

## A STUDY ON RECOIL INTENSITY OF THE CO<sub>2</sub> POWERED RECOIL SIMULATOR

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**Abstract:** *The paper is focused on the study on the recoil intensity of the carbon dioxide (CO<sub>2</sub>) powered recoil simulator. The objective is to develop a mathematical model for the calculation of the force and its impulse acting on the mount of a rifle with a CO<sub>2</sub> powered recoil simulator inside. The problem is solved using the MATLAB environment, and results of the theoretical solution are verified experimentally on the tubeless recoil simulation kit for the assault rifle AK47.*

**Keywords:** *recoil, recoil simulation, force, impulse, recoil intensity, carbon dioxide, AK47*

### 1. INTRODUCTION

The virtual shooting training system including realistic simulated weapons or recoil kits for real firearms has become a solution to increase the effectiveness and safety of shooting and tactical training. There are a number of commercial recoil simulators on the market, for example [1-3]. All of them use the carbon dioxide as the power gas. By using compressed gas instead of live ammunition a large number of simulated rounds can be fired for a minimal cost.

One of engineering challenges in designing recoil simulators is that of obtaining the recoil intensity that is close to that generated by the real firearm. The recoil intensity is represented by the resultant force and impulse transmitted from the device to the shooter.

There is almost no available literature on simulation of the recoil intensity of the CO<sub>2</sub> powered recoil simulator. There are several related publications appearing in the last few years and documenting the development and testing of the experimental spring powered mechanical device for the simulation of the gun's recoil [4], and dynamic analysis of the gas powered impulse generator [5].

In this paper, a mathematical model for the calculation of the force and its impulse acting on the mount of a rifle with a CO<sub>2</sub> powered recoil simulator inside is formulated. The developed mathematical model is validated and experimentally verified on the CO<sub>2</sub> powered recoil simulator for the assault rifle AK47.

## 2. PRINCIPLE OF CO<sub>2</sub> POWERED RECOIL SIMULATOR OPERATION

Figure 1 shows the basic concept of a CO<sub>2</sub> powered recoil simulator consisting of a piston, a control valve system, and a return spring. The cylinder is connected with the pressure tank through the control valve system that controls the amount of CO<sub>2</sub> discharged from the pressure tank into the cylinder.

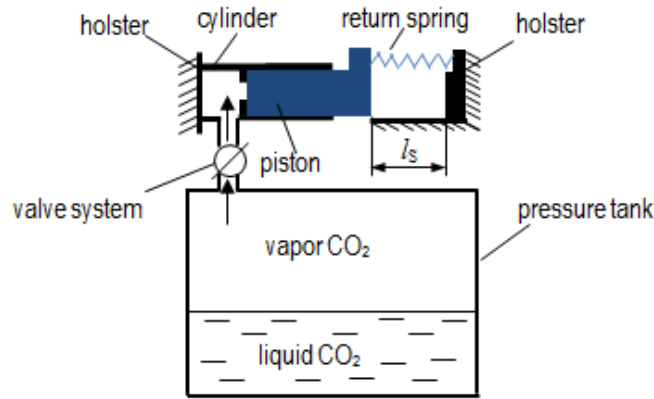


FIG. 1. Schematic of the recoil simulator powered by CO<sub>2</sub>

When the valve is opened by the trigger, a certain amount of CO<sub>2</sub> vapor discharges out of the pressure tank through the valve into the cylinder, in which the pressure increases rapidly, acts on the front of the piston and causes the piston to move backward. At the moment, when the piston reaches its working stroke, it reaches the impact velocity and collides with the device holster in the back position resulting in generating the impact force  $F_{IB}$ . After that, the piston returns to the initial position by the return spring force. Then, it collides with the gun holster in the front position and generates the impact force  $F_{IF}$ . The resultant force of impact forces, the pressure force and the return spring force are transmitted from the device to the mount resulting in the recoil effect.

## 3. MATHEMATICAL MODEL

### 3.1. Dynamics of the recoil simulator

The force and impulse transmitted from the recoil simulator to the mount can be determined based on dynamics of the moving part, i.e. the piston.

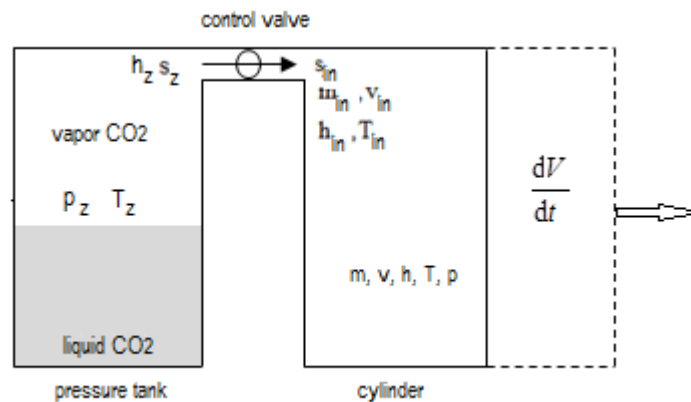


FIG. 2. Open thermodynamic system

Dynamics of the recoil simulator has comprehensively studied in [6], in which the above schematic of the CO<sub>2</sub> powered recoil simulator is replaced by the thermodynamic system shown in Fig. 2. Here, the author developed an equilibrium discharge mathematical model for carbon dioxide tanks in order to assume thermodynamic equilibrium states at every point in time throughout discharging under ambient temperature conditions. The speed of sound in a two-phase saturation is taken into consideration for the calculation algorithm [6]. Results of solution of the mathematical model describing dynamics of the recoil simulator are the piston velocity and displacement time courses, and the time change in pressure behind the piston.

### 3.2. Force and impulse calculation

The value of the force  $F_B$  transmitted from the recoil simulator to the gun's mount is given by the following expression:

$$F_B = -F_p + F_{sp} + F_{IB} + F_{IF}, \quad (1)$$

where:

- $F_p$  is the pressure force,
- $F_{sp}$  is the return spring force,
- $F_{IB}$  is the impact force in the back position,
- $F_{IF}$  is the impact force in the front position.

The pressure force  $F_p$  is given by the difference in the compression cylinder pressure and the atmospheric pressure behind the piston:

$$F_p = A_p (p - p_a). \quad (2)$$

The return spring force  $F_{sp}$  is generally given by the return spring constant  $c$  and the working stroke that is equal to the piston displacement  $x_p$ . It is necessary to take also the return spring preload into consideration. In this case, the return spring is initially compressed. Hence, we can express the spring force in the form

$$F_{sp} = F_{ini} + cx_p, \quad (3)$$

where the force  $F_{ini}$  is the initial compression spring force corresponding the initial spring compression, which is determined by the summation of the working and spring preload.

The resultant impulse of the force  $F_B$  can be calculated by the following formula:

$$I_B = -I_p + I_{sp} + I_{IB} + I_{IF}. \quad (4)$$

Where the impulses of the pressure force and the return spring force can be calculated by Eq.(5) and Eq.(6), respectively.

$$I_p = \int_0^{t_1} F_p dt, \quad (5)$$

$$I_{sp} = \int_0^t F_{sp} dt. \quad (6)$$

In order to determine the impulse of impact force in the back and the front position we apply Newton's impact theory based on the known piston's velocity  $v_p$ . Then, the impulse of impact force in the back position  $I_{IB}$  is given by

$$I_{IB} = m_p (v_{p2} - v_{p1}), \quad (7)$$

where  $m_p$  accounts for the mass of the moving part,  $v_{p1}$  and  $v_{p2}$  represent the piston velocity before and after its collision with the gun's holster, respectively.

The impulse of impact force in the front position is given by:

$$I_{IB} = m_p v_{p3}, \quad (8)$$

where  $v_{p3}$  denotes the piston velocity before it collision with the gun's holster in the front position.

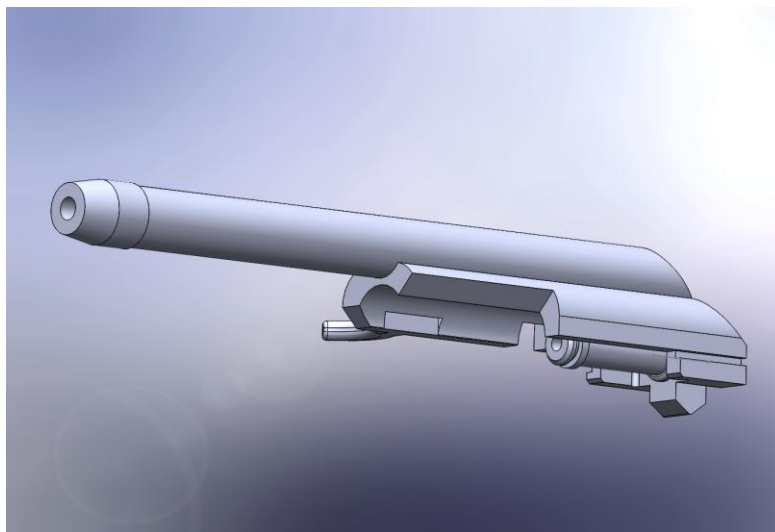
Once, the value of the impulse of impact force is known, the average value of the impact force in the back and the front position can be calculated by:

$$F_{IB} = \frac{I_{IB}}{\Delta t_{IB}}, \text{ and } F_{IF} = \frac{I_{IF}}{\Delta t_{IF}}, \quad (9)$$

where  $\Delta t_{IB}$  and  $\Delta t_{IF}$  is the time of collision in the back and the front position, respectively.

#### 4. VALIDATION AND VERIFICATION OF MATHEMATICAL MODEL

In order to present results of the solution, the above-described algorithm for calculation of the force and impulse acting on the weapon mount is validated on the tubeless recoil system for the AK47. The 3D view of the tubeless is shown in Fig. 3.



**FIG. 3.** 3D view of the tubeless recoil system

The mathematical model presented in [6] describing dynamics of the tubeless recoil system was solved by numerical integration with MATLAB using the explicit fourth-order Runge-Kutta method. The mathematical model considers a range of input data parameters and boundary conditions (see Table 1), i.e. the initial cylinder volume, the initial temperature, the pressure tank's specific enthalpy and entropy of CO<sub>2</sub>, the mass of the piston, the return spring constant, the discharge coefficient, etc.

Table 1. Initial data parameters and boundary conditions

Quantity	Value	Quantity	Value
Initial cylinder volume (ml)	0.085	Return spring constant (N/m)	290
Cylinder diameter (mm)	12	Return spring mass (kg)	0.026
Piston mass (kg)	0.357	Control valve diameter (mm)	4.65
Piston working stroke (mm)	118	Initial cylinder temperature (K)	288
Discharge coefficient	0.7		

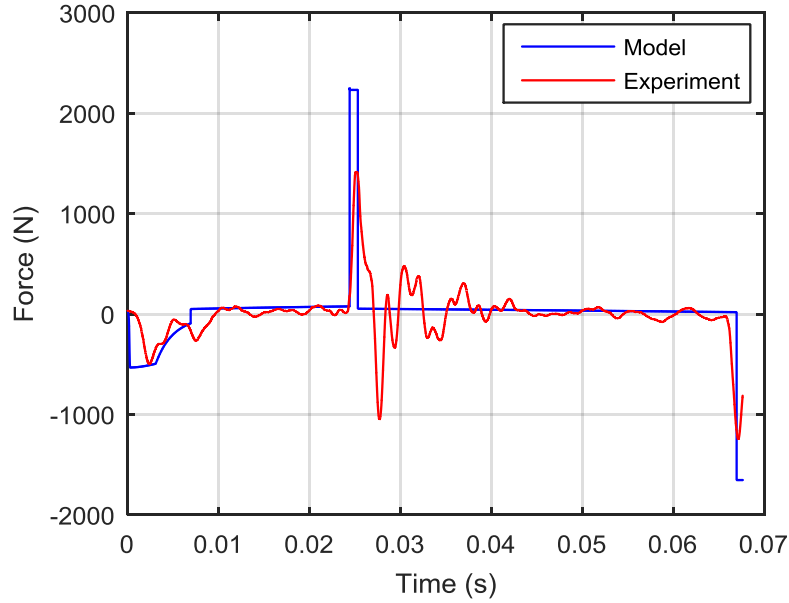


FIG. 4. View of the experimental setup: 1 – ballistic computer, 2 – AK 47 rifle with tubeless recoil system inside, 3 – piezoelectric force sensor, 4 – mobile firing rest, 5 – elastic stay.

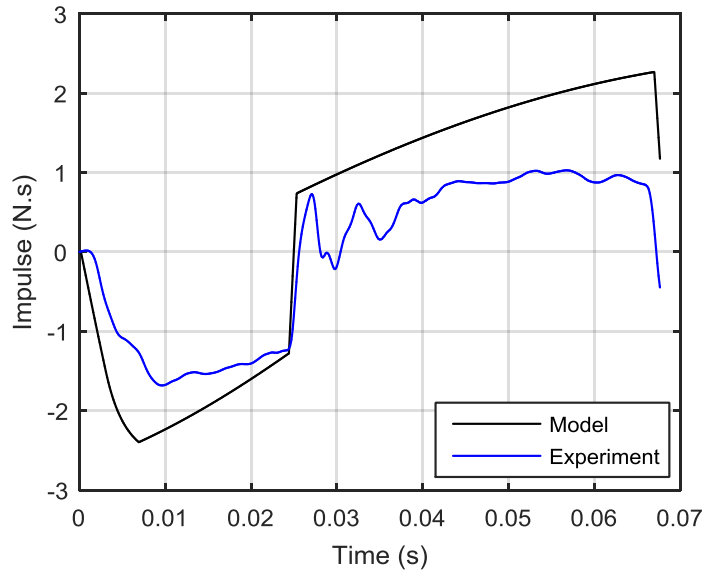
For the purpose of verifying the calculated results experiments were held in the ballistic laboratory of the Department of weapons and ammunition of the University of Defence in Brno. In order to record the force  $F_B$  and the impulse  $I_B$  transmitted from the weapon system to the mount the a piezoelectric annular force sensor is located between the gun back position and the stock of STZA 12 mobile firing rest. Measurement signals are collected by the ballistic computer. The view of the experimental setup is shown in Fig. 4. The mobile firing rest STZA 12 is appointed for the working site the job of which is the testing of small arms, ballistic gauges and cartridges within the caliber up to 12.7 mm. The force piezoelectric sensor KISTLER-9051A of the serial number 1788437 is set to the sampling frequency of 303030.31 Hz. The force measuring range is from 0 kN up to 120 kN, and the nominal sensitivity is - 4.301 pC/N.

The result of the experiment is the time course of the force transmitted from the system to the sensor. Then, the impulse is the integral of the force with respect to time.

The experimentally obtained values of the force and its impulse are compared with the theoretical results of solution of the developed mathematical model in Fig. 5 and Fig. 6.



**FIG. 5.** Time course of force acting on the weapon mount



**FIG. 6.** Time course of the impulse of force acting on the weapon mount

It can be seen that the experimentally obtained values of force transmitted from the gun to the mount are smaller than the calculated values, because the force sensor is connected to the gun stock through an elastic stay (i.e. the rubber layer). The schematic of the sensor arrangement is shown in Fig. 7. We assume that the elastic stay between the gun stock and the sensor has non-linear stiffness  $k$ . Then, the force from the elastic stay is given as bellow:

$$F_{ES} = F_{ES0} + kx, \quad (10)$$

where  $F_{ES0}$  accounts for the initial elastic stay force,  $x$  denotes the compression.

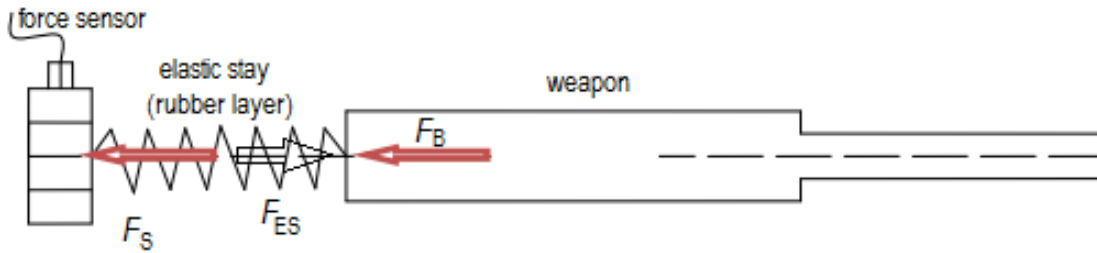


FIG. 7. Schematic of sensor seating

Determination of the exact value of the rubber layer stiffness  $k$  is beyond the scope and purpose of the present research. During shooting, the force  $F_B$  is transmitted from the weapon to the force sensor. The resultant force  $F_S$  acting on the sensor is given by

$$F_S = F_B - F_{ES} \quad (11)$$

Equation (11) indicates that the experimentally obtained force  $F_S$  is smaller than the real force  $F_B$  acting on the weapon while shooting, but the forces  $F_S$  and  $F_B$  have the same tendency.

## 5. CONCLUSIONS

In this paper, the mathematical model for the calculation of the recoil intensity of the CO<sub>2</sub> powered recoil simulator has been formulated. The problem has been solved numerically using the Runge-Kutta method in MATLAB environment.

The developed mathematical model was verified on the tubeless recoil simulation kit for the assault rifle AK47 by the measurement of force acting on the weapon mount using the piezoelectric force sensor. The model provides good agreement with measured data. Obtained results enable us to analyze various influences of changes in several design parameters on the recoil intensity.

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