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Analytical relations for fields and currents in magnetic-pulsed «expansion» of tubular conductors of small diameter

Introduction. *This work was initiated by the problems of cardiovascular diseases, which are one of the main causes of mortality of the population of our planet. More than ten years ago, in 2012, approximately 3.7 million people died of acute coronary syndrome worldwide. The fight against such pathologies is carried out with the help of so-called stents, the manufacture of which can be carried out by the method of magnetic pulse «expansion» from hollow metal cylinders. The limited production possibilities of magnetic pulse «expansion» were caused by the minimum cross-sectional size of the inductor-instrument, which can be practically manufactured. Other tools are required to perform this operation.* ***Novelty.*** *A system of magnetic-pulse expansion of thin-walled pipes of small diameter with an inductor that excites an azimuthal electromagnetic field in the case of direct current passing through the processing object and in the absence of its connection in an electric circuit with an inductor is proposed.* ***Purpose.*** *The main analytical dependencies for the characteristics of the electromagnetic processes taking place in the inductor systems for the expansion of cylindrical conductive pipes of small diameter when direct passage of current through the processed object and when it is not connected to an electric circuit with an inductor (insulated billet) is derived.* ***Methods.*** *The solution of the boundary value problem with given boundary conditions was carried out by applying Laplace transforms and integrating Maxwell's equations.* ***Results****. Analytical expressions were obtained for the main characteristics of the processes: the intensities of the excited electromagnetic fields and currents in the system depending on the parameters of the studied systems. The analysis of possible technical schemes for solving the given problem indicated the choice of the optimal variant of an effective system of magnetic-pulse «stretching» of thin-walled cylindrical conductors of small diameter.* ***Practical value.*** *Based on the qualitative analysis of the obtained results, recommendations for the practical implementation of the proposed system were formulated. The obtained dependences allow us to give numerical estimates of the effectiveness of excitation of magnetic pressure forces on the object of processing and to choose directions for further improvement of the magnetic pulse technology for solving such problems.* References 23, figures 2.

Key words: **pulsed electromagnetic fields, cylindrical conductors of small diameter, solution of a boundary value problem, Laplace transforms.**

Вступ*. Ця робота була започаткована проблемами серцево-судинних захворювань, які є однією з основних причин смертності населення нашої планети. Вже більш десяти років тому, в 2012 році, від гострого коронарного синдрому в усьому світі померло приблизно 3,7 мільйона людей. Боротьба з такими патологіями ведеться за допомогою так званих стентів, виготовлення яких може здійснюватися методом магнітно-імпульсного «роздачі» порожнистих металевих циліндрів. Обмежені виробничі можливості магнітно-імпульсної «роздачі» обумовлювалися мінімальним поперечним розміром індуктора-інструмента, який практично можна виготовити. Для виконання цієї операції потрібні інші інструменти.* ***Новизна****. Запропоновано систему магнітно-імпульсного розширення тонкостінних труб малого діаметра з індуктором, який збуджує азимутальне електромагнітне поле, при прямому пропусканні струму через об'єкт обробки та при відсутності його підключення у електричне коло з індуктором.* ***Мета.*** *Одержано аналітичні вирази для основних характеристик процесів: напруженостей збуджуваних електромагнітних полів і струмів у системі в залежності від параметрів досліджуваних систем.* ***Методи.*** *Розв'язання крайової задачі із заданими граничними умовами проводилось при застосуванні перетворень Лапласа та інтегрування рівнянь Максвела.* ***Результати.*** *Отримано аналітичні вирази для основних характеристик процесів, що протікають: напруженості збуджуваних електромагнітних полів і струмів у системі. Аналіз можливих технічних схем вирішення поставленої задачі вказав на вибір оптимального варіанту ефективної системи магнітно-імпульсного «роздачі» тонкостінних циліндричних провідників малого діаметра.* ***Практична цінність.*** *На основі якісного аналізу отриманих результатів сформульовано рекомендації щодо практичного впровадження запропонованої системи. Отримані залежності дозволяють дати чисельні оцінки ефективності збудження сил магнітного тиску на об'єкт обробки та вибрати напрямки подальшого вдосконалення магнітно-імпульсної технології для вирішення таких задач.* Бібл. 23, рис. 2.

Ключові слова: **імпульсні електромагнітні поля, циліндричні провідники малого діаметра, розв'язання крайової задачі, перетворення Лапласа.**

Introduction. The relevance of this work is determined by many factors, but the first and most significant among them is medicine. So, at present, cardiovascular diseases are one of the main causes of mortality of the population of our planet.

For the work of the cardiovascular system, a large amount of oxygen is needed, for the delivery of which the branched system of the coronary arteries is responsible. Pathological changes in the state of blood vessels, and primarily their narrowing, are one of the main causes of impaired oxygen-rich blood supply and invariably lead to the development of serious and even fatal cardiovascular diseases. The fight against these pathologies is carried out by various methods, among which the so-called stenting is particularly effective [1].

Stenting is a medical minimally invasive surgical intervention to install a stent (a special metal frame that is placed in the lumen of hollow organs and vessels) and provides expansion of the area of the cardiovascular system, which was narrowed by the pathological process.

The history of development of stents began in the late 1970s. But only in the early 1990s, the effectiveness of the stenting method was proven to restore the patency of the coronary artery and keep it in a new state [2, 3].

Stents fabrication is a precision and very expensive technology involving the processing of thin-walled tubular metals [4, 5]. Without dwelling on a detailed criticism of the known methods of manufacturing stents, one can point to the possibility of stamping frameworks from hollow cylindrical conductors using Magnetic Pulse Metal Processing (MPMP, in the west terminology this is Electromagnetic Metal Forming, EMF) methods. Such a non-contact production operation, the so-called «expansion», was successfully tested when processing massive tubular billets with large transverse dimensions in the mode of high-frequency act fields [6, 7].

It should be noted that during magnetic pulse processing of tubular parts, all their parameters are set and all factors that can affect the accuracy of part processing are taken into account [8–10].

The tools of the method (as a rule, single-turn or multi-turn solenoids), also, as in the case of flat stamping [11, 12], were located in the zone subject to deformation [13–15].

As for the processing of thin-walled conductors, the most successful was the production operations to eliminate dents in the low-frequency mode of excited fields, which ensured the attraction of specified damaged areas on the sheet metal's surface [16, 17].

Returning to the magnetic-pulse «expansion», it should be noted that its limitations were established by the minimum transverse dimension of the tool that can be practically made [11, 18]. Nevertheless, if we ignore the traditional approaches and methods of implementing the method, then the magnetic-pulse «expansion» of hollow conducting cylinders, even of small diameter, seems feasible. But other tools are needed to perform this operation. Physically, their principle of operation should be based on the interaction of the azimuthal component of the magnetic field strength with the longitudinal current in the billet metal.

The practical implementation of this proposal can be carried out according to two concepts shown in Fig. 1.

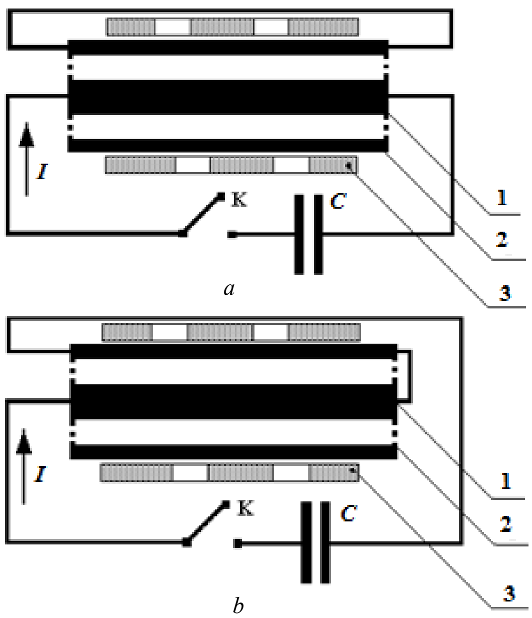

Fig. 1. Principal diagrams of magnetic-pulsed «expansion» of a hollow cylindrical billet: *1* – inductor-current conductor; *2* – tubular billet; *3* – matrix with holes

Problem statement. In the system in Fig. 1,*a*, «expansion» is carried out by the field interaction forces with eddy currents induced in the billet metal.

The difference between this scheme from the analogs known in MPMP is that:

- the source of the magnetic field is a linear conductor, not a solenoid;
- force pressure is excited by the azimuthal rather than the longitudinal component of the magnetic field strength (in traditional designs of inductor systems, the situation is reversed);
- an additional conductor was introduced to ensure the closed circuit for the flow of induced current.

In contrast to the first proposed scheme, the system in Fig. 1,*b* assumes the direct passage of current through the billet. In this case, there must be an electrodynamic interaction between the magnetic field of the current in the inner conductor and the total current (connected and induced) in the billet [19].

A priori, it is obvious that the second scheme is preferable to the first one from the point of view of energy and efficiency of the given technological operation.

The absence of penetration of the magnetic field into the free space through the metal of the processed object is common to the proposed schemes. This means that the force acting on it should be maximal [11, 18, 19].

In fairness, it should be noted that similar technical solutions for the design of magnetic-pulse tools have already been described in the technical literature. Closest to the proposed method (Fig. 1,*b*) is a device for forming pipes of small diameter [20]. This system consists of two electrically conductive pipes isolated from each other and an internal mandrel – a matrix. The discharge current from the capacitor bank is directed through the outer pipe and taken back through the inner pipe. The resulting forces compress it towards the mandrel, which is melted after the operation. As a result, the inner tube takes the required shape of the matrix. Here there is no description of any conditions for the practical performance of the proposed device in the cited publication, although its effectiveness in the case of field penetration through the metal of the inner pipe is doubtful.

It should be noted that from a mathematical point of view, both proposed systems (Fig. 1) require the solution of the same boundary value problem. The features inherent in each of these systems can be taken into account at the final stage of determining the characteristics of the ongoing electromagnetic processes.

In the proposed system with the «direct passage of current», the object of processing is the outer tubular billet. The forces acting on it do not depend on the nature of the ongoing electromagnetic processes and, as already indicated, reach a maximum.

Let us dwell on this design of the inductor system, a characteristic feature of which is the presence of an internal conductor connected in series with an external hollow cylinder. In the terminology familiar to magnetic-pulse processing of metals, we will call the internal current conductor an inductor, a hollow cylinder – a tubular billet to be deformed according to the profile of the matrix. Since we were talking about stents, the holes in the matrix should ensure the punching of the corresponding holes in the tubular billet.

In the future, the proposed system will be called an inductor system for the «expansion» of hollow thin-walled metal cylinders of small diameter with «direct passage of current» through the billet.

The purpose of this work is to derive the main analytical dependencies for the characteristics of the electromagnetic processes taking place in the inductor systems for the expansion of cylindrical conductive pipes of small diameter when direct passage of current through the processed object and when it is not connected to an electric circuit with an inductor (insulated billet).

Fields and currents, analytical dependences. The geometry in the cross-section of the system in Fig. 1,*b*, obtained by a mental cut of a tubular billet with a central internal conductor, is shown in Fig. 2.

Before proceeding to the formulation of the problem, we note the physical feature of the forthcoming consideration. We are talking about the influence of induction effects on the excited fields and currents in the system under consideration. In the simplest approach from the point of view of circuit theory, that is, in the neglect of inductive effects, the magnetic pressure forces are proportional to the square of external currents (from external power sources). But it is obvious that this assumption significantly distorts the adequacy of the calculations and the characteristics of the processes studied with their help [19]. A priori, we can assume that the fields and currents in the system are always determined by the algebraic sum of external and excited components.

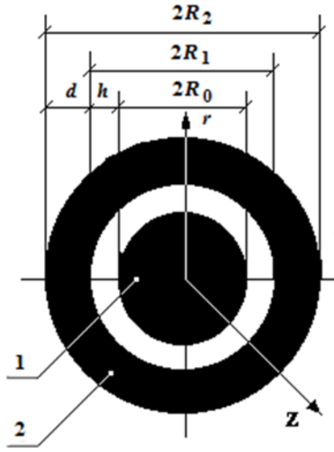

Fig. 2.
Calculation model of the system for magnetic-pulse expansion of a tubular billet of small diameter
(cross section Fig. 1,*b*):
1 – central internal conductor;
2 – conductive thin-walled tubular billet

Let us formulate assumptions that establish the level of adequacy of the accepted calculation model and the real inductor system:

- The matrix is made of a dielectric, so there is free space outside the tubular billet.
- A cylindrical coordinate system is acceptable, related to the considered cross-sectional configuration according to Fig. 2.

The system has a sufficiently large length in the longitudinal direction (perpendicular to the plane of the drawing) and azimuth symmetry, so that

$$\partial/\partial\varphi \approx 0 .$$

- In the metal of the internal current conductor (this is the inductor) and the external tubular billet $I(t)$ current flows, the time parameters of which are such that the ongoing electromagnetic processes can be considered quasi-stationary and

$$\omega R_{1,2}/c << 1 ,$$

where ω is the cyclic frequency of the acting field; c is the velocity of light in vacuum.

- The billet being processed is rather thin-walled, so that

$$\omega \cdot \tau << 1 ,$$

where $\tau = \mu_0\, \gamma\, d^2$ is the characteristic diffusion time of the field into a conductive layer with specific electrical conductivity γ; $d = R_2 - R_1$ is the thickness of the layer; μ_0 is the magnetic table.

- According to the longitudinal geometry of the system under study (Fig. 1,*b*), the currents in the conductor – the inductor and the tubular billet are equal in magnitude, but oppositely directed.
- An electromagnetic field is being excited with non-zero components $E_z(r, t) \neq 0$ and $H_\varphi(r, t) \neq 0$.

Maxwell's equations for the Laplace-transformed non-trivial components of the electromagnetic field vector in the metal of the processed tubular billet are written in the form [18, 21]:

$$\begin{cases} \dfrac{\partial E_z(r,p)}{\partial r} = p \cdot \mu_0 \cdot H_\varphi(r,p); \\ \dfrac{1}{r} \cdot \dfrac{\partial}{\partial r}\left(r \cdot H_\varphi(r,p)\right) = \gamma \cdot E_z(r,p) + j_z(p,r), \end{cases} \qquad (1)$$

where p is parameter of the Laplace transformation; $j_z(p,r)$ is the density of the external current:

$$j_z(p,r) = j(p) \cdot f(r); \quad j(p) \approx \frac{I(p)}{2\pi \cdot R_1 \cdot d},$$

where $f(r)$ is the function of the distribution of the thickness of the pipe.

Within the accepted assumption about its thin walls we have

$$f(r) \approx \begin{cases} 1, & r \in [R_1, R_2]; \\ 0, & r \notin [R_1, R_2]; \end{cases}$$

$$E_z(p, r) = L\{E_z(t, r)\},\ H_\varphi(p, r) = L\{H_\varphi(t, r)\},$$

where $I(p) = L\{I(t)\}$ are L-images of the electrical and magnetic field intensities, as well the currents in the tubular billet metal.

System (1) is reduced to an inhomogeneous differential equation for the longitudinal component of the electric field [22]:

$$\frac{\partial^2 E_z(p,r)}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial E_z(p,r)}{\partial r} - k^2(p) \cdot E_z(p,r) = = p \cdot \mu_0 \cdot j(p) \cdot f(r), \qquad (2)$$

where $k(p) = \sqrt{p \cdot \mu_0 \cdot \gamma}$ is a wave number in the billet metal.

In accordance with the statement of the problem under consideration in the inductor and billet, the currents are equal in magnitude but directed oppositely. From here, the boundary conditions for the excited azimuthal component of the magnetic field intensity will be as follow:

a) on the external side of the tube:

$$H_\varphi(p, r = R_2) = 0\,; \qquad (3)$$

b) on the inner wall of the tube:

$$H_\varphi(p, r = R_1) = \frac{I(p)}{2\pi \cdot R_1}\,. \qquad (4)$$

The general integral of the inhomogeneous equation (2) can be found using the method of variation of arbitrary constants [22, 23]:

$$E(p,r) = C_1(p,r) \cdot I_0(k(p)r) + C_2(p,r) \cdot K_0(k(p)r), \qquad (5)$$

where $I_0(k(p)r)$, $K_0(k(p)r)$ are the modified zero-order Bessel functions; $C_{1,2}(p,r)$ are unknown functions involving arbitrary integration constants.

According to the accepted method for variables $r \in [R_1, R_2]$ we write down the system of equations for unknown functions $C_{1,2}(p,r)$ [22]:

$$\begin{cases} \dfrac{\mathrm{d}C_1(p,r)}{\mathrm{d}r} \cdot I_0(k(p)r) + \dfrac{\mathrm{d}C_2(p,r)}{\mathrm{d}r} \cdot K_0(k(p)r) = 0, \\ \dfrac{\mathrm{d}C_1(p,r)}{\mathrm{d}r} \cdot \dfrac{\mathrm{d}I_0(k(p)r)}{\mathrm{d}r} + \dfrac{\mathrm{d}C_2(p,r)}{\mathrm{d}r} \cdot \dfrac{\mathrm{d}K_0(k(p)r)}{\mathrm{d}r} = p\mu_0 j(p). \end{cases} \qquad (6)$$

We shall find from the first equation of the differential system (6), that

$$\frac{\mathrm{d}C_2(p,r)}{\mathrm{d}r} = -\frac{\mathrm{d}C_1(p,r)}{\mathrm{d}r} \cdot \frac{I_0(k(p)r)}{K_0(k(p)r)}. \qquad (7)$$

We substitute expression (7) into the second equation of system (6). After the necessary identical transformations, we obtain, that

$$\frac{\mathrm{d}C_1(p,r)}{\mathrm{d}r} = p\mu_0 j(p) \cdot r \cdot K_0(k(p)r). \qquad (8)$$

Integrating (8), we can find unknown function $C_1(p, r)$:

$$C_1(p,r) = j(p)\sqrt{p\mu_0/\gamma} \cdot r \cdot K_1(k(p)r) + C_1(p), \qquad (9)$$

where $K_1(k(p)r)$ is the modified first order Bessel function; $C_1(p)$ is an arbitrary constant of integration.

We substitute the derivative from (8) into expression (7). After integration and identical transformations, we obtain a formula for the second unknown function $C_2(p, r)$:

$$C_2(p,r) = -j(p)\sqrt{p\mu_0/\gamma}\cdot r\cdot I_1(k(p)r) + C_2(p), \quad (10)$$

where $I_1(k(p)r)$ is the modified first order Bessel function; $C_2(p)$ is an arbitrary constant of integration.

Let us substitute dependences (9), (10) into the general integral (5). We get that

$$\begin{aligned} E_z(p,r) &= C_1(p)I_0(k(p)r) + C_2(p)K_0(k(p)r) + \\ &+ j(p)\sqrt{p\mu_0/\gamma}\cdot r\cdot B_1, \end{aligned} \quad (11)$$

where B_1 is defined in the form:

$$B_1 = K_1(k(p)r)\cdot I_0(k(p)r) - I_1(k(p)r)\cdot K_0(k(p)r).$$

The expression for the electric field intensity (11) should be substituted into the first equation of system (1). As a result, we find the magnetic field intensity in the tube metal

$$H_\varphi(p,r) = \sqrt{\gamma/p\mu_0}\cdot B_2 + 2j(p)rK_1(k(p)r)\cdot I_1(k(p)r), \quad (12)$$

where B_2 is defined in the form:

$$B_2 = C_1(p)\cdot I_1(k(p)r) - C_2(p)\cdot K_1(k(p)r).$$

From the given boundary conditions, one can determine unknown arbitrary constants in (12). However, finding them in general requires very cumbersome mathematical transformations. This operation can be somewhat simplified if, according to the accepted formulation of the problem, an additional condition is introduced according to which $|k(p)\cdot R_{1,2}| < 1$ [13, 18].

Actually, this mathematical assumption determines the temporal characteristics of the mode of force impact on the processing object, that is, the frequency range of the active fields.

Let us write down this condition and obtain a quantitative estimate of its fulfillment:

$$|k(p)\cdot R_{1,2}| < 1 \Rightarrow \sqrt{\omega\cdot\mu_0\cdot\gamma}\cdot R_{1,2} << 1$$

and obtain a quantitative estimate of its fulfillment

$$f < \frac{1}{2\pi\cdot\mu_0\cdot\gamma\cdot R_{1,2}^2}. \quad (13)$$

Thus, inequality (13) determines the range of operating frequencies, the value of which is acceptable in subsequent numerical estimates. It should be noted that, as shown by the authors of the scientific publication [13], at $R_{1,2} \to d$ (practically corresponds to the ultra-small transverse size of the system), this inequality will simultaneously be the condition for the «transparency» of the processed metal for excited electromagnetic fields.

When (13) is fulfilled, expression (12) takes the form:

$$H_\varphi(p,r) \approx \frac{\gamma\cdot r}{2}\left[C_1(p) - C_2(p)\frac{2}{k^2(p)r^2}\right] + j(p)\cdot r. \quad (14)$$

Now let us determine the unknown constants – $C_{1,2}(p)$.

With help of (3) and (14) we shall find, that

$$C_2(p) = \frac{k^2(p)R_2^2}{2}\left[C_1(p) + \frac{2}{\gamma}\cdot j(p)\right]. \quad (15)$$

We substitute expression (15) into (14), after which we use the second boundary condition from (4). We get:

$$C_1(p) = -\frac{2\cdot j(p)}{\gamma}\left[1 + \left(\frac{d}{R_1}\right)\frac{1}{(R_2/R_1)^2 - 1}\right]. \quad (16)$$

We substitute formulas (15) and (16) into (14). We obtain an analytical dependence for the strength of the magnetic field excited in the metal of a thin-walled tubular billet

$$H_\varphi(t,r) = I(t)\cdot\frac{r\cdot\left((R_2/r)^2 - 1\right)}{2\pi R_1^2\cdot\left((R_2/R_1)^2 - 1\right)}. \quad (17)$$

Next, we find the strength of the excited electric field. The fulfillment of constraint (13) allows us to pass in (11) from modified Bessel functions to their representations in the neighborhood of zero [22, 23].

A further estimate of

$$\left(k(p)\cdot R_{1,2}\right)^2 \ln\left(k(p)\cdot R_{1,2}\right)\Big|_{(k(p)\cdot R_{1,2})\to 0} \sim \left(k(p)\cdot R_{1,2}\right)^2$$

sufficiently small of the second order and significantly simplifies the formula (11). In the result obtained, one should introduce expressions for arbitrary constants $C_1(p)$ and $C_2(p)$.

After the transition to the space of originals, we find the strength of the excited electric field [22]:

$$E_z(t,r) \approx -\frac{I(t)}{2\pi R_1 d\gamma}\left[1 + 2\frac{d}{R_1}\cdot\frac{1}{(R_2/R_1)^2 - 1}\right]. \quad (18)$$

Multiplying expression (18) by the electrical conductivity of the metal of the tubular billet, we obtain a formula for the density of the induced current:

$$j_i(t) \approx -\frac{I(t)}{2\pi R_1 d}\left[1 + 2\frac{d}{R_1}\cdot\frac{1}{(R_2/R_1)^2 - 1}\right]. \quad (19)$$

System with «direct passage of current» through the processed billet. Summing up the density of external and induced currents, in accordance with the right side of the second Maxwell equation from the system (1), we find the integral current in the metal of the tubular billet

$$j_s(t) \approx -\frac{I(t)}{\pi R_1^2}\cdot\frac{1}{(R_2/R_1)^2 - 1}. \quad (20)$$

Thus, the obtained expressions (17), (18) and (20) represent the characteristics of electromagnetic processes in the system with «direct passage of current» through the deformation object (Fig. 1,*b*).

A system with a billet that is isolated from inductor.

There is no extraneous current in the tubular billet without its electrical connection to the inductor (Fig. 1,*a*).

With the excited magnetic field – (17) no longer the total, but only the induced signal – formula (19) will interact. In this case, the set of analytical expressions (17) – (19) will already describe electromagnetic processes in a structure with an electrically isolated object of deformation.

A comparative assessment of the effectiveness and efficiency of the proposed systems is interesting from a practical point of view. From this point of view, it is expedient to obtain appropriate ratios.

With the help of expressions (19), (20), we write the formulas for the density of electrodynamic forces (pondermotive forces per unit volume [22]) on the inner surface of the billets in various designs of the proposed systems and the density ratio of the currents excited in them:

$$\begin{cases} f_s = j_s(t)\cdot H_\varphi(t, r=R_1) = j_0^2(t)\cdot d\cdot\left(\dfrac{R_2 d}{R_1^2}\right)\cdot\dfrac{1}{(R_2/R_1)^2 - 1}; \\ f_i = j_i(t)\cdot H_\varphi(t, r=R_1) = j_0^2(t)\cdot d\cdot\left[1 + 2\dfrac{d}{R_1}\cdot\dfrac{1}{(R_2/R_1)^2 - 1}\right]; \\ \dfrac{j_i(t)}{j_s(t)} \approx \dfrac{R_2^2}{2\cdot d\cdot R_1}, \end{cases} \quad (21)$$

where f_s is the density of electrodynamic forces during the direct passage of current through the processing object;

f_i is the density of electrodynamic forces in the case of an isolated tubular billet; $j_0(t) \approx I(t)/2\pi R_1 d$ is the current density in the billet without taking into account induction effects.

Let us analyze the got results.

- When $r \to R_1$ the intensity of the excited magnetic field is:

$$H_\varphi \to \frac{I(t)}{2\pi \cdot R_1},$$

what corresponds to the law of total current and is evidence of the reliability of the formula (17) [21].

- The densities of excited electrodynamic forces depend significantly on the induction effects in both proposed systems ($f_{s,i}$ in (21)).
- The current densities in the treated objects are proportional to the proportionality factor determined by the geometry of each of the proposed systems ($j_{i,s}$ in (21)).

Conclusions.

1. Magnetic pulse systems was proposed for distributing hollow thin-walled metal cylinders of small diameter both with direct current passing through the object of deformation and without connecting the latter to the electric circuit of the inductor.
2. On the basis of a well-founded physical and mathematical model, the main analytical dependencies for the characteristics of electromagnetic processes occurring in the proposed systems were found.
3. The reliability of the found results was shown with the help of boundary transitions.
4. The significant dependence of excited electrodynamic forces on induction effects in both proposed systems was shown.

Conflict of interest. The authors declare no conflict of interest.

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