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INFLUENCE OF GEOMETRICAL PARAMETERS OF THE INDUCTOR AND ARMATURE ON THE INDICATORS OF A LINEAR PULSE ELECTROMECHANICAL CONVERTER OF AN ELECTRODYNAMIC TYPE

Purpose. The aim of the paper is to study the influence of geometrical parameters, namely, the number of layers and the cross section of the copper tire of the inductor and the armature coils on the power and speed indicators of a linear pulse electromechanical converter (LPEC) of an electrodynamic type. Methodology. On the basis of the developed chain mathematical model, recurrent relations are obtained for the calculation of interconnected electromagnetic, mechanical and thermal processes of LPEC of an electrodynamic type. The effect of the thickness of a square copper tire and the number of its layers in the inductor and armature coils on the characteristics and characteristics of electrodynamic LPEC is investigated. It is these parameters that determine the number of turns and the axial height of the coils with limited radial dimensions. Results. The influence of the geometrical parameters of the inductor and the armature coils with limited radial dimensions on the electrical and mechanical characteristics of LPEC of an electrodynamic type is established. It has been established that with an increase in the thickness of a rectangular cross-section of copper tire from 1 to 2.5 mm, an increase in the amplitude and pulse of electrodynamic forces (EF) occurs. However, the maximum speed of the armature is the highest at LPEC wound with a 1.5 mm thick tire. The highest efficiency value is demonstrated by LPEC, in which the inductor and armature coils are wound with a 2 mm thick tire. With an increase in the number of layers of the inductor coil tire, the amplitude of the EF decreases significantly, and the magnitude of the EF pulse decreases slightly. As a result, the maximum armature speed, efficiency and temperature rise of the coils are reduced. Originality. It is established that the largest amplitude of the EF is realized in LPEC with the minimum number of layers of tires of the inductor and armature coils. The largest value of the pulse EF occurs when the maximum number of layers of the inductor and the armature. In this case, the largest values of the amplitude and pulse of the EF occur under the condition that the number of tire layers of the inductor and the armature coils are the same. Practical value. It has been established that the greatest efficiency 21.82 % is realized in LPEC, in which the number of tire layers is 2 mm thick with inductor and armature coils are 4. A catapult model for launching an unmanned aerial vehicle was made and tested on the basis of LPEC of an electrodynamic type. References 12, figures 6.

Key words: linear pulse electromechanical converter of electrodynamic type, chain mathematical model, recurrent relations, geometrical parameters of inductor and armature coils, electrodynamic forces, efficiency.

Розроблена ланцюгова математична модель лінійного імпульсного електромеханічного перетворювача (ЛІЕП) електродинамічного типу. Отримано рекурентні співвідношення для розрахунку взаємопов'язаних електромагнітних, механічних і теплових процесів. Встановлено, що при збільшенні товщини квадратної мідної шини котушок індуктора і якоря від 1,0 до 2,5 мм збільшуються амплітуда і величина імпульсу електродинамічних зусиль (ЕДЗ). Максимальна швидкість якоря найбільша у ЛІЕП, котушки індуктора і якоря якого намотані шиною товщиною 1,5 мм. Найбільше значення ККД у ЛІЕП, котушки якого намотані шиною товщиною 2,0 мм. При збільшенні кількості шарів шини котушки індуктора амплітуда ЕДЗ знижується істотно, а величина імпульсу ЕДЗ – незначно. Внаслідок цього знижуються максимальна швидкість якоря, ККД і перевищення температури котушок. Найбільша амплітуда ЕДЗ реалізується в ЛІЕП при мінімальній кількості шарів шин котушок індуктора і якоря, а найбільша величина імпульсу ЕДЗ виникає при максимальній їх кількості. При цьому найбільші значення амплітуди і імпульсу ЕДЗ виникають за умови, коли число шарів шини котушок однакові. Найбільший ККД (21,82 %) реалізується в ЛІЕП, у якого котушки індуктора і якоря намотані в чотири шари квадратної шини товщиною 2,0 мм. На базі ЛІЕП електродинамічного типу була виготовлена і випробувана модель катапульты для запуску безпілотного літального апарату. Бібл. 12, рис. 6.

Ключові слова: лінійний імпульсний електромеханічний перетворювач електродинамічного типу, ланцюгова математична модель, рекурентні співвідношення, геометричні параметри котушок індуктора і якоря, електродинамічні зусилля, ККД.

Разработана цепная математическая модель линейного импульсного электромеханического преобразователя (ЛИЭП) электродинамического типа. Получены рекуррентные соотношения для расчета взаимосвязанных электромагнитных, механических и тепловых процессов. Установлено, что при увеличении толщины квадратной медной шины катушек индуктора и якоря от 1,0 до 2,5 мм увеличиваются амплитуда и величина импульса электродинамических усилий (ЭДУ). Максимальная скорость якоря наибольшая у ЛИЭП, катушки индуктора и якоря которого намотаны шиной толщиной 1,5 мм. Наибольшее значение КПД у ЛИЭП, катушки которого намотаны шиной толщиной 2,0 мм. При увеличении количества слоев шины катушки индуктора амплитуда ЭДУ уменьшается существенно, а величина импульса ЭДУ – незначительно. Вследствие этого снижаются максимальная скорость якоря, КПД и превышения температуры катушек. Наибольшая амплитуда ЭДУ реализуется в ЛИЭП при минимальном количестве слоев шин катушек индуктора и якоря, а наибольшая величина импульса ЭДУ возникает при максимальном их количестве. При этом наибольшие значения амплитуды и импульса ЭДУ возникают при условии, когда количество слоев шины катушек одинаковы. Наибольший КПД (21,82 %) реализуется в ЛИЭП, у которого катушки индуктора и якоря намотаны в четыре слоя квадратной шини толщиной 2,0 мм. На базе ЛИЭП электродинамического типа была изготовлена и испытана модель катапульты для запуска беспилотного летательного аппарата. Библ. 12, рис. 6.

Ключевые слова: линейный импульсный электромеханический преобразователь электродинамического типа, цепная математическая модель, рекуррентные соотношения, геометрические параметры катушек индуктора и якоря, электродинамические усилия, КПД.

Introduction. Linear pulse electromechanical converters (LPEC) allow to provide a high speed of the actuator (A) in the short active area and/or to create powerful force pulses at its slight displacement [1-3]. Such converters are used in many branches of science and technology as electromechanical accelerators and shock-power devices [4, 5]. One of the most promising is LPEC of electrodynamic type [6, 7]. In this converter, which has a coaxial configuration, the fixed inductor and accelerated armature are made in the form of monolithic disk coils, which are impregnated with epoxy resin. Serially connected the inductor and the armature are tightly wound with the same copper tire. The current from a pulsed power source containing a capacitive energy storage (CES) is excited in them [4, 8]. The armature is connected to the inductor and to the power source using movable (flexible or sliding) current leads. The inductor and the armature are connected in opposite directions by the magnetic field, as a result of which electrodynamic forces (EFs) of repulsion act between it. These EFs cause axial displacement of the armature relative to the fixed inductor (Fig. 1,a).

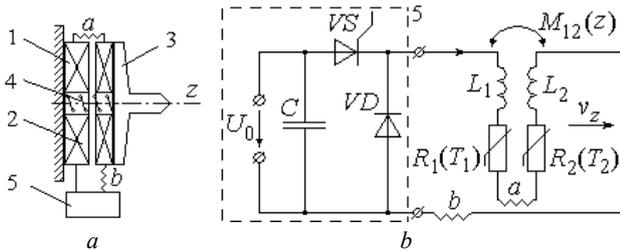


Fig. 1. Constructive (a) and electric (b) circuits of LPEC of electrodynamic type: 1 – inductor; 2 – armature; 3 – actuator; 4 – return spring; 5 – power supply; a, b – flexible current leads

In the process of LPEC operation, a change in the magnetic coupling between the armature and the inductor occurs. In addition, their resistances increase due to heating with high-density pulsed current. These features of the operating process must be taken into account in the mathematical model of LPEC of electrodynamic type [9]. When operating in a dynamic mode with a rapid change of electromagnetic, mechanical and thermal parameters, the efficiency of LPEC is not high enough, which is due, in particular, to the lack of justification for choosing the geometric parameters of active elements – inductor and armature coils.

The goal of the paper is the study of the influence of geometrical parameters, namely, the number of layers and the cross section of the copper tire of the inductor and the armature coils on the power and speed indicators of LPEC of electrodynamic type.

Mathematical model. Consider a mathematical model of LPEC of electrodynamic type, which uses the concentrated parameters of the inductor and the armature. We will assume that the fixed inductor and the accelerated armature are made in the form of coaxially mounted circular multi-turn disk coils that are tightly wound with the same square-section copper tire.

To take into account the interconnected electrical, magnetic, mechanical and thermal processes, as well as a

number of nonlinear dependencies, the solutions of the equations describing the indicated processes will be presented in recurrent form [10].

When a starting pulse is applied to the thyristor *VS*, the inductor and the armature are excited by an aperiodic polar pulse from the CES *C*, shunted by a reverse diode *VD* (Fig. 1,b). We believe that in a pulsed power supply the resistance of the diode *VD* and thyristor *VS* in the forward direction is negligible, and in the opposite direction their conductivity is just as small.

Electrical processes in LPEC of an electrodynamic type on the time interval $\{0, t_1\}$, where t_1 is the time at which the CES voltage is $u_C = 0$, can be described by the equation:

$$[R_1(T_1) + R_2(T_2)] \cdot i + \frac{d\psi}{dt} + \frac{1}{C} \int_0^t idt = 0, \quad u_C(0) = U_0, \quad (1)$$

where $n = 1, 2$ are the inductor and armature indexes, respectively; R_n, T_n, L_n are the active resistance, temperature and inductance of the n -th element; M_{12} is the mutual inductance between the inductor and the armature, moving along the z axis with speed v_z ;

$$\frac{d\psi}{dt} = [L_1 - 2M_{12}(z) + L_2] \frac{di}{dt} - 2iv_z(t) \frac{dM_{12}}{dz}. \quad (2)$$

Substituting equation (2) into (1) we obtain:

$$\left(R_1(T_1) + R_2(T_2) - 2v_z(t) \frac{dM_{12}}{dz} \right) \cdot i + [L_1 - 2M_{12}(z) + L_2] \frac{di}{dt} + \frac{1}{C} \int_0^t idt = 0. \quad (3)$$

The solution of equation (3) can be represented as:

$$i = A_1 \exp(\alpha_1 t) + A_2 \exp(\alpha_2 t), \quad (4)$$

where A_1, A_2 are the arbitrary constants,

$$\alpha_{1,2} = -0,5 \frac{\Theta}{\Xi} \pm \left[0,25 \left(\frac{\Theta}{\Xi} \right)^2 - \frac{1}{\Xi C} \right]^{0,5}$$

are the roots of the characteristic equation; $\Xi = L_1 - 2M_{12}(z) + L_2$;
 $\Theta = R_1(T_1) + R_2(T_2) - 2v_z(t) \frac{dM_{12}}{dz}$.

To represent the solution in a recurrent form, we define the values of arbitrary constants at the time t_k .

If $\Theta > 2\sqrt{\Xi C^{-1}}$, then after a series of transformations we get:

$$A_{1,2} = \frac{u_C(t_k) + \Theta \cdot i(t_k) + \alpha_{2,1} \Xi \cdot i(t_k)}{\Xi \exp(\alpha_{1,2} t_k) (\alpha_{2,1} - \alpha_{1,2})}. \quad (5)$$

Substituting expressions (5) into equation (4), we obtain the expression for the current:

$$i(t_{k+1}) = \frac{u_C(t_k) + \Theta \cdot i(t_k)}{\Xi(\alpha_2 - \alpha_1)} [\exp(\alpha_1 \Delta t) - \exp(\alpha_2 \Delta t)] + \frac{i(t_k)}{\alpha_2 - \alpha_1} [\alpha_2 \exp(\alpha_1 \Delta t) - \alpha_1 \exp(\alpha_2 \Delta t)], \quad (6)$$

where $\Delta t = t_{k+1} - t_k$.

Voltage on the CES:

$$u_C(t_{k+1}) = \frac{u_C(t_k) + \Theta \cdot i(t_k)}{\alpha_2 - \alpha_1} [\alpha_2 \exp(\alpha_1 \Delta t) - \alpha_1 \exp(\alpha_2 \Delta t)] + \varepsilon \frac{i(t_k)}{\alpha_2 - \alpha_1} [\alpha_2^2 \exp(\alpha_1 \Delta t) - \alpha_1^2 \exp(\alpha_2 \Delta t)] \quad (7)$$

If $\Theta < 2\sqrt{\varepsilon C^{-1}}$, then the roots of the characteristic equation can be represented as:

$$\alpha_{1,2} = -\delta \pm j\omega_1 = \omega_0 \exp(j(\pi \pm \theta)), \quad (8)$$

where $\delta = 0,5\Theta\varepsilon^{-1}$; $\theta = \arctg(4\varepsilon\Theta^{-2}C^{-1} - 1)^{0,5}$;

$$\omega_0 = (\varepsilon C)^{-0,5}; \quad \omega_1 = (\varepsilon^{-1}C^{-1} - 0,25\Theta^2\varepsilon^{-2})^{0,5}.$$

Substituting the values of the roots (8) into equations (6), (7) and taking into account that

$$2j\sin(\omega_1 \Delta t) = \exp(j\omega_1 \Delta t) - \exp(-j\omega_1 \Delta t),$$

we get:

$$i(t_{k+1}) = -\omega_1^{-1} \exp(-\delta \Delta t) \left\{ \varepsilon^{-1} [u_C(t_k) + \Theta \cdot i(t_k)] \sin(\omega_1 \Delta t) + \omega_0 i(t_k) \sin(\omega_1 \Delta t - \theta) \right\} \quad (9)$$

Voltage on the CES:

$$u_C(t_{k+1}) = -\omega_0 \omega_1^{-1} \exp(-\delta \Delta t) \left\{ [u_C(t_k) + \Theta \cdot i(t_k)] \times \sin(\omega_1 \Delta t - \theta) + i(t_k) \omega_0 \varepsilon \sin(\omega_1 \Delta t - 2\theta) \right\} \quad (10)$$

If $\Theta = 2\sqrt{\varepsilon C^{-1}}$, then $\delta = \omega_0$ and current is:

$$i(t_{k+1}) = \exp(-\delta \Delta t) \Delta t \left\{ i(t_k) \delta - \varepsilon^{-1} [u_C(t_k) + \Theta \cdot i(t_k)] \right\} \quad (11)$$

Voltage on the CES:

$$u_C(t_{k+1}) = [u_C(t_k) - i(t_k) \varepsilon \delta + \Theta \cdot i(t_k)] (\delta \Delta t + 1) \times \exp(-\delta \Delta t) + i(t_k) (\varepsilon \delta - \Theta) \quad (12)$$

Current in LPEC in the time interval $\{t_1, \infty\}$ varies according to the law:

$$i(t_{k+1}) = i(t_k) \exp(-\Theta \varepsilon^{-1} \Delta t) \quad (13)$$

Mechanical processes in LIEP can be described by the equation:

$$i^2(t) \frac{dM}{dz} = (m_a + m_2) \frac{dv_z}{dt} + K_P \Delta z(t) + K_T v_z(t) + 0,125\pi\gamma_a \beta_a D_{2m}^2 v_z^2(t), \quad (14)$$

where m_2, m_a are the mass of the armature and A, respectively; K_P is the value of elasticity of the return spring; $\Delta z(t)$ is the value of the displacement of the armature with A; K_T is the coefficient of dynamic friction; γ_a is the density of the medium of displacement; β_a is the aerodynamic resistance coefficient; D_{2m} is the outer diameter of the A.

The effectiveness of the axial force action on the armature will be estimated by the value of the impulse of EF [11]:

$$P_1 = \int F(z, t) dt, \quad (15)$$

where $F(z, t)$ is the instantaneous value of axial EF acting on the armature.

Based on equation (14), the value of the displacement of the armature with A can be represented as a recurrent relation:

$$s(t_{k+1}) = s(t_k) + v_z(t_k) \Delta t + g \Delta t^2 / (m_a + m_2), \quad (16)$$

where $v_z(t_{k+1}) = v_z(t_k) + g \Delta t / (m_a + m_2)$ is the speed of the armature with A along the z axis;

$$g = i^2(t_k) \frac{dM}{dz}(z) - K_P \Delta z(t_k) - K_T v_z(t_k) - 0,125\pi\gamma_a \beta_a D_{2m}^2 v_z^2(t_k).$$

Thermal processes. In the absence of displacement of the armature, which occurs either before the start of the forward stroke, or after the return stroke, there is a thermal contact between the inductor and armature coils through the insulation gasket. The temperatures of the n -th active elements of the LPEC of electrodynamic type can be described by the recurrent relation [12]:

$$T_n(t_{k+1}) = T_n(t_k) \xi + (1 - \xi) \left\{ \pi^{-1} i_n(t_k) R_n(T_n) (D_{en}^2 - D_{in}^2)^{-1} + 0,25\pi T_0 D_{en} H_n \alpha_{Tn} + T_m(t_k) \lambda_a(T) d_a^{-1} \right\} \left\{ 0,25\pi \alpha_{Tn} D_{en} H_n + \lambda_a(T) d_a^{-1} \right\}^{-1}, \quad (17)$$

$$\text{where } \xi = \exp \left\{ -\frac{\Delta t}{C_n(T_n) \gamma_n} \left(0,25 D_{en} \alpha_{Tn} + \frac{\lambda_a(T)}{d_a H_n} \right) \right\};$$

$\lambda_a(T)$ is the thermal conductivity of the insulation gasket; d_a is the gasket thickness; D_{en}, D_{in} are the outer and inner diameters of the active elements, respectively; α_{Tn} is the heat transfer coefficient of the n -th active element; C_n is the heat capacity of the n -th active element.

Temperatures of the n -th active elements when the armature is moved and there is no thermal contact between the armature and the inductor can be described by the recurrence relation:

$$T_n(t_{k+1}) = T_n(t_k) \chi + (1 - \chi) \left\{ T_0 + 4\pi^{-2} i_n(t_k) R_n(T_n) \alpha_{Tn}^{-1} \times D_{en}^{-1} H_n^{-1} (D_{en}^2 - D_{in}^2)^{-1} \right\}, \quad (18)$$

$$\text{where } \chi = \exp \left\{ -0,25 \Delta t D_{en} \alpha_{Tn} C_n^{-1} (T_n) \gamma_n^{-1} \right\}.$$

The initial conditions of the mathematical model of LPEC are as follows:

$T_n(0) = T_0$ – the temperature of the n -th active element;

$i_n(0) = 0$ – the current of the n -th active element;

$s(0) = s_0$ – the initial axial distance between the coils of the armature and the inductor;

$u_c(0) = U_0$ – the CES voltage;

$v_z(0) = 0$ – the armature speed along the z axis.

The efficiency of the LPEC of electrodynamic type will be estimated by the relation:

$$\eta = 100 \frac{(m_2 + m_a) v_z^2 + K_P s^2}{CU_0^2} \%. \quad (19)$$

Main parameters of LPEC of electrodynamic type. Consider LPEC, whose movable armature and fixed inductor are made in the form of flat coaxially mounted disk coils. At the armature, one end side faces the inductor, and the second one interacts with A. The inductor ($n=1$) and the armature ($n=2$) are tightly wound with K_{pn} layers of a square-section copper tire with thickness a . The outer diameter of the n -th element is $D_{en}=100$ mm, the inner diameter is $D_{in}=10$ mm. The CES has the following parameters: capacitance $C = 3$ mF, voltage $U_0 = 0,4$ kV. The initial distance between the inductor and the armature is $s_0=1$ mm. The coefficient of elasticity of the return spring $K_P=25$ kN/m. Mass of A is $m_a=0,25$ kg.

We investigate the influence of the thickness a of a copper square tire and the number K_{pn} of its layers in the

inductor and armature coils on the characteristics and indicators of the LPEC of electrodynamic type. These parameters determine the number of turns

$$N_n = Ent \left(0,5 \frac{D_{en} - D_{in}}{a + 2\delta} \right) K_{pn}$$

and the axial height

$$H_n = (a + 2\delta) K_{pn}$$

of the n -th coils with limited radial dimensions, where $Ent(f)$ is the largest integer not exceeding f ; δ is the insulation thickness of the copper tire.

Investigation of operation processes in LPEC.

Consider the electrical and mechanical characteristics of the LPEC of electrodynamic type, in which both the inductor and armature coils are tightly wound in four layers $K_{pn}=4$ with a square tire of different thickness (Fig. 2). As the thickness of the copper tire a increases from 1 to 2,5 mm, the number of turns of each coil N_n decreases from 160 to 68, and the axial height H_n increases from 4,4 to 10,4 mm. In this case, the amplitude of the current i_m increases significantly – from 0,30 to 1,56 kA, and the amplitude of the current density j_m decreases slightly from 304,3 to 250,4 A/mm².

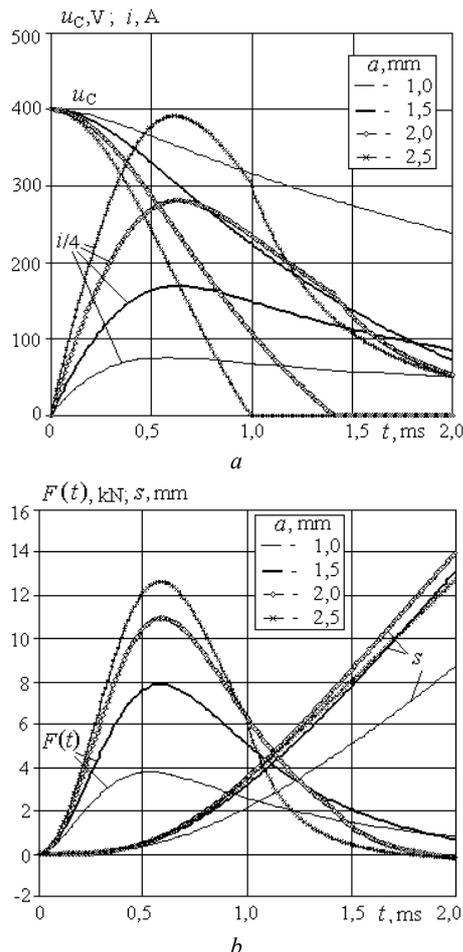


Fig. 2. Electrical (a) and mechanical (b) characteristics of LPEC, the coils of which are wound with a copper tire of different thickness a

An increase in the thickness of the copper tire a changes the regularities of the flow of electrical processes: the CES voltage u_C decreases to zero value

faster, and the current takes the form of a clear pulse with a significant increase in the leading front and falling of the falling front. With an increase in the thickness of the copper tire a from 1 to 2,5 mm, the power indicators of LPEC increase. The amplitude of the EF F_m increases from 3,78 to 12,65 kN, and the impulse of the EF P_1 increases from 4,52 to 9,16 N·s. However, speed indicators depending on the thickness of the tire do not have an unequivocal pattern.

The maximum speed of the armature V_m is the greatest at LPEC, whose coils are wound with a tire of thickness $a = 1,5$ mm, and is 11,24 m/s. If the tire has a smaller or greater thickness, then the speed decreases: at $a = 1$ mm – $V_m = 8,16$ m/s, and at $a = 2,5$ mm – $V_m = 9,44$ m/s.

An ambiguous dependence on tire thickness is also demonstrated by the efficiency of the LPEC of electrodynamic type. The highest efficiency value $\eta = 21,8$ % has LPEC, in which the inductor and armature coils are wound with a tire of thickness of $a = 2$ mm. If the coils are wound with thinner or thicker tires, the efficiency decreases: at $a = 1,5$ mm $\eta = 20$ %, at $a = 2,5$ mm $\eta = 18,8$ %. Note that if the coils are wound with an even thinner tire $a = 1$ mm, then the efficiency takes an even lower value $\eta = 8,5$ %.

With increasing thickness of copper tire a from 1 to 2,5 mm, the temperature rise of the inductor and armature coils θ_n decreases from 0,6 to 0,23 °C.

On the basis of the analysis performed, it can be concluded that the most effective is the LPEC of electrodynamic type, in which the inductor and armature coils are wound with a copper tire with a thickness of $a = 2$ mm. The number of turns of each coil is $N_n = 84$, and their axial height is $H_n = 8,4$ mm.

Investigate the effect of the number of layers of the tire of the inductor coil K_{p1} on the indicators of the LPEC of electrodynamic type. Obviously, as K_{p1} increases, the number of turns N_1 and the axial height H_1 of the inductor coil increase. We will consider LPEC, in which the inductor and armature coils are wound with a copper tire with thickness of $a = 2$ mm. The armature coil is wound in two layers, contains the number of turns $N_2 = 22$ and has the axial height $H_2 = 4,2$ mm. Consider the electrical and mechanical characteristics of LPEC, in which the inductor coil is wound with several layers K_{p1} (Fig. 3).

With an increase in the number of tire layers of the inductor coil K_{p1} three times (from 2 to 6), the amplitude of the current i_m decreases almost in the same proportion (from 2,57 to 0,86 kA), and the current pulse itself becomes more stretched due to an increase in the front and rear fronts. When the parameter K_{p1} is increased, the voltage of the CES u_C decreases to zero value more slowly.

With an increase in the number of tire layers of the inductor coil K_{p1} 3 times the amplitude of the EF F_m decreases 4.1 times (from 18,72 to 4,57 kN), while the impulse of the EF P_1 decreases slightly (from 6,79 to 5,69 N·s). As a result, the maximum speed of the armature with A V_m (from 12,54 to 10,53 m/s), efficiency η (from 18,08 to 13,57%) and temperature rise of the coils θ_n (from 0,73 to 0,3 °C) are reduced. These patterns of change in the maximum speeds V_m depending on the number of layers

of the tire of the inductor coil K_{p1} manifest themselves in a change in the nature of the displacement of the armature with A s (see Fig. 3,b).

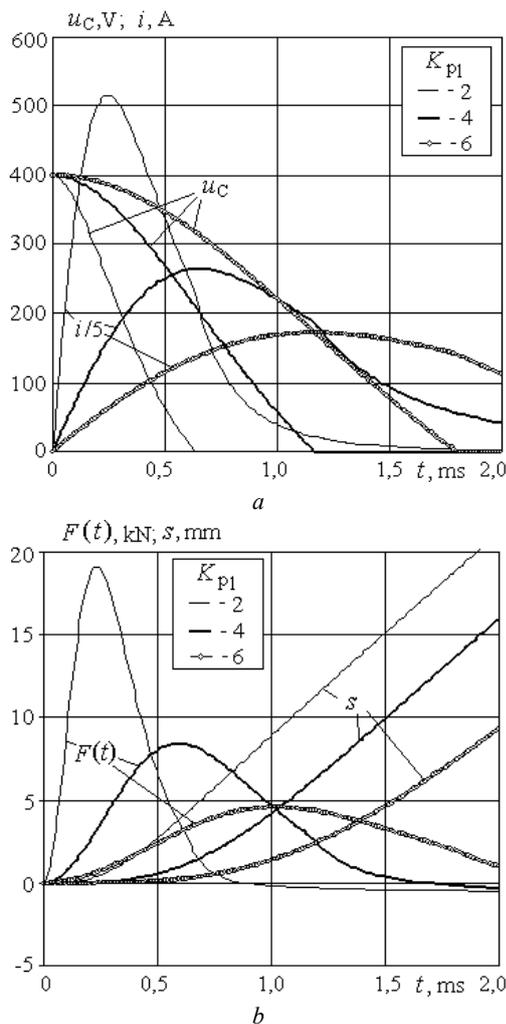


Fig. 3. Electrical (a) and mechanical (b) characteristics of LPEC, the coils of which are wound with tire thickness $a = 2$ mm with a different number of layers of the inductor coil tire K_{p1}

Influence of the number of layers of the tire of inductor and armature coils on the indicators of LPEC. Consider the effect of the mutual ratio of the number of layers of the tire of inductor K_{p1} and armature K_{p2} coils of thickness $a = 2$ mm on operation indicators of LPEC of electrodynamic type. We assume that the maximum number of layers of the tire coils $K_{p1} = K_{p2} = 6$.

With an increase in the number of tire layers of the inductor coil K_{p1} and/or of the armature coil K_{p2} , the amplitude of the current i_m decreases, but in different degrees. So, if the number of tire layers of both coils is minimal $K_{p1} = K_{p2} = 1$, then $i_m = 5,8$ kA. If the number of tire layers of one of the coils is minimal and of the second one is maximum, then the following pattern is observed: at $K_{p1} = 1, K_{p2} = 6$ the current amplitude decreases to $i_m = 0,865$ kA, and at $K_{p1} = 6, K_{p2} = 1$ the current amplitude decreases to $i_m = 0,846$ kA. If the number of tire layers of both coils is maximum $K_{p1} = K_{p2} = 6$, then the current amplitude decreases to the greatest extent (to the value $i_m = 0.7$ kA).

Similar dependencies on the number of tire layers of the inductor K_{p1} and armature K_{p2} coils are observed at the coil temperature rises. The maximum temperature rise ($\theta_{1,2} = 1,5$ °C) occurs at the minimum number of layers of the coil tire $K_{p1} = K_{p2} = 1$ and minimum ($\theta_{1,2} = 0,21$ °C) at the maximum number of layers of the tire $K_{p1} = K_{p2} = 6$. At $K_{p1} = 1$ and $K_{p2} = 6$ the temperature rises $\theta_{1,2} = 0,33$ °C, and at $K_{p1} = 6$ и $K_{p2} = 1$ the temperature rises $\theta_{1,2} = 0,31$ °C.

The ratio of the number of layers of tire of coils significantly affects the power indicators of the LPEC of electrodynamic type (Fig. 4).

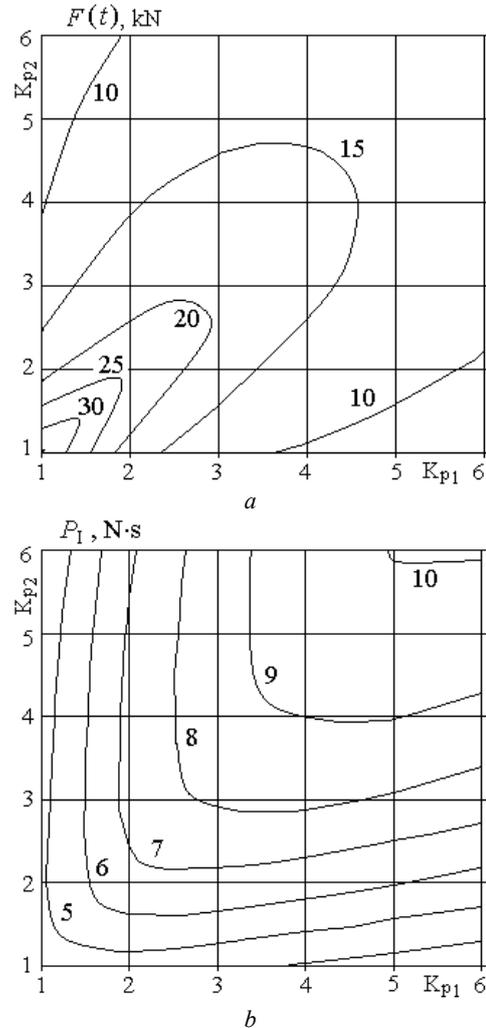


Fig. 4. Distributions of the maximum value (a) and impulse (b) of the EF depending on the ratio of the number of tire layers of the inductor and armature coils of the LIEP

The amplitude of the EF F_m is the greatest at the minimum number of layers of tires of inductor and armature coils. At $K_{p1} = K_{p2} = 1$, the value of $K_{p1} = K_{p2} = 1$ kN. With an increase in the number of layers of the tire of one of the coils, this value is significantly reduced. So, at $K_{p1} = 1$ and $K_{p2} = 6$ the amplitude of the EF is $F_m = 2,75$, and at $K_{p1} = 6$ and $K_{p2} = 1$ the amplitude of the EF is $F_m = 2,34$ kN. If the number of tire turns of the inductor and armature coils is maximum $K_{p1} = K_{p2} = 6$, then the amplitude of the EF increases to $F_m = 7,6$ kN. We can note the following pattern: the largest values of the amplitude of the EF F_m are observed under the condition that the numbers of tire layers of the inductor and armature coils are the same.

Impulse of EF P_1 has a different pattern on the ratio of the number of tire layers of the inductor and armature coils. The largest value of the impulse of EF occurs at the maximum number of layers of the tire of coils. At $K_{p1}=K_{p2}=6$ the value of $P_1=10,06$ N·s. If the number of layers of the inductor and the armature tire is minimal, then the value of the impulse of EF is reduced by more than two times. At $K_{p1}=K_{p2}=1$ the value of $P_1=4,49$ N·s. The highest impulse values of the EF P_1 are realized when the number of tire layers of the inductor and armature

coils is equal. If the number of tire layers of one of the coils is maximal, and in the second one is minimal, then the EF impulse decreases. At $K_{p1}=1$ and $K_{p2}=6$ the impulse of EF $P_1=4,06$ N·s, and at $K_{p1}=6$ and $K_{p2}=1$ $P_1=3,3$ N·s.

Let us consider the regularity of the distribution of the efficiency of LPEC of electrodynamic type as a function of the ratio of the number of tire layers of the inductor and the armature coils for its various thickness a (Fig. 5).

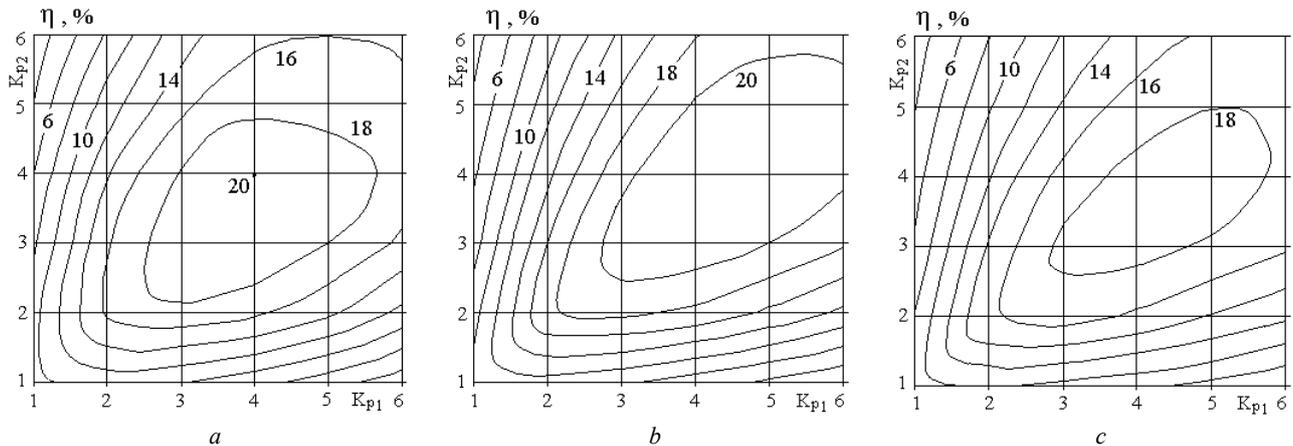


Fig. 5. The LPEC efficiency distributions depending on the ratios of the number of tire layers of the inductor and armature coils at the tire thickness a : 1,5 mm (a); 2 mm (b); 2,5 mm (c)

The highest values of efficiency are realized at a certain ratio of K_{p1} and K_{p2} . If the tire thickness a is equal to 1,5 mm or 2 mm, then the highest efficiency value is realized at $K_{p1}=K_{p2}=4$ and takes the values $\eta = 20,01$ % and $\eta = 21,82$ %, respectively. If the tire thickness is $a = 2,5$ mm, then the greatest efficiency value ($\eta = 18,91$ %) is realized at $K_{p1}=4$ and $K_{p2}=3$.

On the basis of the research carried out, it can be concluded that there is an optimal thickness of the copper tire $a = 2$ mm and the corresponding number of turns in each layer of the inductor and armature coils. From the point of view of power indicators, the number of layers of the tire of coils should be the maximum of the considered range ($K_{p1}=K_{p2}=6$). From the point of view of the efficiency of acceleration of A, coils should have fewer layers ($K_{p1}=K_{p2}=4$).

Taking into account the relationships obtained, on the basis of an LPEC of electrodynamic type a model of a catapult for launching an unmanned aerial vehicle (UAV) was made (Fig. 6).

In this model, both inductor and armature coils are wound with a copper tire and are compounded with epoxy resin in a rectangular insulating frame. The inductor coil is attached to the starting stop wall, and the armature coil is made with the possibility of axial movement along the central guide.

The electrical leads of the inductor and armature coils are located between the two dielectric guide plates and are connected by flexible wires to each other and to the power source. The armature coil is braked by means of an elastic damper attached to the brake stop wall. To the coil of the armature accelerating protrusion is attached that pushes the UAV.



Fig. 6. Model of a catapult for launching an UAV: 1 – guide plates for moving an UAV; 2 – UAV; 3 – guide plates for moving the current leads of the armature coil; 4 – brake stop wall; 5 – brake elastic damper; 6 – accelerating protrusion; 7 – armature coil; 8 – inductor coil; 9 – starting stop wall; 10 – current lead coils

The carried out tests of the model with the parameters set above confirmed the validity of the theoretical studies carried out on the LPEC of electrodynamic type.

Conclusions.

1. On the basis of the developed chain mathematical model, recurrent relations are obtained for the calculation of interconnected electromagnetic, mechanical and thermal processes in LPEC of electrodynamic type.

2. It is established that with an increase in the thickness of the square copper tire of the inductor and armature coils from 1 to 2,5 mm, the amplitude and impulse of the EF increase. However, the maximum speed of the armature is the highest at LPEC, the coils of which are wound with a tire 1,5 mm thick. The highest efficiency value is demonstrated by LPEC, in which the coils are wound with a tire 2 mm thick.

3. With an increase in the number of layers of the inductor coil tire, the amplitude of the EF decreases significantly, while the value of the EF impulse decreases slightly. This reduces the maximum speed of the armature, efficiency and temperature rise of the inductor and armature coils.

4. The greatest amplitude of the EF is implemented in LPEC at the minimum number of tire layers of the inductor and armature coils. The largest value of the impulse of the EF occurs at the maximum number of layers of the tire of coils. In this case, the largest values of the amplitude and impulse of the EF occur under the condition that the number of tire layers of both coils is the same.

5. The highest efficiency (21,82%) is realized in LPEC, in which the inductor and armature coils have four layers of square tire 2 mm thick.

6. A catapult model for launching an unmanned aerial vehicle was made and tested on the basis of the LPEC of electrodynamic type.

REFERENCES

1. Balikci A., Zabar Z., Birenbaum L., Czarkowski D. Improved performance of linear induction launchers. *IEEE Transactions on Magnetics*, 2005, vol.41, no.1, pp. 171-175. doi: **10.1109/tmag.2004.839283**.
2. Tomashevsky D.N., Koshkin A.N. Modeling of linear impulse electric motors. *Russian Electrical Engineering*, 2006, no.1, pp. 24-27. (Rus).
3. Bissal A., Magnusson J., Engdahl G. Electric to mechanical energy conversion of linear ultrafast electromechanical actuators based on stroke requirements. *IEEE Transactions on Industry Applications*, 2015, vol.51, no.4, pp. 3059-3067. doi: **10.1109/tia.2015.2411733**.
4. Bolyukh V.F., Shchukin I.S. *Lineinye induktsionno-dinamicheskie preobrazovateli* [Linear induction-dynamic converters]. Saarbrücken, Germany, LAP Lambert Academic Publ., 2014. 496 p. (Rus).
5. Bissal A., Eriksson A., Magnusson A., Engdahl G. Hybrid multi-physics modeling of an ultra-fast electro-mechanical actuator. *Actuators*, 2015, vol.4, no.4, pp. 314-335. doi: **10.3390/act4040314**.
6. Bolyukh V.F., Oleksenko S.V., Shchukin I.S. Comparative analysis of linear pulse electromechanical converters electromagnetic and induction types. *Technical Electrodynamics*, 2016, no.5, pp. 46-48. (Rus).
7. Bissal A., Magnusson J., Engdahl G. Comparison of two ultra-fast actuator concept. *IEEE Transactions on Magnetics*, 2012, vol.48, no.11, pp. 3315-3318. doi: **10.1109/tmag.2012.2198447**.
8. D.-K. Lim, D.-K. Woo, I.-W. Kim, D.-K. Shin, J.-S. Ro, T.-K. Chung, H.-K. Jung. Characteristic Analysis and Design of a Thomson Coil Actuator Using an Analytic Method and a Numerical Method. *IEEE Transactions on Magnetics*, 2013, vol.49, no.12, pp. 5749-5755. doi: **10.1109/tmag.2013.2272561**.
9. Li W., Koh C.S. Parametric analysis of Thomson-coil actuator using adaptive equivalent circuit method. *Digests of the 2010 14th Biennial IEEE Conference on Electromagnetic Field Computation*, May 2010, pp. 1-9. doi: **10.1109/cefc.2010.5481673**.
10. Bolyukh V.F., Kocherga A.I., Schukin I.S. Investigation of a linear pulse-induction electromechanical converter with different inductor power supply circuits. *Electrical engineering & electromechanics*, 2018, no.1, pp. 21-28. doi: **10.20998/2074-272X.2018.1.03**.
11. Bolyukh V.F., Oleksenko S.V., Schukin I.S. Efficiency of linear pulse electromechanical converters designed to create impact loads and high speeds. *Electrical engineering & electromechanics*, 2015, no.3, pp. 31-40. doi: **10.20998/2074-272X.2015.3.05**.
12. Bolyukh V.F., Schukin I.S. Investigation of thermal processes in a linear pulse-induction electromechanical converter of cyclic action. *Electrical engineering & electromechanics*, 2017, no.5, pp. 14-22. doi: **10.20998/2074-272X.2017.5.02**.

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