CHARACTERISTICS OF THE TIME SEQUENCE FOR THE HIGH-SPEED METAL JET UNDER AXIAL STRONG PULSED MAGNETIC FIELD*

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Abstract

The tanks and armor vehicles can be damaged by high-speed metal jet caused by the High Explosive Anti-Tank (HEAT). In order to improve the effective length and the penetration capacity of the metal jet, the electromagnetic enhancing system for the metal jet is put forward. Aiming to the effect of the time sequence to the performance of the metal jet, the relationship between the times of the high-speed metal jet and the strong pulsed magnetic field is analyzed, and then a numerical simulation model is established based on the Transient Magnetic Solver. After that the validity of the electromagnetic enhancing system for high-speed metal jet is verified, and the distribution characteristics of the magnetic field and the current density are obtained. It can draw the conclusion that the high-speed metal jet can become deformed with the effect of the axial pulsed magnetic field. And then the high-speed metal jet cannot be put off by the stretching force caused by the uneven velocity distribution. Furthermore, the radius of metal jet may become more even and the effective length will be extended. Thus, the penetration capacity of the metal jet will be improved. It also can be seen from the paper that as to the system analyzed in the paper, the best delay time of the metal jet is 122.5 μs when the velocity is 3000 m/s. Meanwhile, the best delay time is to make the peak point of the discharge current just coincide with the time when the center sections of the metal jet and the magnetic field coil are consistent.

I. INTRODUCTION

The passive electromagnetic armor has been studied by many scientists for many years. Generally, the high-speed metal jet generated by the High Explosive Anti-Tank (HEAT) will be heated, diffused by the radial strong magnetic field in the passive electromagnetic armor [1-2]. It can be seen from the principle of the passive electromagnetic armor that the high-speed metal jet is affected by the strong pulsed magnetic field with the effect of electromagnetic force, magnetohydrodynamic instability, and etc [3-4]. Thus, the penetration capacity of the high-speed metal jet to the tanks and armor vehicles is abated under the interaction of the passive electromagnetic armor. However, what will happen to the high-speed metal jet if the strong pulsed magnetic field works along the axial direction of the metal jet? The problem has been put forward just for a few years and has been studied by some researchers. The research results show that the high-speed metal jet may become deformed [5-7]. The phenomenon of the metal jet at the axial strong pulsed magnetic field can be used to improve the effective length of the metal jet, which is beneficial to the improvement of the penetration capacity of metal jet into the tanks and armor vehicles. It means that the axial magnetic field can improve the damage ability of the high-speed metal jet and has bright prospect in the military fields. Thus, it is usually called enhancing system of the HEAT. However, the research results at present do not take the velocity of the metal jet into consideration. Actually, the metal jet generated by the HEAT is characteristics of high speed. Thus, the speed of the metal jet should match with the pulse width of the pulsed magnetic field. Only when the generating of the pulsed magnetic field and the high-speed metal jet comply with a certain time sequence, the metal jet can obtain better performance. Or else, the metal jet may have passed through the pulsed magnetic field generator but the magnetic field does not begin to work. In order to improve the performance of the enhancing system of the metal jet, this paper will discuss the time sequence of the high-speed metal jet and the strong pulsed magnetic field, and then give the determination method of the delay time for the high-speed metal jet.

II. PRINCIPLE OF THE HIGH-SPEED METAL JET WITH STRONG PULSED MAGNETIC FILED

The working diagram of the high-speed metal jet with strong pulsed magnetic field is shown in Fig.1, which is the key subsystem for the new type HEAT.

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* Work supported in part by the China Scholarship Council under contract number 201500930076
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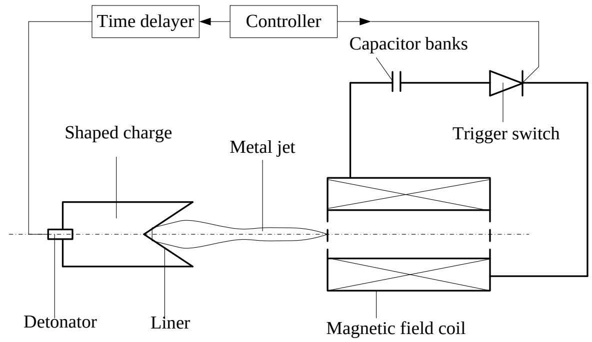

Figure 1. Diagram of working principle

It can be seen from the Fig.1 that it consists of shaped charge, magnetic field coil, detonator, controller, trigger switch, capacitors, time delayer and etc. The working process is as follows: Firstly, the controller sends a trigger signal to the detonator and trigger switch of the magnetic field coil at the same time. After a few of micro seconds delay, the detonator in the shaped charge is ignited, and the shaped charge begins to explode. The liner made of copper in the shaped charge is crushed under the working of the denotation wave and changed into metal jet. As the speed distribution of the metal jet is not even, the metal jet will be stretched along its axial direction. Furthermore, the radius of the metal jet is various at different part along its axial direction.

Meantime, the trigger signal from the controller is sent to the trigger switch of the magnetic field coil. Generally, it may take scores of micro seconds for the switch to be turned on. When the high-speed metal jet passes through the coil in Fig.1, the pulsed power source like capacitor banks will begin to discharge to the coil and generate strong pulsed magnetic field. Meanwhile, the metal jet will be affected by the electromagnetic force and the ohmic heating effect came from the pulsed magnetic field, and then the metal jet becomes deformed. Actually, as the radius of the high-speed metal jet generated by the HEAT is not even, the deformation at different place of the metal jet is not the same. Generally, the deformation at the thin radius place of the metal jet is less than it at the place with large radius. Thus, the radius of the high-speed metal jet may become more even under the working of the pulsed magnetic field, and then the truncation of the metal jet can be avoided. At last, the effective length of the metal jet is improved, and the penetration ability to the tanks and armor vehicles is enhanced. Thus, it is necessary to study the characteristics of the high-speed metal jet under the working of the axial pulsed magnetic field.

III. TIME SEQUENCE OF THE HIGH-SPEED METAL JET AND STRONG PULSED MAGNETIC FIELD

Generally, the minimum velocity of the metal jet is about 3000 m/s, and maximum value may be over 8000 m/s. However, the length of the magnetic field coil is limited for the sake of miniaturization of the enhancing system. It means that it takes much short time for the metal jet to pass through the coil. During the moving of metal jet, the magnetic field coil should provide strong pulsed magnetic field for the metal jet at the same time. As all the time is just a few micro seconds, the time sequence of the high-speed metal jet and the magnetic field is very significant to the performance of the system.

The time for the generating of the metal jet mainly consists of two parts: the response time t_1 of the detonator and the crushing time t_2 of the liner. Thus, the inherent time t_{jet} of the metal jet is as follows:

$$t_{\text{jet}} = t_1 + t_2 \tag{1}$$

However, the strong manetic field generated by the coil is affected by the discharge current of the pulsed power source. Generally, the maximum current means the maximum magnetic field. As the discharge circuit of the magnetic field coil can be seen as an *R*-*L*-C circuit, the time t_0 for the maximum value of the discharge current can be defined as follows:

$$t_0 = \frac{\pi\sqrt{LC}}{2} \tag{2}$$

where, the *C* and the *L* are the equivent capacitance and the equivalent inductance of the discharge circuit, respectively.

Furthermore , a period time *T* of the discharge current or the magnetic field is as follows:

$$T = 2\pi\sqrt{LC} \tag{3}$$

Giving the hypothesis that the length of the magnetic field coil is *d*, the average velocity of the metal jet is *v*, and the length of the metal jet is *l*, then the time t_3 for the metal jet passes through the coil is as follows:

$$t_3 = (l + d) / v \tag{4}$$

Thus, the time sequence of the metal jet and the strong pulsed magnetic field is shown in Fig.2.

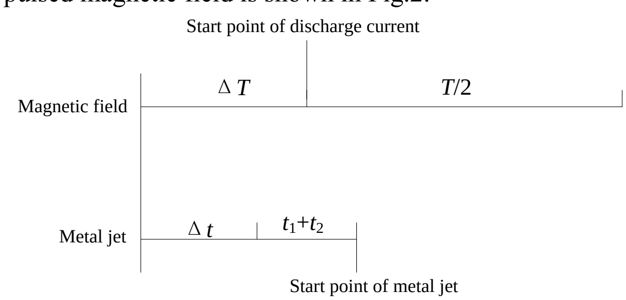

Figure 2. Time sequence of the metal jet and the magnetic field

It can be seend from the Fig.2 that if we want to avoid the truncation of the metal jet and extend the effective length of it under the interaction of the magnetic field, the time sequence should meet the requirments as follows:

$$\Delta T < t_1 + t_2 + \Delta t < \Delta T + \frac{T}{2} \tag{5}$$

where, ΔT is the response time of the trigger switch in the discharge circuit of coil, and Δt is the delay time of the metal jet. Generally, it can use the detonating cord to delay the time.

In the Eq. (5), the ΔT, t_1 and t_2 are always keep constant, which can be obtained by experiment. However, the Δt, which is important to the experiment of the system, is usually estimated according to Eq. (5).

In order to improve the efficiency of the pulsed power source, it should make the maximum area of the discharge current be in the time range of the metal jet passing through the magnetic field coil. Ideally, when the centers of the metal jet and the coil coincide, the discharge current just reaches its peak point. Thus, the Δt can be calculated by the equation as follows:

$$t_1 + t_2 + \Delta t + \frac{t_3}{2} = \Delta T + \frac{T}{4} \tag{6}$$

IV. VERIFICATION OF THE TIME SEQUENCE DETERMINATION METHOD FOR THE METAL JET

In order to analyze the effect of the time sequence to the characteristics of the high-speed metal jet, the numerical simulation model is built and calculated, and some important results are obtained.

A. Establishment of the Simulation Model

As the high-speed metal jet and coil can be seen as a axisymmetric model, the complicate system is simplified as a 2D model. The simulation model is built based on the Transient Magnetic Solver with a RZ coordinate, which is shown in Fig.3.

The band is the motion region of the metal jet, and the region is the calculation area of the solver. The axial length, inner radius, external radius and the turns of the magnetic field coil are 50 mm, 5.8 mm, 17.8 mm, and 10, respectively. The maximum radius and the minimum of the metal jet are 5 mm and 3 mm, respectively. The whole length of the metal jet is 55 mm. Furthermore, both the materials of the coil and the metal jet are copper. The material of the region and the band is air. Besides these parameters, the mass of the metal jet is 100 gram, and the natural boundary condition is set for the boundary condition of the region. The initial position of the metal jet is designed according to the simulation requirements.

In order to improve the simulation accuracy, the excitation source of the coil is provided by an external circuit, which is shown in Fig.4.

It can be seen from the Fig.4 that the capacitance and voltage of the capacitors is 1200 μF and 10 kV, respectively. The equivalent resistance of the discharge circuit is about 20 mohm.

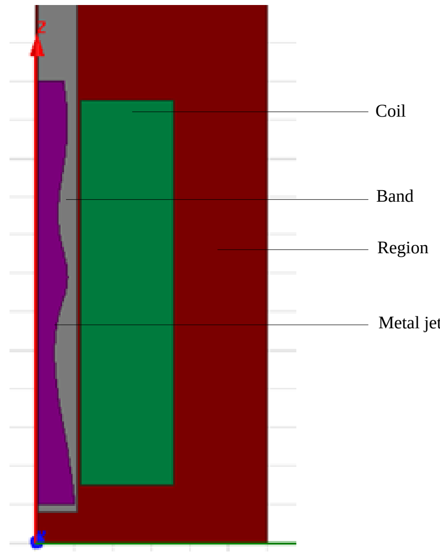

Figure 3. Simulation model

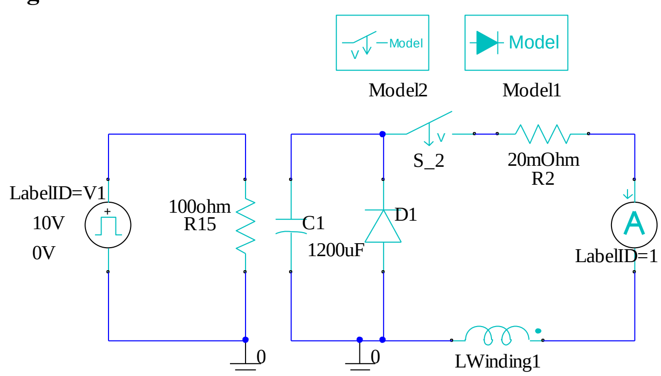

Figure 4. External circuit for the excitation source

B. Simulation Results Without Considering the Velocity of the Metal Jet

Firstly, the simulation model is calculated when the initial velocity of the metal jet is 0. The time step is 0.01ms, and the whole solving time is 0.5 ms. Then the discharge current, distributions of the magnetic field and the current density are obtained, which are shown in Fig.5 - Fig.7.

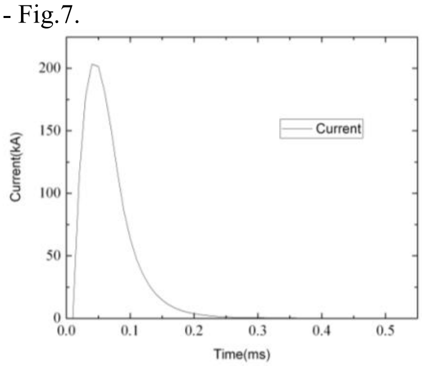

Figure 5. Discharge current

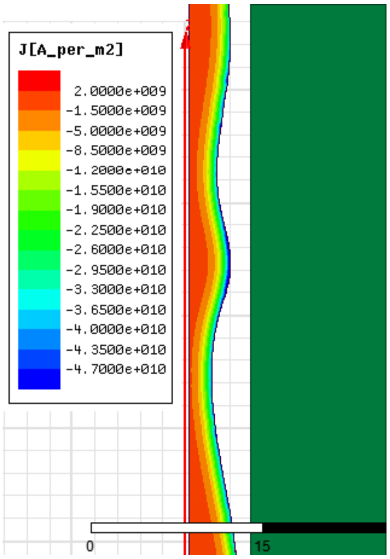

Figure 6. Distribution of the current density

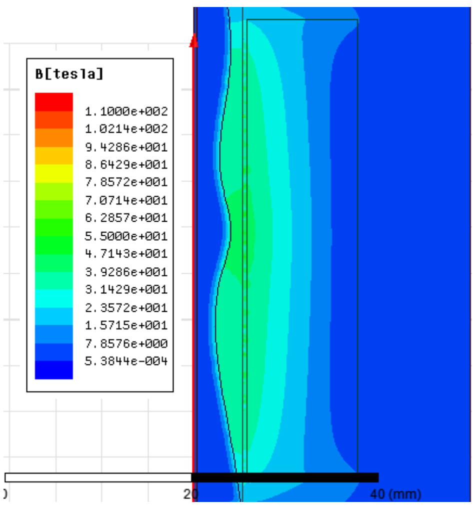

Figure 7. Distribution of the magnetic field

It can be seen from the Fig.5 that the maximum current is about 200kA, and the corresponding time is 0.04 ms. Thus, the time of a period for the discharge circuit is about 0.16 ms.

The Fig.6 is the distribution of the current density in the metal jet at 0.03 ms. According to the electromagnetic induction law, the current in the metal jet is the induced current caused by the pulsed magnetic field. It can be seen from the Fig.6 that the current density at the external surface is larger than it at the inner side for the sake of skin depth effect. Furthermore, the current density of the thick surface in the metal jet is larger than the current density in the thin surface.

The Fig.7 is the distribution of the magnetic field at 0.03 ms. It also can be seen from the figure that the magnetic field at the thick part of the metal jet is stronger than it at the thin place.

Thus, under the interaction of the current and the magnetic field, there is electromagnetic force on the metal jet. Generally, the electromagnetic force can be divided into two parts along the axial direction and the radial direction. The electromagnetic force in the axial direction is to accelerate the metal jet, whose principle is just like a coil launcher. However, according to the Lenz law, the electromagnetic force on the radial direction of the metal jet is pinch force, which can make the metal jet become thinner.

Furthermore, the electromagnetic force F on the metal jet can be calculated as follows:

$$\mathrm{d}F = B \times j \times \mathrm{d}V \tag{7}$$

where $\boldsymbol{B}$ is the magnetic field, $\boldsymbol{j}$ is the current density, V is the volume of the metal jet.

As the current density and the magnetic field at the thick part of the metal jet are larger than them at the thin part, according to the Eq. (7), the electromagnetic force at the thick part is larger too, as well as the radial electromagnetic force. Meanwhile, the deformation at the thick part is bigger than it at the thin part. Thus, the external surface of the metal jet will tend to become more even, and then the putting off tendency of the high-speed metal jet is reversed. Finally, the effective length of the metal jet will be improved and the penetration capacity to the tanks and armor vehicles can be enhanced.

It also can be seen from the simulation results that the period of the discharge current is much short. Thus, the time sequence is very important to the performance of the enhancing system.

C. *Simulation Results When Considering the Velocity of the Metal Jet*

The simulation results above do not take the velocity of the metal jet into consideration. Actually, the velocity of the metal jet cannot be neglected. Giving the hypothesis that the velocity of the metal jet is about 3000m/s. It can be seen from the parameters in the Section A that the length of the metal jet and the coil is 55 mm and 50 mm, respectively. Thus, the time t_3 can be calculated by the Eq.(4):

$$t_3 = 105/3000 = 0.035\text{ms}$$

If the inherent time t_{jet} of the metal jet is 100μs, and the response time ΔT of the trigger switch is 200μs, then the delay time Δt of the metal jet can be calculated by Eq.(6):

$$\Delta t = \Delta T + \frac{T}{4} - \frac{t_3}{2} - t_1 - t_2 = 200 + 40 - \frac{35}{2} - 100 = 122.5\mu\text{s}$$

Therefore, the delay time of the metal jet should be 122.5 μs. In the experiment, the delay time can be realized by the detonating cord. If the velocity of the detonation wave is 6000m/s, the length of the detonating cord should be 73.5 cm.

Though the delay time of the metal jet and the detonating cord cannot be simulated by the Solver, it can set the initial position of the metal jet as a substitute. Thus, in the simulation model in Fig.3, the initial position from the metal jet to the coil is 722.5 mm, which is calculated by the velocity of the metal jet and the sum time of the delay time, inherent time and etc. After calculation, the discharge current of the coil, current density of the metal jet and the magnetic field distribution are shown in Fig.8-Fig.10.

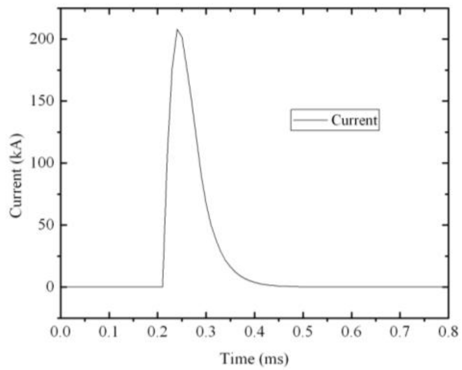

Figure 8. Discharge current

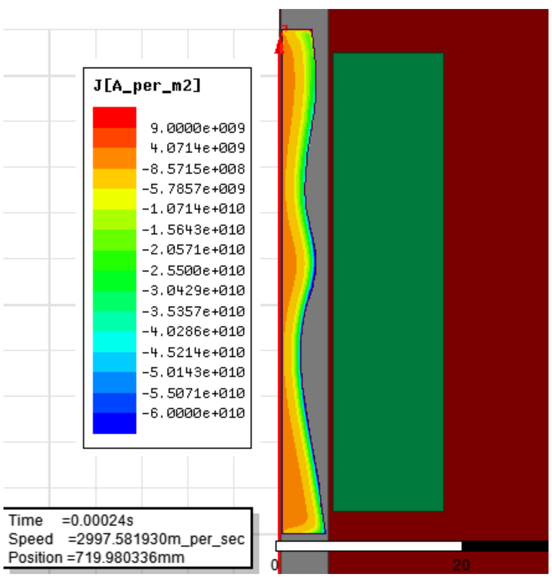

Figure 9. Distribution of the current density

It can be seen from the Fig.8 that the maximum current is about 207.8 kA, and the corresponding time is 0.24 ms. Meanwhile, from the curve of the current, it can find that the beginning point of the current has been delayed for 200 μs, and the period time of the current is consistent with the time in Section B.

The current density of the metal jet is shown in Fig.9. It also can be seen from the figure that the current density at the external surface of the metal jet is bigger that it at the inner surface. Furthermore, the maximum value of the current density is at the thick surface of the metal jet, which is about 6×10^{10} A/m^2.

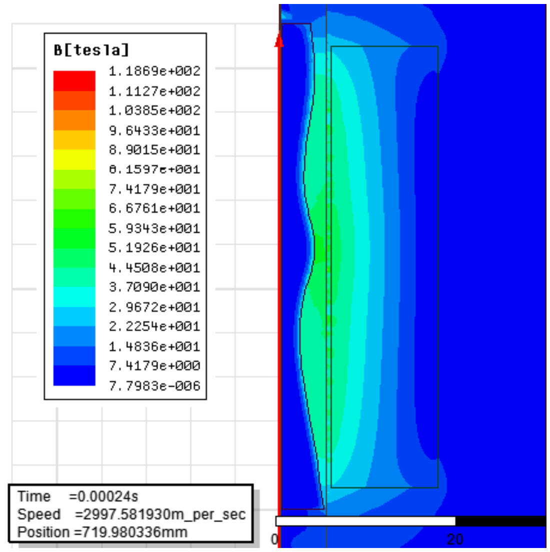

Figure 10. Distribution of the magnetic field

The Fig.10 is the distribution characteristics of the magnetic field. It can be seen from Fig.10 that the maximum value of the magnetic field is about 60 T, which is just at the thick surface of the metal jet.

Furthermore, from the simulation results we can find that when the current reaches its peak point, the centers of the metal jet and the coil coincide. It means that the determination method of the delay time is valid, and the problem of time sequence for the metal jet and discharge current can be solved. Most of all, it can calculate the delay time of the metal jet and design the length of the detonating cord, which is very significant to the experiment design of the enhancing system.

V. SUMMARY

Through the theoretical analysis and simulation, it can draw the conclusion that the high-speed metal jet can be affected by the axial strong pulsed magnetic field. To some extent, the metal jet with uneven radius can be reshaped by the electromagnetic force, and the external surface of the metal jet will be more smooth and even. Thus, the effective length of the metal jet can be improved and the putting off of the metal jet can be avoided, which is beneficial to the improvement of the penetration ability for the metal jet. Furthermore, the problem of the time sequence for the metal jet and the magnetic field can be solved by the period time of the discharge current, the inherent time of the detonator and SCJ, response time of the trigger switch, and etc. Meanwhile, the determination method of the delay time for the metal jet has been obtained based on the time sequence relation. When the velocity of the metal jet is 3000 m/s, the delay time of the metal jet in the paper is about 122.5 μs.

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