

# Analysis of Muzzle Velocity Measuring Device for Small Arms Grenade

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**Abstract.** Munition's velocity measuring device is the key to realize accurate strike, its measuring accuracy and the reliability of whole system have great influence on the effect of munition's air-burst. A muzzle velocity measuring device with dual-excitation coils is proposed, which is adapted to small arms grenade launchers. The electromagnetic model of the velocity measuring device based on the principle of electromagnetic induction is established, and the theoretical expression of its signal is given. Factors affecting the signal are analyzed in MATLAB, through which conclusions of device's structural parameters, the turns of coils, and the carrying current of excitation coils, etc. are drawn.

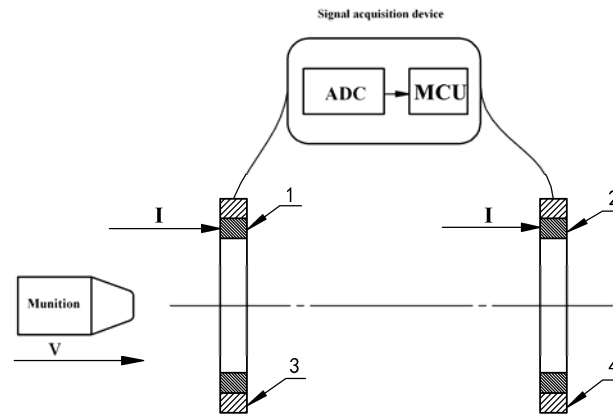
## 1. Introduction

Muzzle velocity measuring device consisted of coils and timer, usually known as the typical Soviet type, is still widely used in shooting ranges nowadays, which carries out the measurement by using the straight section of trajectory, multi-layer coil with large diameter, winded by thick copper wire, is inevitable in this type of device, in order to fit different sizes of projectiles, and it also requires high current supply [1-4]. The muzzle velocity measuring device of small arms grenade must be portable and has low power consumption, since battery capacity of the launcher is quite limited. In order to obtain the pulse signal suitable for acquisition, it is necessary to design the muzzle velocity measuring device for small arms grenade. This paper mainly studies a kind of excitation coil for velocity measurement applied to the grenade launcher, and designs the key parameters of this system, which has great significance of engineering.

## 2. Principles of the excitation coil

The whole excitation coil can be divided into two sets of coils. Each set includes two layers: the inner layer named excitation coil, in which a constant magnetic field is generated when it carries direct current, and the outer one is induction coil. When the projectile passes through the coil area, the flux changes in this region, and the pulse signal is excited in the induction coil. The structure of excitation coil is shown in Figure 1.

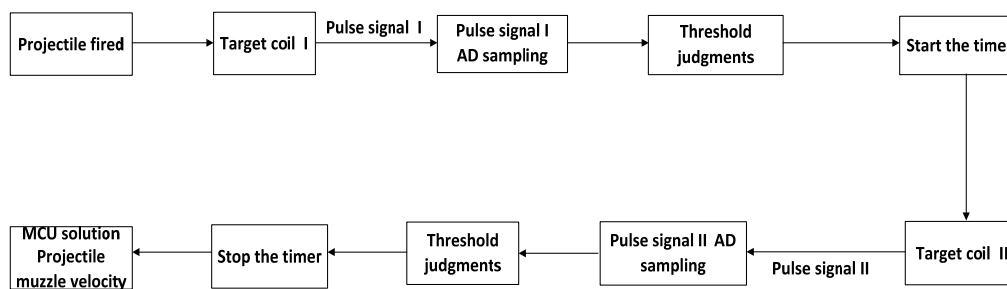




1, 2 for the excitation coil; 3, 4 for the induction coil

**Figure 1.** Excitation coil structure

The working process of the excitation coil is shown in Figure 2.



**Figure 2.** Working process of excitation coil

### 3. Electromagnetic characteristics of muzzle velocity measuring device

The essence of this device is to estimate the velocity of a projectile using two pulse signals that control the start/stop of the timer. Since the acquisition program controlling the timer by the voltage threshold, it is necessary to study the amplitude of signals. The initial velocity fluctuation of the projectile has an affect on the frequency of the section signal directly, and then determines the time resolution of MCU, so it is also necessary to study the frequency characteristics of the signal.

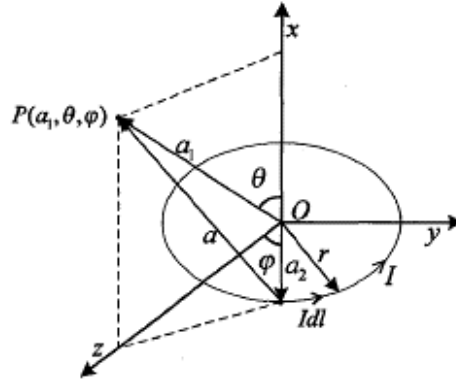
#### 3.1. Electromagnetic model of double-layer coils

Due to the identical structure of two sets of coils, only one of them is analyzed. The width of the coil is insignificant compared with the velocity (about 245m/s) of projectiles, so the excitation coil can be regarded as an n-turn circular current loop, and induction electromotive force generated in induction coil can be expressed as follows.

$$U(t) = -n_0 n_1 \frac{d\Phi}{dt} = -n_0 n_1 \frac{dB}{dt} S \quad (1)$$

In the equation(1),  $n_0$  is the turns of excitation coil,  $n_1$  is the turns of induction coil,  $\Phi$  is the magnetic flux in the coil area,  $S$  is the closed area of the coil, and  $B$  is the magnetic induction in the coil area.

According to Biot-Savart law, the magnetic induction of the circular current loop in space can be analyzed by the model shown in Figure 3. [5]



**Figure 3.** Magnetic induction model of the circular current loop

The magnetic induction distribution is the same for any two planes that cross the loop's radius and are perpendicular to it. In Figure 3, the vector of  $P$  with respect to the current element  $Id\vec{l}$  is  $\vec{a}$ , and  $\vec{i}$ ,  $\vec{j}$ ,  $\vec{k}$  are unit vectors of  $x$ ,  $y$  and  $z$ . The current element  $Id\vec{l}$  and the position vector  $\vec{a}_1$ ,  $\vec{a}_2$  can be expressed as follow.

$$Id\vec{l} = Ir \sin \varphi d\varphi \vec{k} - Ir \cos \varphi d\varphi \vec{j} \quad (2)$$

$$\vec{a}_1 = a_1 \cos \theta \vec{i} + a_1 \sin \theta \vec{j} \quad (3)$$

$$\vec{a}_2 = r \cos \varphi \vec{j} + r \sin \varphi \vec{k} \quad (4)$$

$\vec{a}$  can be expressed as:

$$\vec{a} = \vec{a}_1 - \vec{a}_2 = (a_1 \sin \theta - r \cos \varphi) \vec{j} + a_1 \cos \theta \vec{i} + r \sin \varphi \vec{k} \quad (5)$$

According to Biot-Savart law, the magnetic induction at point P can be expressed as:

$$\begin{aligned} B &= \frac{\mu_0}{4\pi} \int_0^{2\pi} \frac{Id\vec{l} \times (\vec{a}_1 - \vec{a}_2)}{a^3} \\ &= \frac{\mu_0 r I}{4\pi} \int_0^{2\pi} \frac{[a_1 \cos \theta \cos \varphi \vec{k} + (r - a_1 \sin \theta \cos \varphi) \vec{i} + a_1 \sin \varphi \cos \theta \vec{j}] d\varphi}{a^3} \end{aligned} \quad (6)$$

$\mu_0$  is the permeability of the vacuum,  $\mu_0 = 4\pi \times 10^{-7} \text{ N/A}^2$ . As the point  $P$  is in the plane  $XOZ$  and  $\varphi = 0$ , the equation (6) can be changed to:

$$B = \frac{\mu_0 r I}{4\pi} \int_0^{2\pi} \frac{[a_1 \cos \theta \cos \varphi \vec{k} + (r - a_1 \sin \theta \cos \varphi) \vec{i}] d\varphi}{a^3} \quad (7)$$

No variable related to  $\vec{j}$  is included in the equation (7), so the magnetic induction produced by the circular current loop actually is:

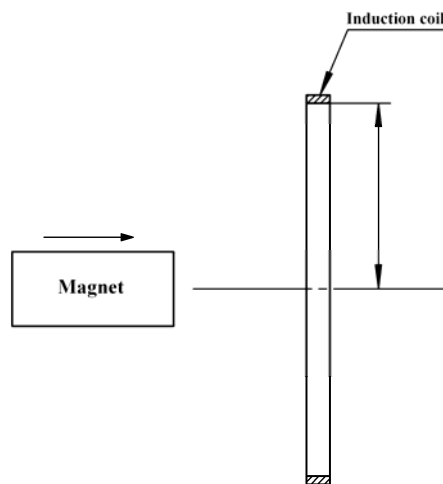
$$B = \sqrt{B_x^2 + B_z^2} \quad (8)$$

The magnetic characteristics of the region surrounded by excitation coil is analyzed in this paper only in the case of the magnetic shielding device taken into consideration, which limits most of the magnetic field to inside of the device.

Combined with equation (1) and (7), the induction electromotive force is mainly affected by the turns of coils and the current intensity. Meanwhile, the change of magnetic field caused by the projectile is the only source of pulse signals. It is clear that the mapping between the force and these three parameters should be elaborated by establishing electromagnetic model of the whole measuring device, even including the projectile.

### 3.2. The equivalent model of the measuring device

The projectile and the excitation coil can be equivalent to a strip magnet with speed  $V$ , therefore, the whole measuring device is equivalently shown in Figure 1. [6]



**Figure 4.** Equivalent model of the measuring device

The flux changes  $\Delta\Phi$  in the surrounded area of the induction coil are provided by the motion of the projectile when only DC in the excitation coil. Combined with equation (7),  $\Delta\Phi$  should be expressed as:

$$\begin{aligned} \Delta\Phi &= \mu\pi R^2 H = \mu\pi R^2 \frac{B}{\mu_0} \\ &= \frac{\mu R^2 r I}{4} \int_0^{2\pi} \left[ \frac{a_1 \cos\theta \cos\varphi \vec{k} + (r_1 - a_1 \sin\theta \cos\varphi) \vec{i}}{a^3} \right] d\varphi \end{aligned} \quad (9)$$

Where  $H$  represents the magnetic field strength,  $\mu$  is the permeability of the projectile,  $R$  is the radius of the projectile, and the rest of the symbols have the same meaning as before.

Since  $B_z \ll B_x$  in this region, equation (9) can be rewritten as:

$$\Delta\Phi \approx \mu\pi R^2 \frac{B_x}{\mu_0} = \frac{\mu R^2 r I}{4} \int_0^{2\pi} \frac{r_1 - a_1 \sin\theta \cos\varphi}{a^3} d\varphi = \mu\pi R^2 H_x \quad (10)$$

Point  $P$  in Cartesian coordinates can be expressed as  $P(x, 0, z)$ , so the  $x$ -axis magnetic field strength  $H_x$  can be expressed as:

$$H = \frac{B_x}{\mu_0} = \frac{1}{2} I n_1 r (x^2 + r^2)^{-3/2} \quad (11)$$

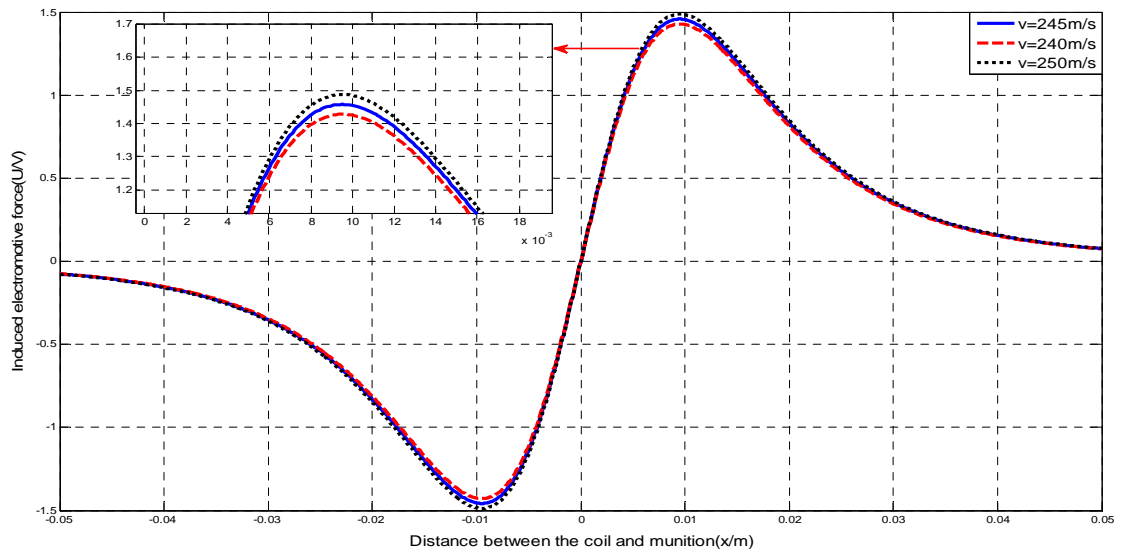
Based on simultaneous equations (1), (10) and (11), the induced electromotive force can be expressed as:

$$\begin{aligned} U &= -n_0 n_1 \frac{d\Delta\Phi}{dt} = -n_0 n_1 \mu\pi R^2 v \frac{dH_x}{dx} \\ &= \frac{3}{2} \mu n_0 n_1 \pi R^2 I r v x (x^2 + r^2)^{-5/2} \end{aligned} \quad (12)$$

According to equation (12), the changes of the induced electromotive force could be calculated with different turns of coils ( $n_0$  and  $n_1$ ), velocity of the projectile ( $v$ ), and current intensity ( $I$ ).

#### 4. Simulation and analysis of the induced electromotive force

Limited by the size of the entire system, the coil radius ( $R$ ) can only reach 19mm. Analyzing the first set of coil, assuming it's center is the origin, and the direction of  $v$  is positive, the  $U-x$  curves are gained in Matlab when  $v$  is 240m/s, 245m/s and 250m/s, shown in Figure 5.



**Figure 5.**  $U-x$  curves with different  $v$

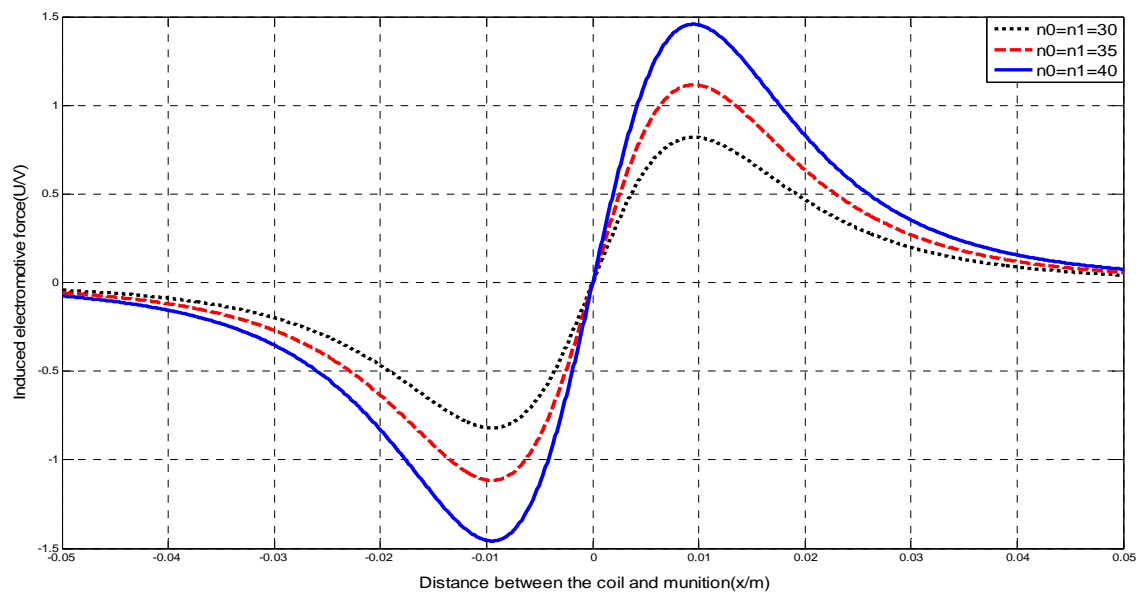
From Figure.5, the conclusion can be drawn that in the range of  $v$ , signal's amplitude is basically unaffected, and it's peak under different velocities is shown in Table.1.

**Table 1.** Signal's peak under variable  $v$

muzzle velocity/m/s	signal's peak/V
240	1.43
245	1.46
250	1.49

The data in Table.1 shows that the MCU for acquisition can use a single threshold to start and stop the timer.

Figure.6 gives  $U - x$  curves under different  $n_0$  and  $n_1$  ( $n_0$  and  $n_1$  change synchronously) when  $v$  is 245m / s.



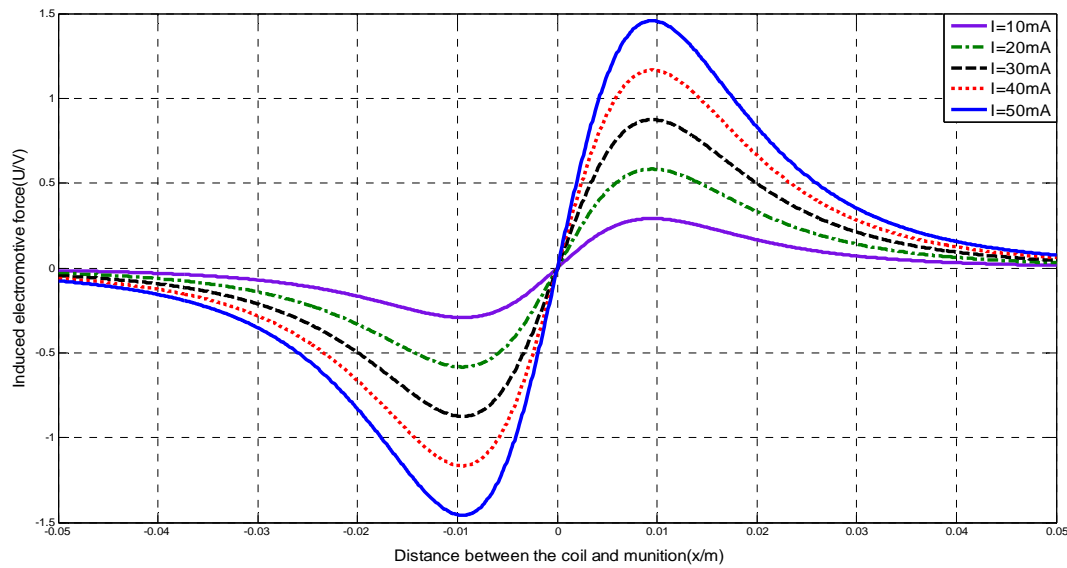
**Figure 6.**  $U - x$  curves with different  $n_0$  and  $n_1$

As shown in Figure 6, turns of coils have a great influence on the amplitude of the signal. Turns should be increased as far as possible within the quality and volume limits. Table.2 shows the signal's peak under different turns.

**Table 2.** Signal's peak under different turns

turns of coils	signal's peak/V
30	0.82
35	1.12
40	1.46

The current of the excitation coil is easily influenced by the power supply capacity of the device, so  $I$  changes from 10mA to 50mA with a step of 10mA, then  $U - x$  curves are calculated when  $n_0 = n_1 = 40$ , and  $v = 245\text{m/s}$ , as shown in Figure 7.



**Figure 7.**  $U - x$  curves with different  $I$

Figure. 7 shows that stable current output capacity must be guaranteed since the signal is quite sensitive current changes. The signal's peak at under currents is shown in Table.3.

**Table 3.** Signal's peak under different currents

current/mA	signal's peak/V
10	0.29
20	0.58
30	0.87
40	1.17
50	1.46

The diameter of copper wire used is 0.1mm, and it's upper limit of the recommended safety current under natural heat dissipation is 40mA. Signal acquisition system requires peak amplitude to exceed 1V. In combination with the data in Table.3, 40mA DC of excitation coil is determined

According to the previous analysis, the time interval between two pulse signals is 0.2ms ~ 0.208ms, that is equal to 4.8kHz and 5kHz in frequency, which requires the timing accuracy of the MCU to be at least 0.1μs.

## 5. Summary

Based on magnetic induction analysis of a circular current loop, the electromagnetic model of muzzle velocity measuring device for small arms grenade is established, and through which the theoretical expression of the induced electromotive force is obtained. Influences of turns of coils, fluctuation of velocity and the current variation on the acquisition signal are analyzed.

## References

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