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Unclosed Foucault Currents in Dynamics of Aerospace Electromagnetic Thruster

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Abstract *The main part of a thruster is an unclosed conductor in which an alternating Foucault electric current flows, created by an alternating field source. The average self-force with which the unclosed conductor acts on itself is compensated by the hidden Abraham force acting on the displacement currents that arise between the ends of the open conductor. The average value of other forces acting in the system is equal to zero and does not compensate for the self-action force. The average value of the force acting on the system is proportional to the square of the current strength and the square of the frequency of current change in the source of an alternating magnetic field*.

Key Word: Self*-force, Displacement Current, Abraham Force, Foucault Current, Alternative Current*

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I. Introduction

A conventional jet engine with a mass loss of the working substance is by no means the most efficient and suitable thruster for movement in empty space. That is why attempts to theoretically predict and experimentally discover other ways of non-reactive propulsion do not stop [1]. Some of them are contrary to the laws of physics, others are ineffective. The well-known electrodynamic effect, noted by Richard Feynman [2], turned out to be neglected. Vacuum polarization as a support for such motion [3] has not been experimentally discovered. Moreover, this effect is described electrodynamically [4] and experimentally confirmed [5]. A charged cylindrical capacitor, located in a magnetic field, turns out to be able to rotate, repelled by an electromagnetic field. We are more interested in the possibility of infinite rather than rotational motion. An electromagnetic field has not only mass, but also momentum [6]. Therefore, the so-called hidden force can be attributed to a variable magnetic field [7], with which one or another system that creates an alternating field acts on an electromagnetic field. Experimentally, such a force has been measured [8], but, unfortunately, it has not been theoretically explained even on the basis of considering the simplest model of such a thruster. The calculation of a system with an electromagnet inside which there is a massive conductor subjected to the action of Foucault currents [8] is not an easy problem. It is necessary to consider a real system that, on the one hand, would correspond to the electromagnetic motion of the system in empty space, and, on the other hand, would be accurately calculated. Any unreasonable hypotheses and assumptions in solving this problem are not allowed.

II. Abraham Force

The thruster must contain an unclosed conductor *L*, on which the electromagnetic field acts Fig. **1**. It is this force that makes such a mover to be real. This force is experimentally found and satisfies the law of conservation of momentum, according to which the sum of all forces acting in a closed system must be strictly equal to zero. The alternating current in the conductor creates a circular conductor *W* with alternating current, which plays the role of a simple electromagnet. The axes of the source of the magnetic field and the conductor coincide. This means that the current in the conductor is a Foucault current. Of course, this current is not closed; it is closed by displacement currents [9] arising between ends *C* and *S* of the conductor. At points where the total electric current suffers a break, there is an accumulation of charge, the displacement current is equal to the rate of change of the magnetic field induction $\partial\mathbf{D}/\partial t$ [9,10]. The electric field of the charge accumulated at the point is described by the Coulomb field, therefore, in accordance with the condition of continuity of the total current, the displacement current density created by the conductor at point *P* must be described as

$$\frac{\partial\mathbf{D}}{\partial t} = \frac{J}{4\pi}\left(\frac{\mathbf{r}_+}{r_+^3} - \frac{\mathbf{r}_-}{r_-^3}\right), \tag{1}$$

where $\mathbf{r}_+$ and $\mathbf{r}_-$ are position vectors of the field point P relative points *C* and *S*, respectively (Fig. **1)**.

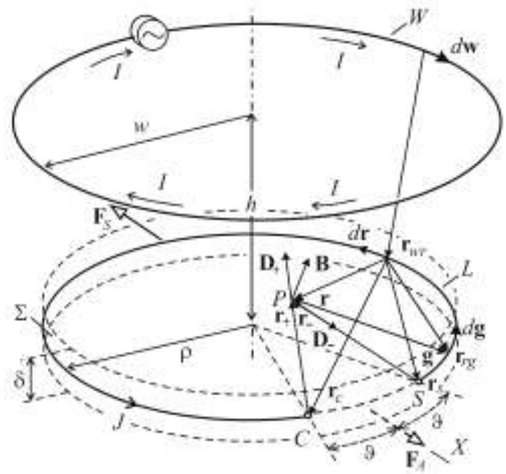

Fig. 1. Model of electromagnetic thruster.

The linear momentum density carried by electromagnetic field is related to the Poynting vector [**D**×**B**], therefore the force carried by the displacement currents is

$$\mathbf{F}_A = \frac{\mu_0 J^2}{(4\pi)^2}\Big(\int_V dv\Big[\frac{\mathbf{r}_+}{r_+^3}\times\int_L \frac{[d\mathbf{l}\times\mathbf{r}]}{r^3}\Big] - \int_V dv\Big[\frac{\mathbf{r}_-}{r_-^3}\times\int_L \frac{[d\mathbf{l}\times\mathbf{r}]}{r^3}\Big]\Big), \tag{2}$$

with integration over the contour L of the unclosed conductor and over infinite volume V occupied by displacement currents. Since $\mathbf{r}_+/r_+^3=-\mathrm{grad}(1/r_+)$, then the force created by the point C can be rewritten as

$$\mathbf{F}_{A+} = -\frac{\mu_0 J^2}{(4\pi)^2}\int_V dv \int_L \Big[\nabla_+ \frac{1}{r_+}\times\frac{[d\mathbf{l}\times\mathbf{r}]}{r^3}\Big]\,. \tag{3}$$

The use of the vector identity

$$[\nabla\times(\psi\mathbf{b})] = \psi\,[\nabla\times\mathbf{b}] - [\mathbf{b}\times\nabla\psi]$$

enables to transform volume integral from *curl* to the surface integral over surface of infinite radius r_+, that gives

$$\mathbf{F}_{A+} = -\frac{\mu_0 J^2}{(4\pi)^2}\int_L \Big(\oint_{S\to\infty}\Big(\frac{1}{r_+}\frac{[d\mathbf{l}\times\mathbf{r}]}{r^3}\Big)ds - \int_V \frac{1}{r_+}\Big[\nabla_+\times\frac{[d\mathbf{l}\times\mathbf{r}]}{r^3}\Big]dv\Big)\cdot \tag{4}$$

The functional structure of the first integral in (4**)** guarantees the vanishing the integral since $r<<r_+$. Remaining integral can be evaluated using the vector identity

$$[\nabla\times[\nabla\times\mathbf{a}]] = -\Delta\mathbf{a} + \nabla(\nabla\cdot\mathbf{a}),$$

and using the Lorentz condition for vector potentials. Therefore, the force exerted by the displacement currents due to the charge at point C is

$$\mathbf{F}_{A+} = -\frac{\mu_0 J^2}{(4\pi)^2} \int_L \int_V \frac{d\mathbf{l}}{r_+} \Delta \frac{1}{|\mathbf{r}_+ + \mathbf{r}_c|} dv \cdot \tag{5}$$

Since [11]

$$\Delta \frac{1}{|\mathbf{r}_+ + \mathbf{r}_c|} = -4\pi\delta(\mathbf{r}_+ + \mathbf{r}_c),$$

then the displacements current created by the both ends of the conductor is acted upon by the force

$$\mathbf{F}_A = J(\mathbf{A}(\mathbf{r}_c) - \mathbf{A}(\mathbf{r}_s)), \tag{6}$$

where

$$\mathbf{A}(\mathbf{r}_c) = \frac{\mu_0 J}{4\pi} \int_L \frac{d\mathbf{l}}{r_c};\ \mathbf{A}(\mathbf{r}_s) = \frac{\mu_0 J}{4\pi} \int_L \frac{d\mathbf{l}}{r_s}, \tag{7}$$

are vector potentials at points C and S respectively. The force (6**)** is not always equal to zero. For a linear conductor, the potentials (7**)** are equal in magnitude and in direction; in this case, the forces $J\mathbf{A}(\mathbf{r}_c)$ and $-J\mathbf{A}(\mathbf{r}_s)$ are equal in magnitude and opposite in direction; bending the conductor results in a non-zero force of (6**)**, called the Abraham force. If the conductor acts on the field, then the electromagnetic field must also act on the conduction currents flowing in the conductor. Without consideration of the corresponding force, which should be treated as a reactive force, the analysis cannot be considered complete.

III. Reactive Force

Before solving the problem of calculating the reactive force, attention should be paid to expression (2). Formally, this expression coincides with the Biot-Savart force, with which the magnetic field created by the currents of the elements of the conduction currents acts on the elements of the displacement currents. For a magnetic field created by elements of displacement currents, the density of which is $\partial\mathbf{D}/\partial t$, such a formalism is rather doubtful. Maxwell's equations also describe electrodynamic systems with displacement currents. Therefore, for a uniquely defined displacement current density (1**)**, the Maxwell equation

$$\frac{1}{\mu_0}[\nabla \times \mathbf{B}] = \frac{J(\mathbf{r} - \mathbf{r}_c)}{4\pi |\mathbf{r} - \mathbf{r}_c|^3},$$

after introducing the vector potential

$$\mathbf{B} = [\nabla \times \mathbf{A}],$$

corresponds to the Poisson equation

$$\Delta\mathbf{A} = -\frac{\mu_0}{4\pi} \frac{\mathbf{r} - \mathbf{r}_c}{|\mathbf{r} - \mathbf{r}_c|^3} \cdot$$

The solution of this equation is absolutely equivalent to the Biot-Savart force

$$\mathbf{F}_{R+} = \frac{\mu_0}{4\pi} \int_L [J d\mathbf{l} \times \int_V [\frac{J\mathbf{r}_+}{4\pi r_+^3} \times \frac{-\mathbf{r}}{r^3}] dv], \tag{8}$$

in which the density of conduction currents is replaced by the density of displacement currents.
Since $\mathbf{r}=\mathbf{r}_+ + \mathbf{r}_c$, then

$$\mathbf{F}_{R+} = \frac{\mu_0 J^2}{(4\pi)^2} \int_L [d\mathbf{l} \times \int_V [\frac{\mathbf{r}_c}{r_+^3} \times \nabla \frac{1}{|\mathbf{r}_+ + \mathbf{r}_c|}]] d^3 r_+ \cdot$$

This integral can be converted to the surface integral over sphere of infinite radius r_+, and since $r_c \ll r_+$, then

$$\mathbf{F}_{R+} = \frac{\mu_0 J^2}{(4\pi)^2} \int_L [d\mathbf{l} \times \oint_{S\to\infty} \frac{(\mathbf{r}_c d\mathbf{s})}{r_+^3 |\mathbf{r}_+ + \mathbf{r}_c|}] = 0 \cdot \quad (9)$$

The same applies to the displacement currents created by the charge at point *S*. A rather strange situation arose: the magnetic field created by the displacement currents does not affect the conduction currents flowing in the conductor, which creates not only currents, but also displacement currents, and hence the Abraham force. Newton's third law, also known as the rule of equality and collinearity of action and reaction, is not fulfilled in such an elementary form. Therefore, this law does not have to be fulfilled for an unclosed conductor either. Otherwise, the sum of all forces acting in a closed system, including the unclosed conductor with current and an electromagnetic field, will not be equal to zero.

IV. Self-force

The force by means of which an unclosed conductor with direct or alternating current acts on itself is experimentally found and measured [12] and satisfies the law of conservation of linear momentum [13].Current elements $Jd\mathbf{r}$ and $Jd\mathbf{g}$ belonging to one unclosed conductor (Fig. **1)** interact with each other producing the Biot-Savart force

$$\mathbf{F}_S = \frac{\mu_0}{4\pi} \int_L [Jd\mathbf{g} \times \int_L \frac{[Jd\mathbf{l} \times \mathbf{r}_{rg}]}{r_{rg}^3}] \cdot \quad (10)$$

Getting rid of the double vector product, one can write

$$\mathbf{F}_S = \frac{\mu_0 J^2}{4\pi} (-\int_L d\mathbf{l} \int_L (d\mathbf{g} \nabla \frac{1}{r_{rg}}) - \int_L \int_L \frac{\mathbf{r}_{rg}(d\mathbf{g} d\mathbf{l})}{r_{rg}^3}) \cdot$$

Since $\mathbf{r}_{rg} = -\mathbf{r}_{gr}$, then the integrand in the second term of this integral is anti-symmetric with respect to the replacement of the current element, hence this term vanishes. The integrand in the first term is exact differential of $1/r_{rg}$. This means that the self-force acting on the conductor *L* is

$$\mathbf{F}_S = -\frac{\mu_0 J^2}{4\pi} \int_L d\mathbf{l} (\frac{1}{r_{rc}} - \frac{1}{r_{rs}})$$

$$= -J(\mathbf{A}(\mathbf{r}_c) - \mathbf{A}(\mathbf{r}_s)), \quad (11)$$

.

with vector potentials defined in (7**)**. This force is found to be equal and opposite to the Abraham force Eq. **6** and the total linear momentum conserves. Quantitative arguments are needed in order to make sure with a significant self-action force acting on the conductor. An attempt to calculate this force for an absolutely thin open conductor runs into the problem of the divergence of this force. On the one hand, the infinite value of this force is a physical result, and this is a positive fact. On the other hand, this should be verified. One way to do this is to replace the line current with, say, a surface current flowing on the surface Σ of a conductor of height δ. The self-force for such an unclosed conductor is known [14] and equals to

$$F_S = -\frac{\mu_0 J^2}{2\pi\eta} \int_{\vartheta}^{2\pi-\vartheta} d\varphi \int_{-\eta/2}^{\eta/2} \frac{\sin\varphi d\kappa}{(2(1-\cos(\varphi-\vartheta)+\kappa^2)^{1/2}}, \quad (12)$$

where $\eta = \delta/\rho$, ρ is radius of the conductor, 2ϑ is angle of a sector between ends *C* and *S* (Fig. **1**).The results of such a relatively simple calculation are shown in Fig. 2.

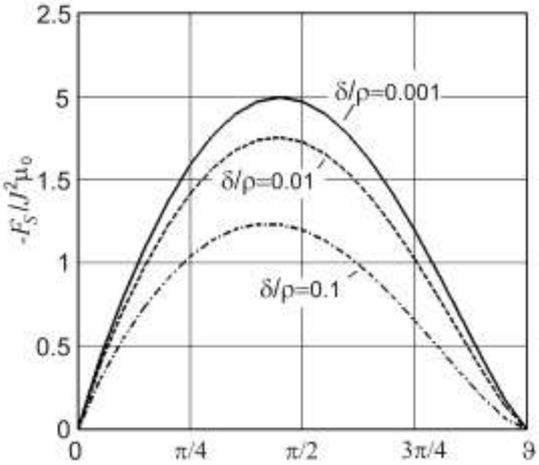

Fig. 2. Angular dependence of the self-force at various highs of conductor.

First of all, note that this force is proportional to the square of the current. Since the current is alternating, the average over the oscillation period is not equal to zero. In a certain sense, the calculation results shown in Fig. 2 are universal, i.e. valid for any values δ/ρ. This also confirms the validity of the approach to the problem described above. The Abraham force is maximal not at small distances between points *C* and *S*. It remains to ensure the maximum value of the Foucault current created by the source of the alternating magnetic field.

V. Foucault currents

The only component of the electric field in conductor which produces the electric current is E_φ, therefore in cylindrical coordinates the Maxwell equation

$$[\nabla \times \mathbf{E}] = -\frac{\partial \mathbf{B}_w}{\partial t},$$

can be rewritten as

$$\frac{1}{\rho}\frac{\partial}{\partial \rho}(\rho E_\varphi) = B_z(\rho, h)\omega f(t),$$

where B_z is amplitude of the magnetic field created by the ring conductor *W*. For axially symmetric magnetic field, the electric field does not depend on φ, therefore the electric current in conductor is

$$J = \frac{\omega}{\lambda} A_w(\rho, h) f(t), \tag{13}$$

where λ is resistance of the conductor per unit of length, ω is frequency of changing the magnetic field B_w, the vector potential of which equals to

At small distances *h* between the circular loop *W* of radius *w* and the unclosed conductor *L*, the amplitude of current (13) can be very large, as shown in Fig. 3.The sharp increase in current at the radii of the source of the magnetic field close to the radius of the conductor did not come as a surprise.

$$A_w(\rho, h) = \frac{\mu_0 I}{4\pi}\int_0^{2\pi} \frac{w\cos\varphi d\varphi}{(\rho^2 - 2\rho w\cos\varphi + w^2 + h^2)^{1/2}}.$$

At small distances *h* between the circular loop *W* of radius *w* and the unclosed conductor *L*, the amplitude of current (13) can be very large, as shown in Fig. 3.The sharp increase in current at the radii of the source of the magnetic field close to the radius of the conductor did not come as a surprise. Most likely, this is a confirmation of the large values of the lifting force when the conductor is located on the periphery of the electromagnet. Attention should also be paid to the quadratic dependence of the self-force on the frequency of oscillations of an alternating external magnetic field. This is true, since the strength of the Foucault current is proportional to the frequency, and the self-force is proportional to the square of the Foucault current.

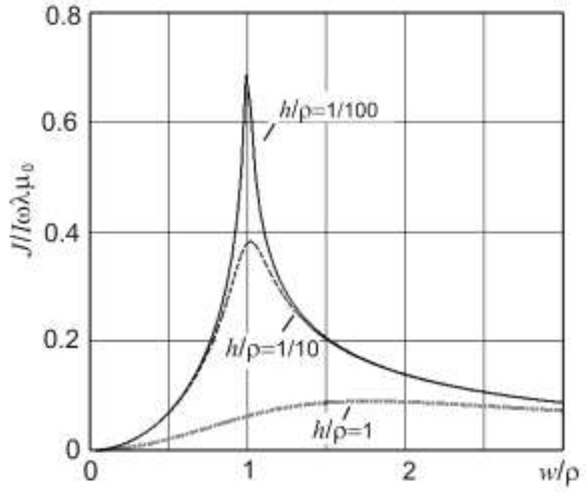

Fig. 3. Foucault current versus radius of circular source of magnetic field.

VI. Conclusion

All that is said above is based on experimentally verified and confirmed laws of classical electrodynamics. This also applies to the existence of self-action, according to which an unclosed current-carrying conductor experiences a force with which the conductor acts on itself. On the other hand, the current flowing in an open conductor acts on the rest of the closed current, the role of which can be played by the displacement current. An alternating current in an open conductor can be a Foucault current. Being an ordinary induction current, this current may not be closed. The self-action force created by the displacement currents is proportional to the square of the Foucault current, which means that its average over the period of change is not equal to zero. The strength of the Foucault current in an open conductor is proportional to the strength of the current in the source of an alternating magnetic field and the frequency of its oscillations. Of course, the source of the magnetic field acts on an open conductor, creating a force proportional to the induction of the magnetic field and the strength of the Foucault current. Since the Foucault current is inductive, the average value of such a force over the period of change of the magnetic field is zero. The same applies to the effect of conduction currents and displacement currents on the source of the magnetic field. Since the phase shift between these currents and the current in the magnetic field source is π, the average value of the force with which they interact is zero. That is why these forces were not considered in detail in this work. The whole there system, which includes a source of an alternating magnetic field and an open conductor, experiences the action of an average non-zero self-force. With the same equal in magnitude but opposite in direction force, the system acts on an alternating electromagnetic field created by displacement currents. In fact, the action of such an electromagnetic propulsion is based on this.

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