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Projectile's Velocity Effect for Voltage Induced at Sensing Coil for Applying to Air Bursting Munition

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We designed a model composed of a ring type magnet, a yoke, and a sensing coil embedded in a projectile for simulating the muzzle velocity. The muzzle velocity was obtained from the master curve for the induced voltage at sensing coil and the velocity as the projectile pass through the magnetic field. The induced voltage and the projectile's velocity are fitted by the 2nd order polynomial. The skin effect difference between projectiles which consist of aluminum-aluminum and aluminum-steel was small. The projectile will surely be burst at the pre-determined target area using the flight time and the projectile muzzle velocity calculated from the voltage induced at the sensing coil on the projectile.

Keywords : Air Bursting Munition (ABM), eddy current (EC), muzzle velocity, skin effect, finite element method (FEM)

1. Introduction

Development of the projectile that burst at a programmed distance from the muzzle can be variously used for military purposes. In order to detonate at a present round-to-target distance, the velocity and trajectory of the projectile must be measured when it leaves from a muzzle. As the projectiles start from the muzzle, the projectile's velocities gained from the kinetic energy of the chemical explosion are not constant. For correctly bursting a projectile on the target area, the velocity information measured at the muzzle must be inputted to the projectile shell by communicating between the device attached at a flash suppressor and the equipment attached to the projectile.

The two measurement methods of the projectile's velocity are used. One is the projectile measures own velocity, the other the velocity measures at muzzle [1-3]. The 40 mm low/medium velocity air burst munitions (ABMs) system having a micro-radar sensor was developed [3]. The magnetic induction sensor using geomagnetism for the turn count of small-caliber ammunition was developed [4]. To meet current and future threats, the 40 mm low velocity ABM system was developed [5]. The 40 mm × 53 ABM for automatic grenade launchers with two receive coils for measuring the projectile's velocity at the muzzle and a transmitter coil for feeding the projectile on the information for the velocity as the projectile goes pass the muzzle was developed [1]. Two methods for measuring the projectile's velocity are schematically shown in Fig. 1. In Fig. 1(a), the sensing coil embedded in the projectile measures the voltage induced on its own self as it passes through the magnetic field produced by permanent magnets. In Fig. 1(b), the receive coils measure the voltage induced on themselves when the permanent magnet passes through the receive coils.

In this work, we simulated the velocity effect of the projectile at the model composed of a permanent magnet, a yoke, and a sensing coil. The relation between the induced voltage at the sensing coil and the projectile's velocity was obtained in order to estimate the velocity by the measured voltage. Before manufacturing the experiment system, the influence of skin effect for the voltage induced at the sensing coil was studied.

2. Measurement of Projectile's Velocity by Magnetic Method

The projectile's own velocity is measured by the sensing

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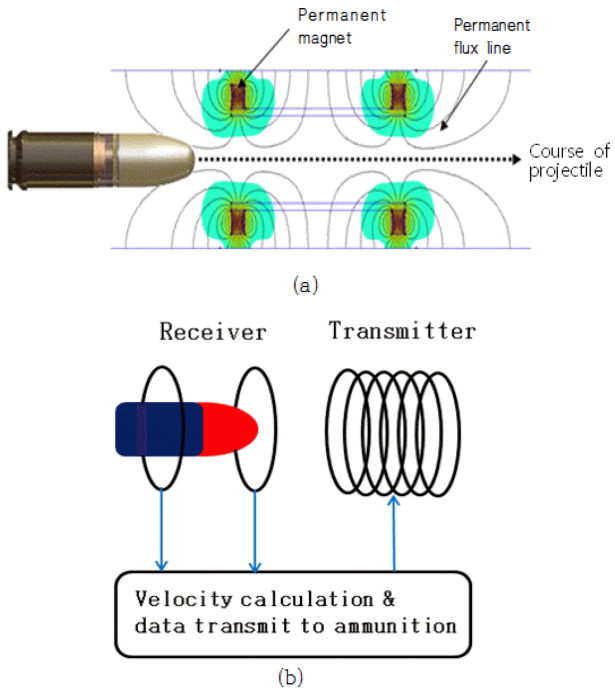

Fig. 1. (Color online) Method for measuring the velocity of a projectile; (a) The projectile measures its own velocity using the permanent magnets. (b) One pair of receive coils measures the velocity of the projectile, and the transmitter coil feeds the projectile on the information for the velocity as the projectile goes past the receive coils.

coil wound on the projectile and the voltage is induced at the sensing coil by the linking flux as the projectile passed through the magnetic field produced by the exterior permanent magnet. The electromotive force (V) induced at the sensing coil is described with Faraday's law of induction as follows;

$$V(t) = -\frac{\partial \phi(t)}{\partial t} \tag{1}$$

$$\phi(t) = \int \boldsymbol{B} \cdot d\boldsymbol{A} \tag{2}$$

where $\phi(t)$ is the magnetic flux, $\boldsymbol{B}$ is the magnetic flux density, and $\boldsymbol{A}$ is the effective cross-sectional area. The eddy current (EC) was produced by the high speed of the projectile as it passed into the magnetic field. The EC was described by Maxwell's equation,

$$\nabla \times \boldsymbol{J} = -\sigma \frac{\partial \boldsymbol{B}}{\partial t} \tag{3}$$

where $\boldsymbol{J}$ is the current density and σ is the electric conductivity. The EC is proportional to the rate of change in the flux, and the electric conductivity. The direction of the magnetic field produced by the EC is opposed to the one of the original magnetic flux density $\boldsymbol{B}$. So the EC hinders the flow of the magnetic field into the conductor. This phenomenon is known as the skin effect, and the penetration depth (δ) is the depth when the magnetic fields reach half of its original intensity. The skin depth was given by Eq. (4).

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \tag{4}$$

where f is the frequency and μ is the permeability of the

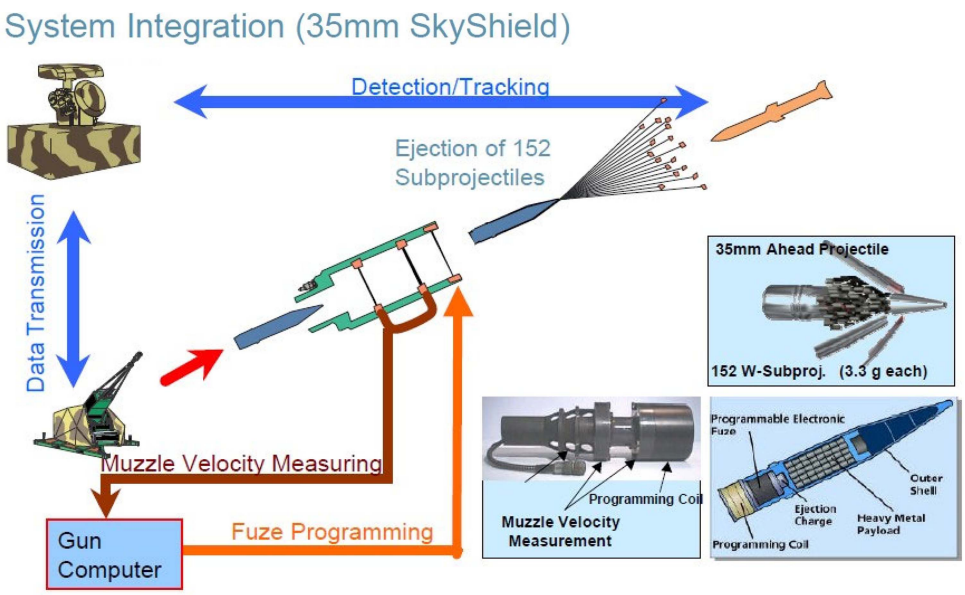

Fig. 2. (Color online) Compensating method of muzzle velocity variation; the receive coils measure the velocity of the projectile, and the transmitter coil feeds the projectile on the information for the velocity as the projectile goes past the muzzle [1].

magnetic material.

The projectile's speed is faster and the electromotive force is increased by Eq. (1), but it is also decreased by the skin effect of Eq. (4). In order to obtain the best magnetic flux from the magnetic circuit using permanent magnets, the electromotive force induced at the sensing coil embedded in the projectile must be simulated by a computer.

3. Simulation for the Velocity of Projectile

Two types of methods for measuring the projectile's velocity are used as shown in Fig. 1. The magnetic field production system, using the bar magnets for measuring the projectile's velocity, is shown in Fig. 1(a). One pair of receive coils measures the projectile's velocity, and the transmitter coil feeds the projectile on the information for the muzzle velocity as the projectile goes past the receive coil as shown in Fig. 1(b). Fig. 2 shows the system compensating the muzzle velocity variation developed by Oerlikon Contraves Pyrotec AG [1]. The system using bar magnets is very simple, but the uniform magnetic field is not produced for the circumference direction of the coil.

Moreover, the strong magnetic field produced by this system draws near the ferromagnetic materials, because of the adhesion of ferromagnetic bulks on the muzzle device by the magnetic fields.

In this study, the system constructed a ring type Nd magnet and a yoke was used for simulating the projectile's velocity as shown in Fig. 3(a). The schematic diagram and the model designed by Maxwell v15 3D are shown Fig. 3(b) [6]. Fig. 4 presents the mesh configuration for the designed model. The solver for the finite element method (FEM) was the Transient, and the size of mesh was approximately 60,500 tetrahedra. The projectile is generally composed of two parts, one part is the aluminum embedded sensing coil and the other is the steel for striking a hard blow to the target. We used two models for comparing the influence of the induced voltage of the sensing coil by steel and changing aluminum for steel. The projectile used for simulating was composed of two parts, one is the aluminum embedded sensing coil and the other is the aluminum or steel in order to survey the effect of EC for the two metals. The voltage profiles simulated by the FEM are shown Fig. 5(a) and Fig. 5(b). In case of Fig. 5(a), the results are simulated in various speeds of the projectile as two parts of the projectile are aluminum. Fig. 5(b) is the simulating results for the various projectile's speed as the one part is aluminum, the other is the 1008 steel. Many noisy peaks on the right side of the graph were conjectured arising from the finite number of meshes and higher permeability of 1008 steel. The peak of the graphs in the fourth quadrant will be used to give the muzzle velocity variation to the projectile.

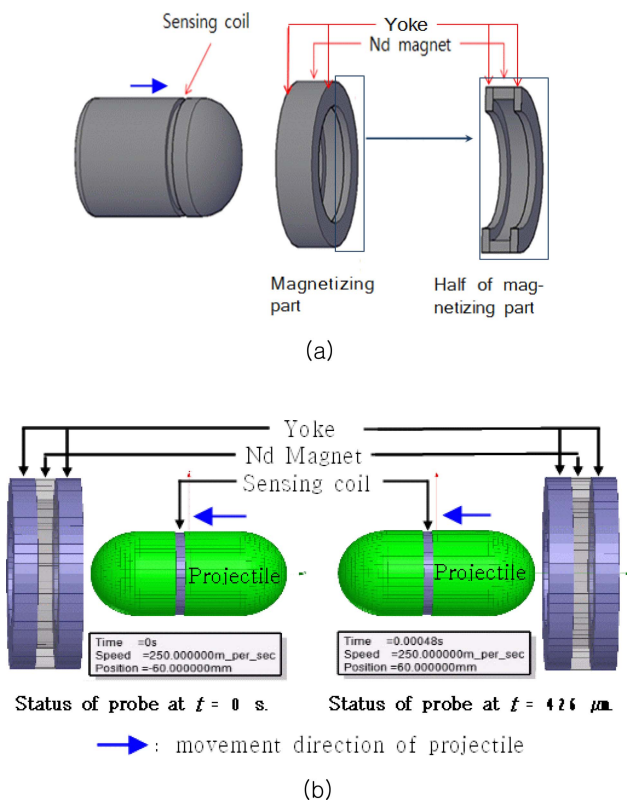

Fig. 3. (Color online) Designed model for simulating the projectile's velocity; (a) Schematic diagram. (b) Maxwell model with the probe status at the projectile's velocity = 250 m/s.

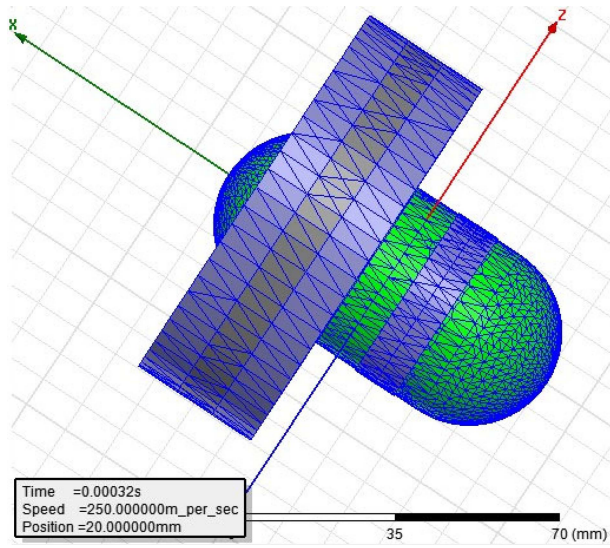

Fig. 4. (Color online) Mesh configuration for simulating the velocity of the projectile. Only the parts of magnets, yokes, and the projectile are shown in this figure. The size of the mesh was about 60,500 tetrahedra.

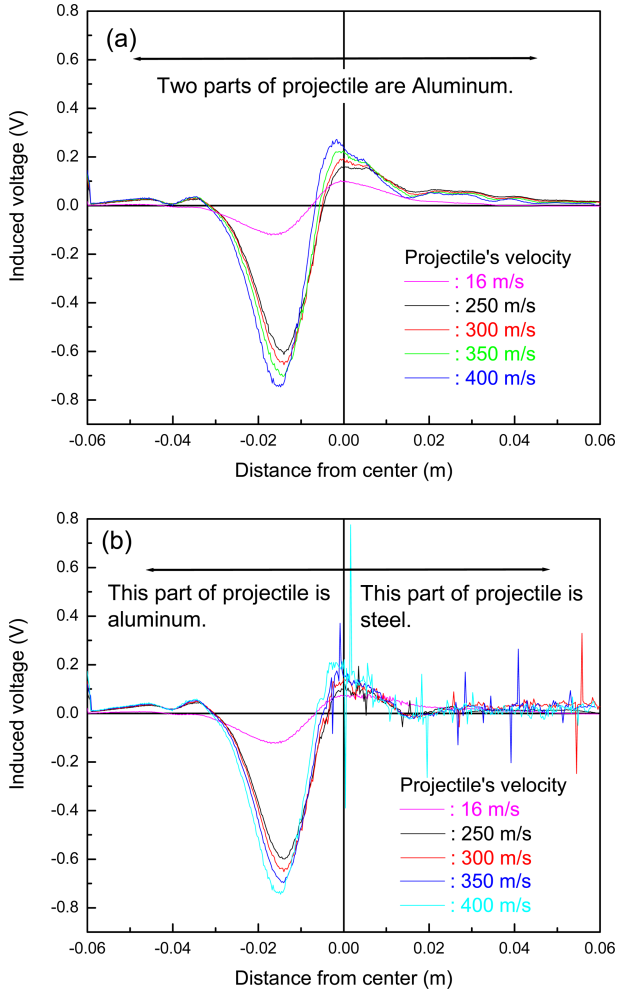

Fig. 5. (Color online) Simulated voltage profiles induced at the sensing coil as the projectile passes through the magnetic field at various velocities; (a) The materials of two parts of the projectile are all aluminum. (b) The materials of one part of the projectile are aluminum and the other is steel.

Fig. 6 shows the voltage (V) induced at the sensing coil embedded in the projectile as the projectile passed through the magnetic field. Two curves increase with increasing velocity. Fig. 6(a) is the curve as two parts are aluminum, and Fig. 6(b) is the curve as one part is aluminum, and the other steel.

As shown in Fig. 6, the induced voltages for two materials are not different up to the velocity 400 m/s, so the difference in EC effect between the two models is not large. The dot and solid lines are fitted by the 2nd order polynomial. The relationships of two lines are as follows:

$$V = A_1 + B_1 \times v + C_1 \times v^2 \quad (5)$$

$$V = A_2 + B_2 \times v + C_2 \times v^2 \quad (6)$$

where v is the projectile's velocity. A_1, A_2, B_1, B_2, C_1, and C_2 are 7.82×10^{-2}, 8.19×10^{-2}, 2.84×10^{-3}, 2.71×10^{-3},

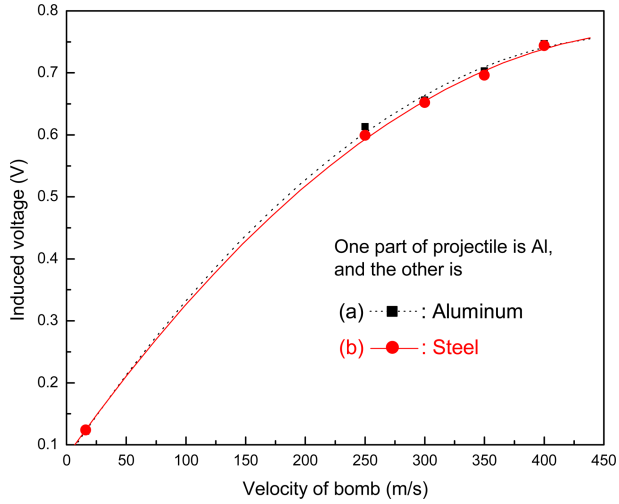

Fig. 6. (Color online) The voltage induced at the sensing coil vs. the projectile's velocity. One part of projectile is aluminum, and the other is (a) aluminum or (b) steel.

-2.96×10^{-6}, and -2.68×10^{-6}, respectively. The standard deviations of the induced voltage for the dot and solid lines are 1.1×10^{-2} and 8.07×10^{-2}, respectively. The ABM will be effectively exploded using the projectile muzzle velocity calculated from the voltage induced at the sensing coil on the projectile.

4. Conclusions

The model for simulating the muzzle velocity of the projectile was presented. The model has two ring type magnets, the yokes, and a sensing coil embedded in a projectile. The master curve for the induced voltage and the projectile's velocity was obtained. The induced voltage and the projectile's velocity are fitted by the 2nd order polynomial. The muzzle velocity could be calculated by measuring the voltage induced in the sensing coil. The skin effect difference between the projectile which consists of aluminum-aluminum and aluminum-steel was small. The projectile may precisely burst at the target area by inputting the information of muzzle velocity calculated with the master curve to the projectile.

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