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Theoretical analysis of the acceleration effect of the magnetic field on the shaped charge jet

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ABSTRACT

This work analyzes the magnetic field produced by the solenoid and its acceleration effect on a shaped charge jet (SCJ) with the radial component of the field being considered. A theoretical model was developed to analyze the acceleration mechanism of the field on the SCJ. The results show that the axial velocity of the jet particles can be increased due to the existence of the magnetic field produced by the solenoid. In addition, the related X-ray experiments were conducted to verify the theory. The theoretical results correlate with the experimental results reasonably well.

1. Introduction

Shaped charge jets (SCJs) are used extensively in many industrial sectors, including petroleum and defense ones because of their significant penetration capability. The velocity of the jet tip can reach 6000–8000 m/s, even up to 10,000 m/s, with the tail element flying at a velocity of approximately 2000 m/s. The SCJ can experience considerable stretching at a strain rate ranging from 10^4 to 10^5 s^{-1} [1]. However, the SCJ becomes unstable and breaks up into many pieces with approximately equal size for a certain length of time (Breakup time) [2,3]. After breakup of a SCJ, the particles do not remain aligned with the SCJ axis, instead of starting rotation [4]. The breakup and the rotation after breakup of the SCJ can significantly degrade the performance of the SCJ. Based on the related penetration theory of the SCJ, the increase of the jet velocity is beneficial to improve the penetration ability of the SCJ [5,6]. In the past a few decades, some scholars devoted themselves to improve the penetration ability of SCJs. Previous methods mainly focus on improving the physical–mechanical properties of SCJ materials and the machining process, as well as optimizing the shape and size of liners. However, the current penetration capability of SCJs still cannot satisfy the practical requirements.

Previous studies showed that the penetration capability of shaped charges could be improved by electromagnetic actions. Littlefield [2] theoretically analyzed the stability of rapidly stretching and perfectly plastic jets when they were subjected to axial magnetic fields. In his study, the jet was assumed to be uniformly elongated, infinitely long and isothermal. Linear perturbation theory was also employed to calculate the time evolution of small disturbances. The results indicated that the axial magnetic field imposed on the SCJ could effectively inhibit the growth rates of perturbation. Fedorov et al. [7–9] and Babkin et al. [10] showed that jet stretching with a diffused magnetic field is accompanied by magnetic field compression inside the jet, thereby generating radial stretching electromagnetic forces. In their studies, an increase of 10% in the depth of penetration (DOP) was obtained when the magnetic induction intensity was changed from 1 Tesla to 10 Tesla. The authors then introduced several types of electromagnetic actions controlling the jet at different stages of shaped charge firing. They considered the salient deformation features of metal cumulative jets in a longitudinal low-frequency magnetic field based on a model of a uniformly stretching cylindrical incompressible rigid-plastic conducting rod. Ma et al. [11–17] analyzed the coupling process between the external magnetic field and the SCJ. They explored the inhibiting effect of the electromagnetic force on rotational motion of particles after the breakup of the SCJ. Their numerical simulations and theoretical models were verified by the corresponding experiments.

Although the coupling mechanisms between the SCJ and the magnetic field were extensively studied, the magnetic field produced by the solenoid was only regarded as a longitudinal field. As the results, the radial component of the field was neglected.

In this work, the magnetic field produced by the solenoid was analyzed by considering both the longitudinal and radial components of the field. Based on the Gauss's law, the expression of the radial component of the magnetic field was proposed. Following the law of electromagnetic induction, the electromagnetic force of the SCJ with the overall influence of the magnetic field was analyzed. Therefore, a comprehensive theoretical model was developed to describe the acceleration

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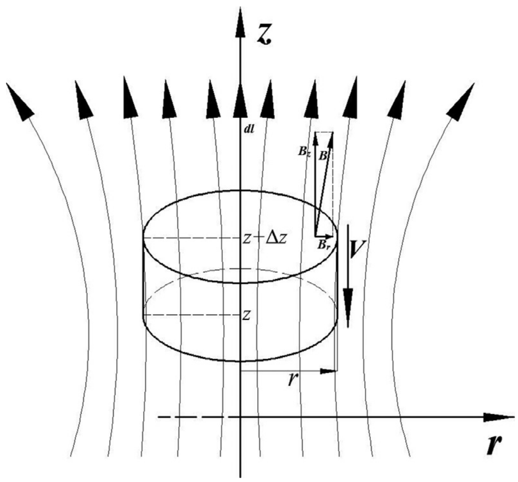

Fig. 1. Model for acceleration of a shaped charge jet element inside the external magnetic field.

mechanisms of the SCJ in the magnetic field. In addition, the X-ray experiments were conducted to verify the theoretical predictions.

2. Acceleration model of the SCJ inside the axial magnetic field

2.1. Analysis of the magnetic field produced by the solenoid

For the convenience of discussion, a cylindrical coordinate system is used, as shown in Fig. 1. The axis of the solenoid is set to z-axis, and the radial direction is r-axis. For a magnetic field B produced by a finite long solenoid, there are two components: the radial one B_r and the axial one B_z. The field is variable along the z direction. In fact, it gradually grows stronger from the entrance of the solenoid to the neutral position of the axis, then becomes weaker after passes the neutral position.

Since the magnetic field is passive, the net flux of the magnetic field out of any volume of the jet element is zero. Based on the magnetic version of Gauss's law, we can obtain [18]:

$$\nabla \cdot B = 0 \tag{1}$$

According to Fig. 1, there is [19]:

$$\pi r^2\left(-B_z(z) + B_z(z+dz)\right) + 2\pi r B_r \Delta z = 0 \tag{2}$$

Thus, according to Eq. (2), the relationship between B_r and B_z can be obtained as:

$$B_r = -\frac{r}{2}\frac{\partial B_z}{\partial z} \tag{3}$$

2.2. Force model of the SCJ inside the external magnetic field

For simplicity, it is assumed that: (1) the field is considered to be strictly symmetric about the z axis, (2) the component B_r is concentrated on the surface of the SCJ, (3) During the calculation of the magnetic induction imposed on the jet element, the motion of the jet element in the magnetic field is regarded as the uniform one and (4) air resistance and gravity are ignored.

According to the law of electromagnetic induction, the following relation can be obtained:

$$E \cdot 2\pi r = -\frac{d\phi}{dt} \tag{4}$$

here, E is the electric field induced, $\emptyset$ is the magnetic flux, and t is time.

The coupling process of the SCJ includes two stages, the first one is from the SCJ beginning to enter the solenoid to the moment of the external magnetic field diffusing into the SCJ completely; the second one begins from the end of the first stage to the jet leaving the solenoid.

However, the SCJ is only accelerated in the first stage rather than the second stage. At the first one, the variation of the magnetic flux is mainly caused by the change of both the cross-section of the SCJ and the magnetic induction intensity produced by the solenoid. Therefore, it arrives:

$$\frac{d\phi_1}{dt} = B_1\frac{dS_1}{dt} + S_1\frac{dB_1}{dt} \tag{5}$$

Where $\emptyset_1$ is the magnetic flux, B_1 is the magnetic induction intensity produced by the solenoid, and the S_1 is the cross-section of the SCJ at the first stage.

A low-frequency field can be diffused into the SCJ material and result in a "freezing effect" as mentioned in Refs. [7–9,20]. The time of magnetic field diffusing into the jet material can be calculated as 10.5 μs for the front-end of the SCJ according to the theory in Ref. [7], when the front-end of the SCJ has reached the initial position of the second stage at this moment. Therefore, at the second stage, the magnetic flux is constant due to the freezing effect of the magnetic field, i.e.

$$\phi_2 = \int B_2 dS_2 = C \tag{6}$$

here, $\emptyset_2$ is the magnetic flux, B_2 is the magnetic induction intensity inside the SCJ, the S_2 is the cross-section of the SCJ at the second stage, and C is a constant.

Combining Eqs. (4) and (6), the induced electric field inside the SCJ can be obtained as.

$$E_2 = 0 \tag{7}$$

Here, E_2 is the electric field induced at the second stage.

According to the result from Eq. (7), it is clearly that it has no action of electromagnetic force on the front-end of the SCJ, so that the SCJ cannot be accelerated at the second stage due to the freezing effect.

Based on the assumption of volume conservation [10], the radial velocity on the surface of the shaped charge jet can be obtained as:

$$V_r = -\frac{\dot{\varepsilon}_0 r_0}{2(1+\dot{\varepsilon}_0 t)^{\frac{3}{2}}} \tag{8}$$

The relationship between the initial radius r_0 and the current radius r of the shaped charge jet can be expressed as follows.

$$r = \frac{r_0}{\sqrt{1+\dot{\varepsilon}_0 t}} \tag{9}$$

Here, $\dot{\varepsilon}_0$ is the initial strain rate.

Combining Eqs. (4)–(9), the induced electric field due to the magnetic field coupling with the shaped charge jet can be expressed as:

$$E = \frac{B\dot{\varepsilon}_0}{2}\frac{r^3}{r_0^2} - \frac{r}{2}V_z\frac{\partial B}{\partial z} \tag{10}$$

Considering the differential form of the Ohm's law [7], the induced electric field can be also written as:

$$E = \eta j \tag{11}$$

Where η is the resistivity of the SCJ material and j is the density of the induced currents.

Based on Eqs. (10) and (11), the density of the current induced can be obtained during the magnetic field coupling with the SCJ.

$$j = \frac{B\dot{\varepsilon}_0}{2\eta}\frac{r^3}{r_0^2} - \frac{r}{2\eta}V_z\frac{\partial B}{\partial z} \tag{12}$$

Due to the skin effect [21], the induction current can be assumed to mainly act on the surface of the SCJ. Therefore, the induction current on the cross section of the SCJ can be considered as a circular current loop with a radius r, located in the magnetic field produced by the solenoid.

Based on the above assumption, the force on the jet element can be expressed as follows.

$$F = 2\pi r I B_r \tag{13}$$