CONTACTLESS INDUCTION ACCELERATION OF CONDUCTORS UP TO HYPERSONIC SPEEDS

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The results of an experimental investigation of the induction acceleration of ring conductors having a mass of 0.5-3 g in the pulsed magnetic field of a single-turn inductor are presented. It is shown that low-inductive capacitive energy stores in conjunction with single-turn single-shot inductors are very efficient. A speed of 3.7 km/sec was obtained experimentally with an aluminum conductor of mass 0.77 g. Methods of measuring the very high speeds of projected objects are described. The interaction of the accelerated conductor with thick and thin barriers was investigated, and the possibility of controlling the area of the damaged surface is pointed out. The results of the experiment agree well with calculations carried out on a computer which indicate the possibility of a further increase in the speed of projection.

Devices which project objects at high speeds are used at the present time in many areas of science and technology to investigate the properties of materials under pulsed loading conditions, to test welds when subjected to high-speed impacts, to investigate the formation of craters due to high-speed impacts, to study aerodynamic and physical or physicochemical phenomena which occur in high-speed flight, etc.

Of the various methods available [1, 2, 3] for accelerating solid bodies up to high and superhigh speeds the most promising one is the acceleration of conductors in a pulsed magnetic field. A velocity of the order of 1 km/sec has been obtained [4] in projecting aluminum disks of mass 10-30 g in the pulsed field of a plane inductor. To increase the limiting speed set by heating, "current division" between the projected object and the inductor has been used [5] and speeds of up to 10.5 km/sec have been obtained in short aluminum conductors of mass $(1\text{-}3)\cdot 10^{-4}$ g. However, in a number of investigations it is necessary to project large masses.

In this study we investigated the projection of conductors of mass 0.5-3 g up to speeds of 3-5 km/sec using capacitive energy storage to produce intense magnetic fields.

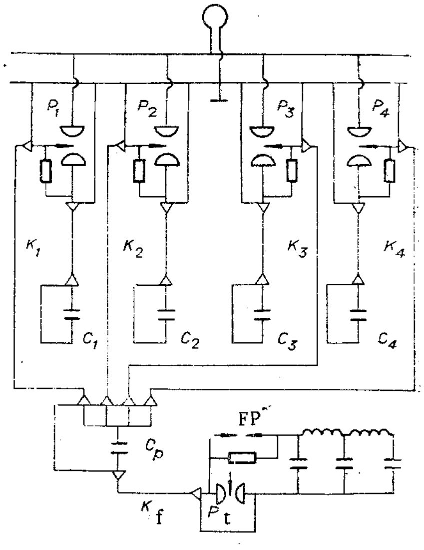

Fig. 1

EXPERIMENTAL ARRANGEMENT

The use of high-voltage capacitive energy stores (CES) in conjunction with a low-inductance discharge circuit enables one to increase the current gradient and hence reduce the magnetic field buildup time.

Figure 1 shows the basic electric circuit of the experimental setup. The capacitors of each of the four blocks of the CES (C_1, C_2, C_3, and C_4) are connected by means of coaxial cables to the respective dischargers P_1, P_2, P_3, and P_4. Trigatron dischargers with ring electrodes operating with a high pressure of air in the operating

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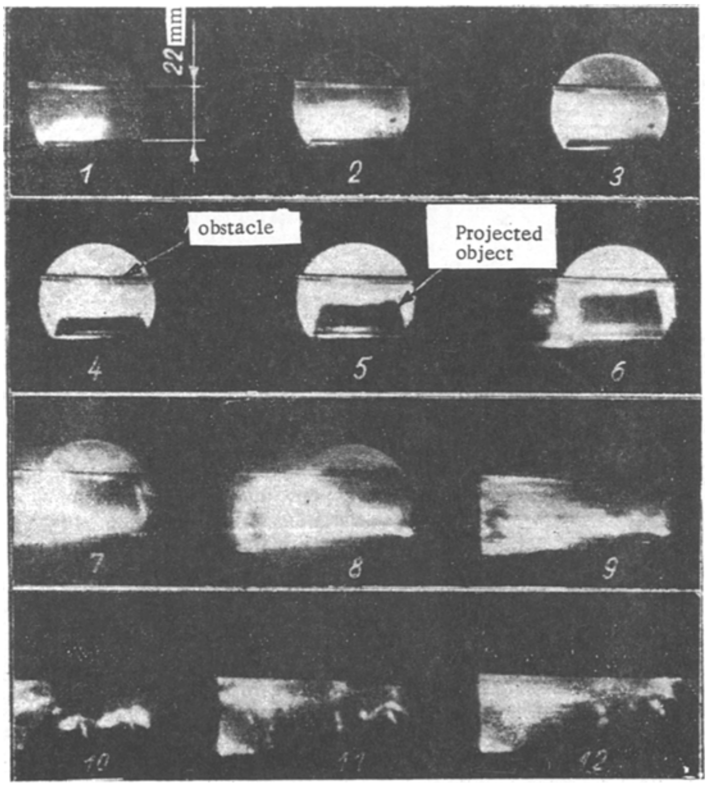

Fig. 2

volume are used as the main switches. The dischargers are connected by flat leads of Duralumin having low inductance for connection of the inductor system.

The capacitors are charged up to the required voltage from a charging device. The necessary undervoltage in the gap between the electrodes of the dischargers is controlled by the pressure of the air in the operating chambers. A voltage of opposite sign is applied to one of the plates of the isolating capacitor C_p and the firing cable K_f. When a voltage pulse is applied from the control panel to the firing electrode of the triggering discharger (P_t), breakdown occurs and a voltage pulse propagates along the cables (K_f, K_1, K_2, K_3, K_4) to the firing electrodes of the dischargers. When the dischargers break down the four CES blocks discharge through the inductor.

INDUCTOR SYSTEM

When accelerating ring conductors up to very high velocities, in view of the limited energy capacity of the stores, high-speed projection can be obtained for bodies of comparatively small mass which inevitably leads to a reduction in the diameter of the ring, since to achieve high limiting speeds when heat is produced it is necessary to increase the cross section of the projected conductor. To eliminate the radial component of the force acting on the projected ring the diameters of the ring and the inductor must be equal [6].

Multiple operation of a single-turn inductor of small dimensions without its complete or partial disintegration when high pulsed currents pass through it is limited by the mechanical strength of the inductor [7, 8], and for fields of the order of 100 T and higher is impracticable. Extremely intense fields can be produced using a thin-walled inductor, which does not possess a high mechanical strength. Thus, in experiments to produce extremely high magnetic fields, (up to 250 T) we have used a very simple coil construction [9]: by bending a copper plate of thickness 1 mm we produced a single-turn solenoid. Due to the extremely small rise time (about 1.8 μsec) the magnetic field reaches a maximum before any appreciable deformation and thermal breakdown of the solenoid occurs. In the present investigation we used a ring winding of copper sheet of width 4 mm and thickness 1.8 mm as the inductor. This winding is part of the inductor system which enables us to connect the inductor to the store quite safely and to replace it rapidly after the discharge.

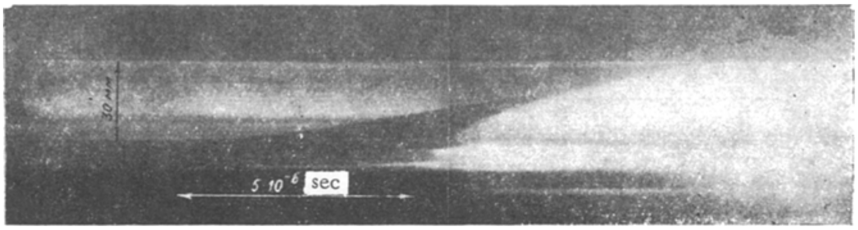

Fig. 3

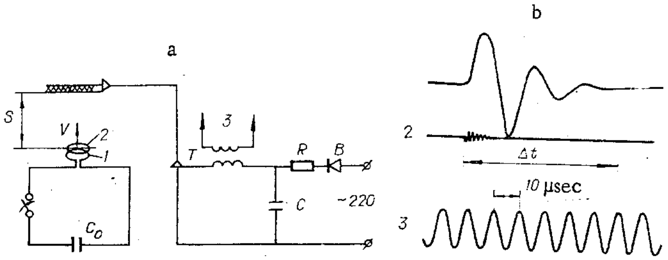

Fig. 4

MEASUREMENT OF THE SPEED OF THE PROJECTED OBJECT

One of the difficult problems in high-speed acceleration is to determine the speed of the body. In this investigation we measured the speed using an SFR-2M high-speed photorecorder and a contact method.

High-speed photography of the acceleration process was carried out under time-loop conditions with photographic recording in transmitted light by the shadow method. For illumination we used the optical system of the OU-2 illuminator with a spark light source. The spark obtained its energy from a shaping line which produced the required illumination intensity and duration. Figure 2 shows a typical high-speed photograph of the acceleration process under time-loop conditions. The dense layers of air obstruct the transmission of light so that parts of the space behind the body are blacked out. Frame 7 illustrates the collision of the body with an obstacle. In frames 7-9 one can see the active propagation of ionized gases when the inductor explodes. After breakdown of the aluminum obstacle of thickness 1 mm the products of the interaction between the body and the obstacle continue to move with approximately the same speed (frames 8-10).

When photographing the acceleration process the parts of the body which are on a line passing through the center of the disk were projected through a narrow slit onto the photographic film. Figure 3 shows typical photographs of the acceleration process. The photographs enable us to see parts of the acceleration and the further practically uniform motion of the body.

The electric circuit for measuring the speed by the contact method (the capacitor-probe method) is shown in Fig. 4a (1 is the inductor, 2 is the projected object, and 3 are the leads to the oscilloscope). Knowing the base distance S and the time of flight of the object along this path we can determine the speed as $V = S/\Delta t$. In this way we determined the average speed of the body, since the acceleration path is included in the base distance. However, since the base distance in the experiments was chosen to be much greater than the acceleration region, the measured value of the speed differs from the actual value within the limits of experimental error. The base distance was measured before each experiment and the time of flight of the object along the path S was found from the oscillograms (Fig. 4b).

The error in measuring the speed is determined by the accuracy with which the high-speed photographs and the oscillograms are processed and is 5-10%.

EXPERIMENTAL RESULTS

The experiments were carried out for average inductor and object diameters from 25 to 40 mm. The width of the object was determined by the width of the copper strip from which the inductor was made, and was 4 mm. The energy of the store varied from 24 to 54 kJ. Speeds of up to 3.7 km/sec were obtained with an efficiency of up to 16%. The results of some of the experiments are shown in Table 1.

TABLE 2

No. of the experiment	Material of the body	Mass of the body, g	Mean diameter, mm	Initial voltage of the CES, kV	Speed, km/sec	Efficiency, %
1	Aluminium	0,91	30	30	3,0	7,6
2	»	0,93	30	30	3,4	10,0
3	»	0,90	30	30	3,5	10,2
4	»	0,70	25	27	3,0	7,2
5	»	0,77	25	30	3,7	9,8
6	»	1,14	35	25	2,1	6,7
7	»	1,00	35	25	2,0	5,3
8	»	1,05	35	20	1,3	3,5
9	»	0,82	30	30	3,5	9,4
10	»	1,22	35	30	3,2	11,5
11	»	1,32	40	30	3,6	15,9
12	Copper	2,34	30	30	1,9	7,8
13	»	2,65	25	30	1,8	8,0

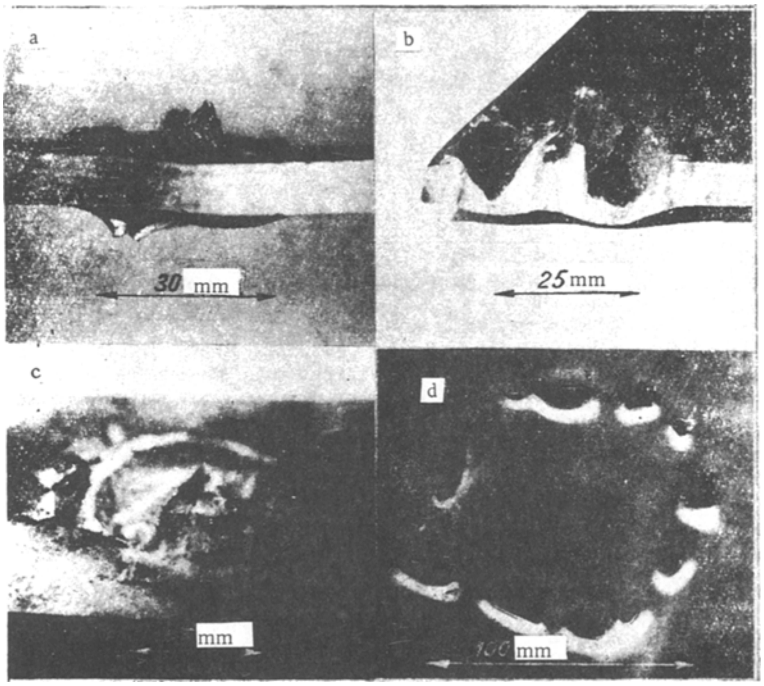

Fig. 5

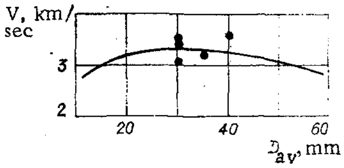

Fig. 6

The photographs showed that the active acceleration of the conductor only occurred along a short section of the path (0.3 D_{av}, where D_{av} is the average diameter), after which the speed remains practically constant.

The main factors that affect the speed are the initial store voltage, the insulation of the gap between the object and the inductor, the mass of the object, the extent to which the dischargers operate in synchronism, the accuracy with which the object is placed in the inductor, etc., as a result of which there will be a spread in the value of the speed for the same parameters.

When the geometrical dimensions (the external and internal diameter) of the inductor and the object are the same the ring shape of the body does not change during the acceleration. However, thin (1 mm) aluminum disks when thrown with a speed greater than 2 km/sec become fractured in the region where the field is weakened over the inductor slit. This can be judged from the craters in the obstacles. It should be noted that even for a small increase in the diameter of the object compared with the diameter of the inductor the presence of a radial component of the force leads to fracture of the body into individual fragments, which fly off in a radial–axial direction and, depending on the distance from the obstacle, strike a greater or lesser part of its area (Fig. 5d). In this case the craters from the collision between the parts of the object and the obstacle are spaced around a circle. A reduction in the average diameter of the object compared with the diameter of the inductor leads to construction of the ring, and a concentrated impact crater remains on the obstacle. In this case the diameter of the crater is less than the external diameter of the accelerated object. Typical forms of the craters due to collisions between the ring conductor and the obstacle are shown in Fig. 5 (a, b correspond to an object mass of 0.77 g, and a speed of 3.0 km/sec; c corresponds to a mass of 0.8 g and a speed of 3.0 km/sec; and d corresponds to a mass of 1 g, an external diameter of 37 mm, a speed of 2 km/sec, and an obstacle of aluminum 1 mm thick).

Comparison of the experimental results with the theoretical results obtained on a computer using the method described in [10] (Fig. 6) showed good agreement, which confirms the possibility of further increasing the speed when the parameters of the CES are increased and when the inductor system is improved.

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