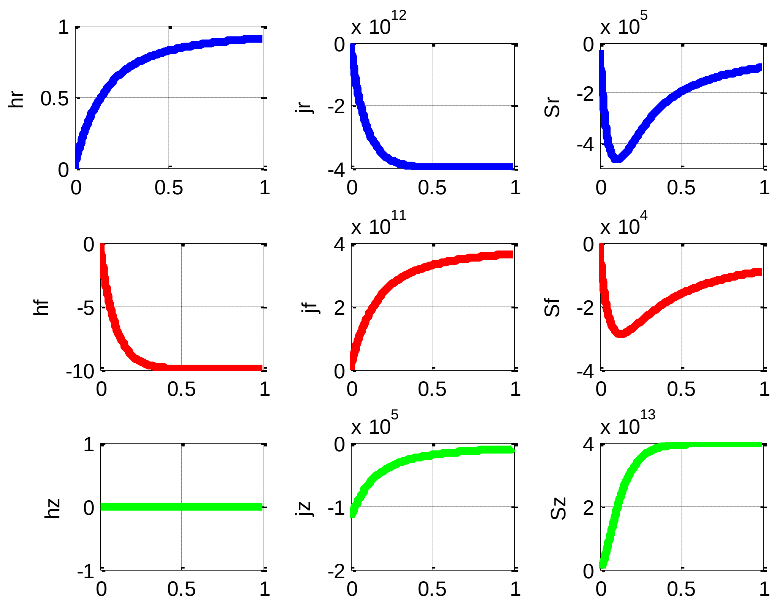

Fig.3. TokPotok33.m, mode=41

Example 2. Beside a solid wire we can consider also a **tubular conductor.** In this example $h_\varphi(r) = 10 \cdot \left(e^{11000r} - 1\right)$. Fig. 4 shows the graphs of functions $j_r(r),\ j_\varphi(r),\ j_z(r),\ h_r(r),\ h_\varphi(r),\ h_z(r)$. These functions are calculated for $\alpha = 0.1,\ \chi = -4 \cdot 10^{11}$. The main difference is in the fact that the region of integration is limited: $R_1 \le r \le R$, while $R = 0.005,\ R_1 = 0.2 \cdot R$, and the initial condition is $j_r(R_1) = 0$.

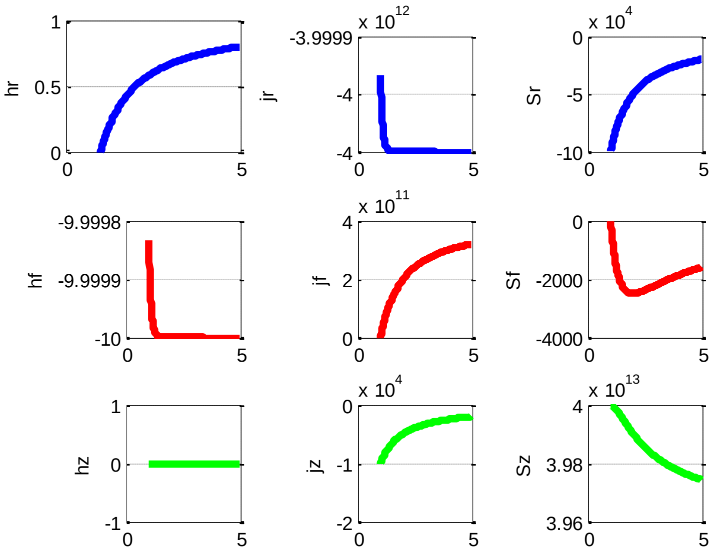

Fig.4. TokPotok33.m, mode=3

3. Energy Flows

The density of electromagnetic flow is Pointing vector

$$S = E \times H . \tag{1}$$

The currents are being corresponded by eponymous electrical intensities, i.e.

$$E = \rho \cdot J , \tag{2}$$

where ρ is electrical resistivity. Combining (1, 2), we get:

$$S = \rho J \times H . \tag{3}$$

In cylindrical coordinates $r, \ \varphi, \ z$ the density flow of electromagnetic energy has three components $S_r, \ S_\varphi, \ S_z$, directed along вдоль the axis accordingly. They are determined by the formula

$$S = \rho (J \times H) = \rho \begin{bmatrix} J_\varphi H_z - J_z H_\varphi \\ J_z H_r - J_r H_z \\ J_r H_\varphi - J_\varphi H_r \end{bmatrix} . \tag{4}$$

From (2.12-2.17, 3.4) it follows that

$$S = \begin{bmatrix} S_r \\ S_\varphi \\ S_z \end{bmatrix} = \rho \iiint_{r,\varphi,z} \begin{bmatrix} (j_\varphi h_z - j_z h_\varphi) \cdot si^2 \\ (j_z h_r - j_r h_z) \cdot si \cdot co \\ (j_r h_\varphi - j_\varphi h_r) \cdot si \cdot co \end{bmatrix} dr \cdot d\varphi \cdot dz . \tag{5}$$

Fig. 3 and Fig. 4 shows the functions

$$\overline{S}(r)=\begin{bmatrix}\overline{S_r}(r)\\ \overline{S_\varphi}(r)\\ \overline{S_z}(r)\end{bmatrix}=\begin{bmatrix}\left(j_\varphi h_z - j_z h_\varphi\right)\\ \left(j_z h_r - j_r h_z\right)\\ \left(j_r h_\varphi - j_\varphi h_r\right)\end{bmatrix}. \tag{6}$$

From (4), as is shown in Appendix 2, it follows that

$$S_z = \frac{\rho}{4\alpha}\cdot\left(1-\cos(4\alpha\pi)\right)\int_r \left(\overline{S_z}(r)\cdot dr\right). \tag{7}$$

$$S_\varphi = \frac{\rho}{4\alpha}\cdot\left(1-\cos(4\alpha\pi)\right)\int_r \left(\overline{S_\varphi}(r)\cdot dr\right), \tag{8}$$

$$S_r = \pi\rho\int_r \left(\overline{S_r}(r)\cdot dr\right). \tag{9}$$

This values is independent of $t,\ \varphi,\ z$ and this corresponds to the law of conservation of energy.

The full energy flow is equal to power P, transmitted by the wire, i.e.

$$\overline{\overline{S}} = P, \tag{10}$$

where

$$P = R_H\int_r\left(\int_\varphi J_o^2 d\varphi\right)dr = 4\pi R^2 R_H J_o^2, \tag{11}$$

where R_H is the load resistivity.

Example 3. For the conditions of Example 1 and special resistivity of copper wire $\rho = 0.0175\cdot 10^{-6}$ further we find the value of energy flow for $\overline{S_z}\approx 1000$. The power $P\approx 1000$ equal to this value is consumed in the resistivity $R_H\approx 110$ for main current density $J_o = 10^6$. It is important to note that the energy flow along the wire significantly exceeds the energy flows by the radius and by the circle. In our example $\overline{S_z}=1000,\ \overline{S_r}=-10^{-5},\ \overline{S_\varphi}=-5\cdot 10^{-7}$.

Example 4.

In the conditions of Example 3 we shall now change one of the values $\alpha,\ \chi$, leaving the other one unchanged. Table 1 shows the values of $\alpha,\ \chi$ and the power P, and Fig. 5 shows the corresponding graphs.

Table 1.

Variant	$\alpha/0.1\,\alpha$	$\chi/-4\cdot10^{11}$	P
41	1	1	1000
43	1	0.8	830
44	1	1.2	1240
45	1.5	1	1300
46	0.5	1	580

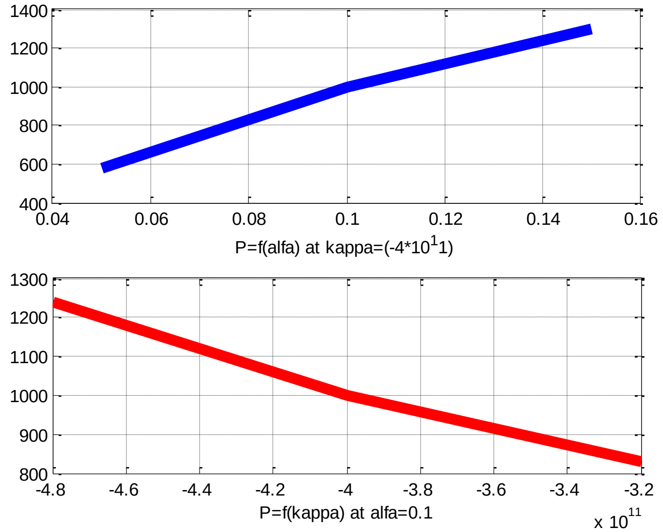

Fig. 5.

4. Discussion

Thus, the energy flow along the wire's axis S_z is created by the currents and intensities directed along the radius and the circles. This energy flow is equal to the power released in the load R_H and in the wire resistance. The currents flowing along the radius and the circle are also creating heat losses. Their powers are equal to the energy flows S_r, S_φ, directed along radius and circle.

The question of the way by in which the electromagnetic energy creates current is considered in [8]. There it is shown that there exists a fourth electromagnetic induction created by a change in electromagnetic energy flow. Further we must find the dependence of emf of this induction from the electromagnetic flow density and from the wire parameters.

It is shown that direct current has a complex structure and extends inside the wire along a spiral. In the case of constant current the density of spiral trajectory decreases with the decrease of the remaining load resistance. There are two components of the current. The density of the first component J_o is permanent of the whole wire section. The density of the second component is changing along the wire section so that the current is spreading n a spiral. In cylindrical coordinates r, φ, z this second component has coordinates J_r, J_φ, J_z. They can be found as the solution of Maxwell equations.

There is a known experiment which can serve as an experimental proof of this structure of direct current.

With invariable density of the main current in a wire the power transmitted by it depends on the structure parameters (α, χ) which influence the density of the turns of spiral trajectory. Thus, the same current in a wire can transmit various values of power (depending on the load).

Let us again look at the Fig 1. On segment **AB** the wire transmits the load energy **P.** It is corresponded by a certain values of (α, χ) and the density of coils of the current's spiral path. On the segment **CD** the wire transmits only small amount of energy. It corresponds to small value of χ and small density of the coils of current's spiral path.

Naturally, the resistivity of the wire itself is also a load. Thus, as the current flows within the wire, the spiral of the current's path straightens.

The dependence of current density and intensity density was considered in detail in [2]. Generally, the mathematical model presented in [2] may be considered as a consequence of the described model for $\chi \to 0$.

Thus, it is shown that there exists such a solution of Maxwell equations for a wire with constant current which corresponds to the idea of

- law of energy preservation
- spiral path of constant current in the wire,
- energy transmission along and inside the wire,
- the dependence of spiral path density on the transmitted strength.

Appendix 1

Let us consider the solution of equations (2.5-2.9) in the form of (2.12-2.17). Further the derivatives of r will be designated by strokes.

We rewrite the equations (2.5-2.9) in the form

$$\frac{j_r(r)}{r}+j_r'(r)+\frac{j_\varphi(r)}{r}\alpha+\chi\cdot j_z(r)=0, \quad (1)$$

$$\frac{h_r(r)}{r}+h_r'(r)+\frac{h_\varphi(r)}{r}\alpha+\chi\cdot h_z(r)=0, \quad (2)$$

$$\frac{1}{r}\cdot h_z(r)\alpha-h_\varphi(r)\chi=j_r(r), \quad (3)$$

$$-h_r(r)\chi-h_z'(r)=j_\varphi(r), \quad (4)$$

$$\frac{h_\varphi(r)}{r}+h_\varphi'(r)+\frac{h_r(r)}{r}\cdot\alpha-j_z(r)=0, \quad (5)$$

We multiply (5) to $(-\chi)$. Then we get:

$$-\frac{\chi\cdot h_\varphi(r)}{r}-\chi\cdot h_\varphi'(r)-\frac{\chi\cdot h_r(r)}{r}\cdot\alpha+\chi\cdot j_z(r)=0, \quad (6)$$

Comparing (1) and (6), we see that they are the same, if

$$-h_\varphi(r)\chi=j_r(r), \quad (7)$$

$$-h_r(r)\chi=j_\varphi(r). \quad (8)$$

It is important to note that this comparison is valid only for $j_z(r)\neq 0$. Equations (7, 8) coincide with (3, 4) for $h_z(r)=0$. Consequently, if $j_z(r)\neq 0$ and $h_z(r)=0$ equation (1) can be eliminated and the system (1-5) is simplified and takes the form

$$\frac{h_r(r)}{r}+h_r'(r)+\frac{h_\varphi(r)}{r}\alpha=0, \quad (9)$$

$$-h_\varphi(r)\chi=j_r(r), \quad (10)$$

$$-h_r(r)\chi=j_\varphi(r), \quad (11)$$

$$\frac{h_\varphi(r)}{r}+h_\varphi'(r)+\frac{1}{r}\cdot h_r(r)\alpha=j_z(r). \quad (12)$$

Now consider the case when $j_z(r)=0$. In this initial system will take the form:

$$\frac{j_r(r)}{r}+j_r'(r)+\frac{j_\varphi(r)}{r}\alpha=0, \quad (13)$$

$$\frac{h_r(r)}{r}+h_r'(r)+\frac{h_\varphi(r)}{r}\alpha+\chi\cdot h_z(r)=0, \quad (14)$$

$$\frac{1}{r}\cdot h_z(r)\alpha-h_\varphi(r)\chi=j_r(r), \quad (15)$$

$$-h_r(r)\chi-h_z'(r)=j_\varphi(r), \quad (16)$$

$$\frac{h_\varphi(r)}{r} + h'_\varphi(r) + \frac{1}{r}\cdot h_r(r)\alpha = 0. \qquad (17)$$

Substituting (15, 16) in (13). Then we get:

$$\frac{1}{r^2}\cdot h_z(r)\alpha - \frac{1}{r}\cdot h_\varphi(r)\chi + \frac{1}{r}\cdot h'_z(r)\alpha - h'_\varphi(r)\chi - \left(h_r(r)\chi + h'_z(r)\right)\frac{\alpha}{r} = 0$$

or

$$\frac{1}{r^2}\cdot h_z(r)\alpha - \frac{1}{r}\cdot h_\varphi(r)\chi - h'_\varphi(r)\chi - h_r(r)\frac{\chi\alpha}{r} = 0 \qquad (18)$$

Thus to calculate the three intensities obtain three equations (14, 17, 18). We exclude $h'_\varphi(r)$ from the (17, 18):

$$\frac{1}{r^2}\cdot h_z(r)\alpha - \frac{1}{r}\cdot h_\varphi(r)\chi + \left(\frac{1}{r}\cdot h_\varphi(r) + h_r(r)\frac{\alpha}{r}\right)\chi - h_r(r)\frac{\chi\alpha}{r} = 0$$

or $\frac{1}{r^2}\cdot h_z(r)\alpha = 0$.

Thus, and when $j_z(r) = 0$ must comply with conditions $h_z(r) = 0$. Thus, the system of equations (9-12) is executed for any $j_z(r)$.

Appendix 2.

In section 3 shows that the total energy flux passing in wire cross-section,

$$S = \begin{bmatrix} S_r \\ S_\varphi \\ S_z \end{bmatrix} = \rho \iiint_{r,\varphi,z} \begin{bmatrix} \overline{S_r}(r)\cdot si^2 \\ \overline{S_\varphi}(r)\cdot si\cdot co \\ \overline{S_z}(r)\cdot si\cdot co \end{bmatrix} dr\cdot d\varphi\cdot dz. \qquad (1)$$

In the point z = 0 of axis OZ, taking into account (2.10, 2.11), we have:

$$S = \begin{bmatrix} S_r \\ S_\varphi \\ S_z \end{bmatrix} = \rho \iint_{r,\varphi} \begin{bmatrix} \overline{S_r}(r)\cdot \sin^2(\alpha\varphi) \\ \overline{S_\varphi}(r)\cdot(-\sin(\alpha\varphi)\cdot\cos(\alpha\varphi)) \\ \overline{S_z}(r)\cdot(-\sin(\alpha\varphi)\cdot\cos(\alpha\varphi)) \end{bmatrix} dr\cdot d\varphi. \qquad (2)$$

Let us first consider the flow

$$S_z = \rho \iint_{r,\varphi} \left(\overline{S_z}(r)\cdot(-\sin(\alpha\varphi)\cdot\cos(\alpha\varphi))dr\cdot d\varphi\right) \qquad (3)$$

or

$$S_z = -\frac{\rho}{2}\int_r \left(\overline{S_z}(r)\cdot\left(\int_\varphi \sin(2\alpha\varphi)\cdot d\varphi\right)dr\right) \qquad (\mathbf{4})$$

or

$$S_z = \frac{\rho}{4\alpha} \cdot (1 - \cos(4\alpha\pi)) \int_r \left(\overline{S_z}(r) \cdot dr \right). \qquad (5)$$

Similarly,

$$S_\varphi = \frac{\rho}{4\alpha} \cdot (1 - \cos(4\alpha\pi)) \int_r \left(\overline{S_\varphi}(r) \cdot dr \right), \qquad (6)$$

$$S_r = \pi\rho \int_r \left(\overline{S_r}(r) \cdot dr \right). \qquad (7)$$

Obviously, for any choice of the point $z = 0$ on the axis oz last relation is maintained.

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