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The application of the ballistic pendulum for the bullets velocity measurements

J M Milutinović[1], N P Hristov[2], D D Jerković[2], S Z Marković[2] and A B Živković[1]

[1]University of Kragujevac, Faculty of Engineering, Sestre Janjić 6, 34000 Kragujevac, Serbia
[2]Military academy, University of Defence, Pavla Jurišica Šturma 33, 11000, Belgrade, Serbia

E-mail: nebojsahristov@gmail.com

Abstract. The accurate values of the initial velocity of bullets are significant for the quality and precision of small arms. The application of the simple measurement methods, during the tests of the weapon and ammunition, enables the determination of the velocity values from the group of shoots. The accuracy of bullet trajectory, appropriate trajectory correction parameters and terminal ballistics parameters are depended of the quality of initial conditions as initial velocity. The ballistic pendulum, as simple and old-design device, enhanced with optoelectronic encoder sensor and computer acquisition system, can be one of the good start-up device platform for measurement of velocity and observation of the terminal ballistics effects. The function principle of the considered device is based on the energy conservation. Initial data are mass of bullet, mass and dimension of pendulum, and result is velocity, according to the values of time and angle of pendulum. The output signals of measured angle in time are captured, and as required values for calculation the velocity on the microprocessor platform, for each shoot in the test group. The microprocessor platform saves measured and calculated values in memory and generates statistic report of results. The presented method can improve weapon and ammunition tests, by decreasing the time of measurement acquisition and increasing the quality and speed of results without errors. The method and system is simple and low-cost, and enables the design of small arms ammunition database of testing results.

1. Introduction

The range of projectiles directly depends on the muzzle velocity. The muzzle velocity of projectiles are significant for the quality and precision of classic weapon systems. This parameter is of utmost crucial for the proper function of ballistic systems. The quality of ammunition and weapons are determined by this essential quantitative parameter. It effects on flight stability of the projectiles and precision and accuracy parameters [1]. The muzzle velocity deviation values are defined by standards (MIL, STANAG, SORS, CIP, ..) according to which a qualitative assessment of ammunition and weapons. Depending on the type of weapons, the muzzle velocity ranges from 100 to 2000 meters per second. Measuring the projectile speed as a physical size is very complex. Generally it is performed by various indirect methods. The main methods are with chronographs, electromagnetic fields, sensors for measuring force, displacement, acceleration or other physical size. At first method, the law of energy conservation has been applied. The Benjamin Robins, a British mathematician and military engineer, was the first who invented device and practical method for measuring the velocities of projectiles. He described his work in New Principles of Gunnery, first published in 1742. By developing science and technology, this method has been improved.

A ballistic pendulum is a device for measuring a projectiles momentum, primarily for small arms. From which it is possible to calculate the velocity and kinetic energy. Ballistic pendulums have been largely rendered obsolete by modern chronographs, which allow direct measurement of the projectile velocity. It can be used to measure any transfer of momentum [2, 3, 4].

In a perfectly inelastic collision, a bullet is fired into the stationary pendulum, which captures the bullet and absorbs its energy. The stationary pendulum now moves with a new velocity just after the collision. While it isn’t all of the energy from the bullet transformed into kinetic energy for the pendulum (some is used as heat and deformation energy), the momentum of the system is conserved. By measuring the height of the pendulum's swing, the potential energy of the pendulum, when it stops can be measured. In the case of a pendulum total mechanical energy is conserved. So kinetic energy of the pendulum (after firing) is fully converted to potential energy. Thus the pendulum's initial velocity can be calculated. Using the law of conservation of momentum, the velocity of the bullet can be computed [2, 3].

The improvement of the described measurement method is possible with application of sensors and microprocessor platforms. The data can be permanently stored in the digital records and automatic statistical processing can be performed for the fired group of bullets.

2. Mathematical method

There are two ways for the calculation of the velocity of the bullet. The first method (approximate method) assumes that the pendulum and bullet together act as a point mass located at their combined center of mass. This method does not take rotational inertia into account. It is somewhat quicker and easier than the second method, but not as accurate.

The second method (exact method) uses the actual rotational inertia of the pendulum in the calculations. The equations are slightly more complicated, and it is necessary to take more data in order to find the moment of inertia of the pendulum, but the results obtained are generally better [2,3].

2.1. Approximate Method

Begin with the potential energy of the pendulum at the top of its swing,

$$\Delta E_p = M \cdot g \cdot \Delta h \tag{1}$$

where M is the combined mass of pendulum and ball, g is the acceleration of gravity, and Δh is the change in height. Substitute for the height,

$$\Delta h = R(1-\cos\theta) \tag{2}$$

where R is the distance from the pivot point to the center of mass of the pendulum/ball system [2,3].

$$\Delta E_p = M \cdot g \cdot R(1-\cos\theta) \tag{3}$$

This potential energy is equal to the kinetic energy of the pendulum immediately after the collision,

$$E_k = \frac{1}{2} M v_p^2 \tag{4}$$

The momentum of the pendulum after the collision is just,

$$P_p = Mv_p \tag{5}$$

which we substitute into the previous equation to give,

$$E_k = \frac{P_p^2}{2M} \tag{6}$$

Solving this equation for the pendulum momentum gives,

$$P_p = \sqrt{2M \cdot E_k} \tag{7}$$

This momentum is equal to the momentum of the bullet before the collision,

$$P_b = mv_b \tag{8}$$

Setting these two equations equal to each other and replacing kinetic energy with our known potential energy gives us,

$$mv_b = \sqrt{2M^2 gR\left(1-\cos\theta\right)} \tag{9}$$

Solve this for the bullet velocity and simplify to get,

$$v_b = \frac{M}{m}\sqrt{2gR\left(1-\cos\theta\right)} \tag{10}$$

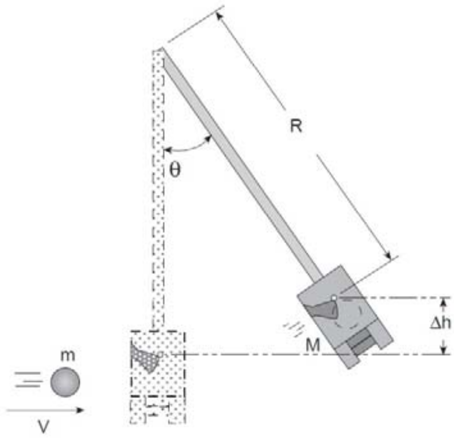

Figure 1. The motion of pendulum.

2.2. Exact Method

The potential energy is found in a way identical to the way shown previously,

$$\Delta E_p = M \cdot g \cdot R\left(1-\cos\theta\right) \tag{11}$$

For the kinetic energy, we use the equation for angular kinetic energy instead of linear, and substitute into it the equation for angular momentum [2, 3].

$$E_k = \frac{1}{2}I\omega^2 \tag{12}$$

Here I is the moment of inertia of the pendulum and bullet combination, and ω is the angular velocity immediately after the collision.

The moment of movement of the pendulum is,

$$L_P = I\omega \tag{13}$$

$$E_k = \frac{L_P^2}{2I} \tag{14}$$

$$L_P = \sqrt{2IE_K} \tag{15}$$

This angular momentum is equal to the angular momentum of the bullet before the collision, as measured from the pendulum pivot point.

$$L_b = mR_b^2\omega = mR_b v \tag{16}$$

where R_b is the distance from the pendulum pivot to the bullet. This radius is not in general equal to R, which is the distance from the pivot point to the center of mass for the pendulum and bullet system.
These two angular momenta are equal to each other, and,

$$mR_B v = \sqrt{2IMgR\left(1-\cos\theta\right)} \tag{17}$$

$$v = \frac{1}{mR_B}\sqrt{2IMgR\left(1-\cos\theta\right)} \tag{18}$$

Now we need to find I, the moment of inertia of the pendulum and bullet. To do this, we start with the rotational equivalent of Newton's second law,

$$\tau = I\alpha \tag{19}$$

where τ is torque, I is moment of inertia, and α is angular acceleration.

The force on the center of mass of the pendulum is just Mg, and the component of that force directed towards the center of the pendulum swing is, Figure 2,

$$F = -Mg\sin\theta \tag{20}$$

The torque on the pendulum is thus,

$$I\alpha = -RMg\sin\theta \tag{21}$$

For small angles θ, $sin\theta \approx \theta$, so if we make this substitution and solve for α we get,

$$\alpha \approx -\frac{MgR}{I}\theta \tag{22}$$

This angular equation is in the same form as the equation for linear simple harmonic motion,

$$\alpha = -\omega^2 x \tag{23}$$

So if we compare these two equations, linear and angular, we can see that the pendulum exhibits simple harmonic motion, and that the square of the angular frequency (ω^2) for this motion is just,

$$\omega^2 = \frac{MgR}{I} \tag{24}$$

Solving this for I gives us the desired result,

$$I = \frac{MgR}{\omega^2} = \frac{MgRT^2}{4\pi^2} \tag{25}$$

where T is the period of the pendulum.

The projectile velocity calculation is more accurate using the exact method, but the difference is minimal (less than 2 %). In this case, the approximate method was used for simpler calculation.

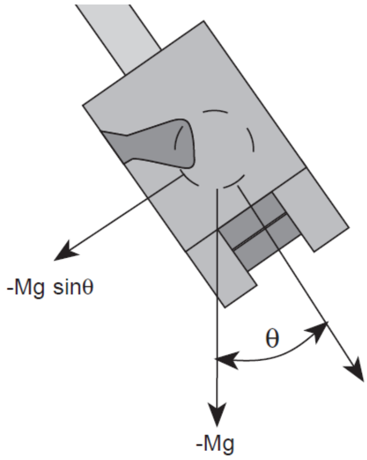

Figure 2. The forces direction.

3. Conceptual design

Conceptual design for model is presented in the Figure 3. The system consists of the pendulum, the encoder and microprocessor platforms connected to the computer. The encoder registers the angle of movement after the collision of the projectile and the pendulum. The mass of pendulum and bullet are known in advance. The microprocessor calculate the output signal of the encoder with the corresponding mathematical model. The characteristics of the encoder is presented in the Table 1.

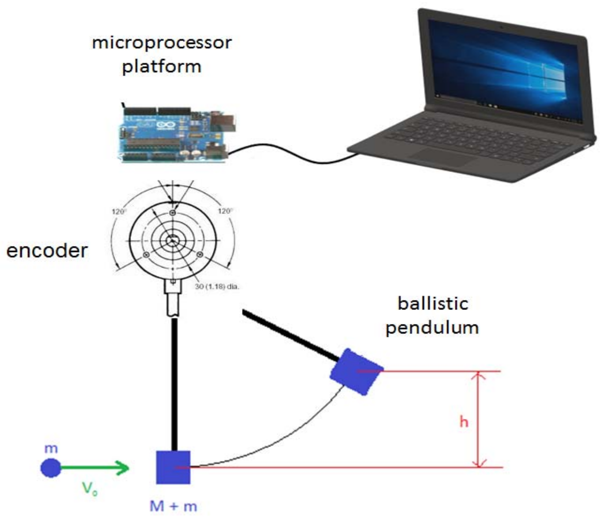

Figure 3. Principal scheme of system.

Table 1. Technical specifications of Encoder.

Model E6B2-CWZ6C	Model E6B2-CWZ6C
Operating Voltage	5 ÷24 V
Resolution (pulses/rotation)	2000
Output capacity	Applied voltage: 30 VDC max. Sink current: 35 mA max. Residual voltage: 0.4 V max. (at sink current of 35 mA)
Maximum response frequency	100 kHz
Rise and fall times of output	1 μs max. (Control output voltage: 5 V, Load resistance: 1 kΩ, Cable length: 2 m max.)
Starting torque	0.98 mN·m max.
Maximum permissible speed	6,000 r/min
Temperature range	Operating:-10 to 70°C (with no icing)
Shock resistance	Destruction: 1,000m/s^2 3 times each in X, Y, and Z directions
Weight	100 g

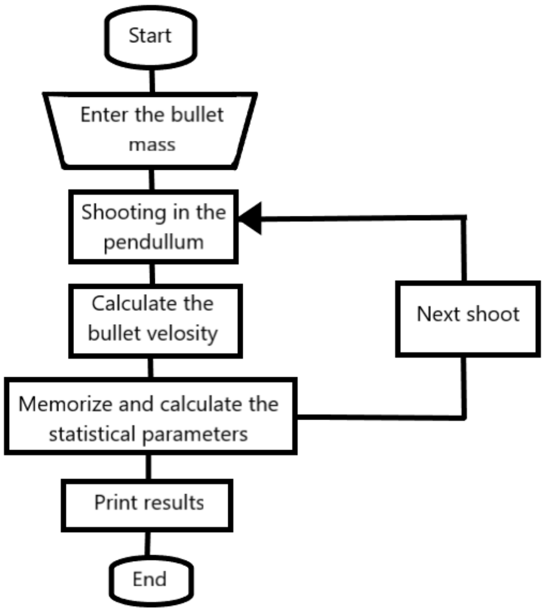

Figure 4. Algorithm of solution.

For this system is used Arduino Uno microprocessor board platform with USB interface. This platform has all functions for controls and can be directly connected to the computer through the USB connection. The software solution was made according to the mathematical model and algorithm, presented in the Figure

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4. The software is designed to record velocities of each single shoot, then process the statistical parameters of the shooting group (10 to 100 shoots). The calculation outputs are the mean of projectiles velocity, maximum and minimum velocity value, standard deviation and mean square deviation as statistical parameters. The software solution was made in the open Arduino code.

4. Conclusion

In the paper is presented solution for the bullets velocity measurements using application of the ballistic pendulum. This is a practical application of theoretical settings in combination with modern sensors and microprocessors. The concept required measuring the physical measures indirectly and translating it into an electrical digital signal. Also, the research requires signal processing and application of statistical tools. This is very demanding challenge for engineering practice and requires knowledge of different technical disciplines. The next step is to check the measuring technique by a validated method, and this is in progress. The testing will be performed for different types of small arms, and then a final evaluation of measuring method will be given.

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