METHOD OF INCREASING THE EFFICIENCY OF AN ELECTROMAGNET INDUCTION CONDUCTOR ACCELERATOR

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One of the methods of producing supersonic velocities in solids to investigate high-speed interactions is to accelerate conductors in a pulsed magnetic field [1, 2]. In the induction acceleration of ring conductors of relatively low mass using capacitor batteries the efficiency of the acceleration process is reduced due to the escape of the accelerated body from the inductor magnetic field [3]. The efficiency of the conversion of electromagnetic energy into kinetic energy of the accelerated conductor can be increased by forcing the magnetic pressure either by keeping the accelerated body in the initial position until the energy density of the field of the electromagnet supplied to the inductor system from the external source reaches a sufficiently high level corresponding to the required value [4], or by increasing the rate at which the energy of the electromagnet is introduced into the inductor system. In this paper we consider a method of increasing the efficiency of a high-speed induction accelerator of ring conductors by increasing the rate at which the electromagnet energy is introduced into the inductor system.

In the practical application of a high-speed solid accelerator the need arises to cover the maximum possible range of velocities of projected bodies of different mass. When the parameters of the load and the energy source in the induction accelerator are correctly matched one can obtain high conversion efficiency of the electromagnet energy into kinetic energy of the accelerated body [3]. However, when projecting relatively small masses good matching and the achievement of high velocities are limited by the rate at which the energy can be transferred from the capacitive store to the inductor system.

It is possible to increase the rate at which energy is introduced into the inductive load within certain limits by reducing the inductance of the discharge circuit and increasing the charging voltage of the capacitor battery. A large rate of increase of the magnetic field in the inductor system can also be obtained by switching the energy store discharge current into parallel circuits (accentuating the current leading edge).

Figure 1 shows the equivalent circuit of an induction accelerator of ring conductors with a current leading edge accentuator in the inductor.

While the capacitor battery is charging the switches S_1 and S_2 are open, and the switch S_3 is closed. After S_1 is connected the battery discharges through the inductance L_0, the resistance of the discharge circuit R_0, and the resistance of the switch R_S. If at a certain instant of time the switch S_3 is opened and S_2 is closed, then in the branch L_1 there will be a sharp increase in the current, the rate of rise of which is higher than in the usual RLC circuit.

We can use ordinary switching components used in high-current pulse techniques (dischargers and ignitrons) as the components S_1 and S_2. The switch S_3, which must discharge higher currents at higher voltages, is a more complex component. A suitable type of switch exists, based on the principle of exploding metal wires or foil. Despite the large number of papers devoted to an investigation of the processes in a conductor when it is electrically exploded, so far there appears to be no generally accepted theory which would

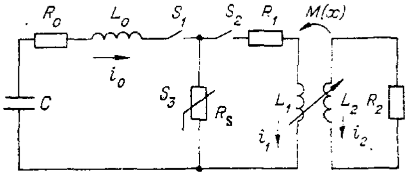

Fig. 1

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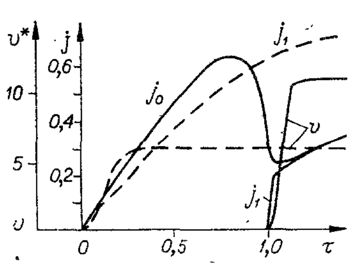

Fig. 2

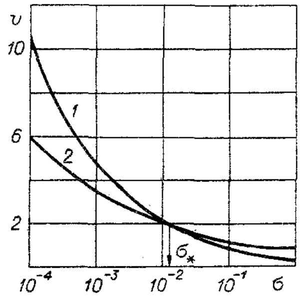

Fig. 3

enable one to explain and give a quantitative description of these processes. In [5], using a number of simplifying assumptions, a mathematical simulation of the first current pulse which occurs in the electrical explosion of conductors is given, and it is shown that a computer calculation of the main parameters characterizing the electrical explosion of conductors as a function of the quantity $\Pi = GU_0^6C^5l/L_0^2S^7$ gives good agreement with experimental results. Here U_0 is the initial voltage across the capacitor battery, L_0 is the inductance of the discharge circuit, l and S are the lengths and area of transverse cross section of the exploding conductor, $G_{Cu} = 6.72 \cdot 10^{-60}$ kg · m^{15}/A^8 · sec^6, and $G_{Al} = 1.25 \cdot 10^{-59}$ kg · m^{15}/A^8 · sec^6. A similar set of parameters for the discharge circuit and the geometrical dimensions of the exploding wire was used in [6] to calculate certain parameters of the electrical explosion of conductors. The quantity Π can be represented in terms of the similarity criteria $\pi_1 = \rho_0 l/ZS$ and $\pi_2 = W_0/ZS^2$ introduced in [6] as $\Pi = G\pi_1\pi_2$, where W_0 is the energy stored in the capacitors, $Z = \sqrt{L_0/C}$ is the wave impedance of the discharge circuit, and ρ_0 is the initial resistivity of the exploding wire.

When investigating the circuit we used the mathematical model of an electrically exploded conductor proposed in [5], and in addition we made the following assumptions: 1) The resistances R_0, R_1, and R_2, and the inductances L_0, L_1, and L_2 of the circuit remain constant during the discharge, 2) the switches S_1 and S_2 are ideal, i.e., the switching occurs instantaneously and without loss, 3) the switch S_2 closes at the instant corresponding to maximum voltage on the switch S_3, and 4) the resisting forces acting on the accelerated ring are small.

The set of equations describing the processes in the accelerator have the following dimensionless form:

$$dj_0/d\tau + r_0j_0 + r_s(\tau)(j_0 - j_1) + \varphi_0 = 0; \tag{1}$$

$$d\varphi_0/d\tau = j_0; \tag{2}$$

$$\frac{dj_1}{d\tau} + \frac{L_0}{L_1} r_1j_1 + \frac{L_0}{L_1} r_s(\tau)(j_1 - j_0) + \frac{d}{d\tau}[\mu(\varepsilon)j_2] = 0; \tag{3}$$

$$\frac{dj_2}{d\tau} + \frac{L_0}{L_2} r_2j_2 + \frac{d}{d\tau}[\mu(\varepsilon)j_1] = 0; \tag{4}$$

$$\frac{d^2\varepsilon}{d\tau^2} = \frac{1}{\sigma}\frac{d\mu(\varepsilon)}{d\varepsilon} j_1j_2. \tag{5}$$

The dimensionless and dimensional quantities are connected by the following relations:

$$j = i/i_{nd};\ U/U_{nd} = \varphi;\ r = R/R_{nd};\ \tau = t/t_{nd}\ \varepsilon = x/x_{nd};\ \mu = M/M_{nd};\ \sigma = m/m_{nd}$$

We took the following as the basic quantities:

$$R_{nd} = \sqrt{L_0/C},\ L_{nd} = L_0,\ M_{nd} = L_1,\ i = U_0\sqrt{C/L_0},$$
$$U_{nd} = U_0,\quad t_{nd} = \sqrt{L_0C},\quad m_{nd} = C^2U_0^2L_0/D^2,\quad x_{nd} = D,$$

where m is the mass of the accelerated ring, x is the coordinate of the displacement, and D is the mean diameter of the inductor and the body.

In this case, we take as the basic inductance (unlike [3]), the inductance of the store L_0, and not L_1, since in this case the problem of determining the mass of the conductor for which accentuation of the current leading edge leads to an increase in its final velocity is made easier.

The system of differential equations (1)-(5) was integrated on the ES-1020 computer using the Runge-Kutta method with a variable step. The error in calculating the variables was 0.1%. In the integration we neglected the heating of the inductor and of the accelerated ring, and their mutual inductance was calculated

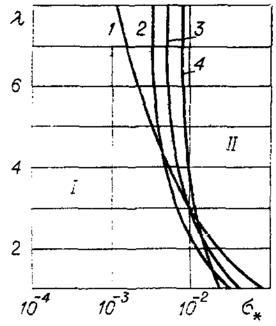

Fig. 4

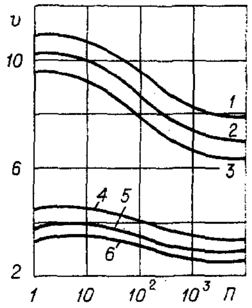

Fig. 5

as in [7]. To monitor the correctness of the program compiled and the reliability of the results obtained we calculated the energy balance. The error in calculating the total energy in the system varied from 0.1% to 3%.

Figure 2 shows the results of a calculation of the acceleration transient of a ring conductor of circular cross section when the diameter of the inductor and of the accelerated ring are the same in an accelerator with accentuation and without accentuation (the continuous and dashed curves, respectively) of the current leading edge in an inductor with $r_1 = r_2 = 0$. Here and later the relative initial gap between the inductor and the body $\varepsilon_0 = 0.01$.

Figure 3 shows the results of a calculation of the final relative velocity of the conductor as a function of the parameter σ for $\Pi = 10$, $\lambda = L_0/L_1 = 3$, and $r_1 = r_2 = 0$. It can be seen from a comparison of the curves that accentuation of the current leading edge in an inductor when projecting bodies the relative mass of which is less than a certain critical value σ_* leads to an increase in the velocities obtained. The efficiency of the accentuation increases as σ is reduced. Thus, for $\sigma = 10^{-4}$ the increase in the velocity due to current accentuation is 72% compared with 36% for $\sigma = 10^{-3}$ and 6% for $\sigma = 10^{-2}$. The relation between the critical relative mass of the accelerated conductor and the parameter λ for $\Pi = 10$ is shown in Fig. 4. In zone I accentuation of the current leading edge in the inductor leads to an increase in the final velocity of the conductor. Here we show the effect of the relative resistances of the inductor r_1 and the accelerated ring r_2 on the change in the zone I [1) $r_1 = r_2 = 0$; 2) $r_1 = r_2 = 0.05$; 3) $r_1 = r_2 = 0.1$; 4) $r_1 = r_2 = 0.2$].

The variation of the final velocity of the projected conductor as a function of the quantity Π for different relative masses [1-3) $\sigma = 10^{-4}$; 4-6) $\sigma = 10^{-3}$] and different ratios of the internal inductance of the source to the inductance of the inductor [1, 4) $\lambda = 3$; 2, 5) $\lambda = 5$; 3, 6) $\lambda = 7$] is shown in Fig. 5.

To obtain the maximum value of the final velocity of the conductor it is necessary to choose Π in the range from 1 to 10. This is particularly important for the correct choice of the transverse cross section of the exploding wire of the switch S_3.

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