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Development of the Preliminary Numerical Model of the Short Recoil Operated Weapon Using the Multibody Systems

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Abstract. The paper contains a literature review of studies on several firearms operation systems and a review of articles on modern methods of calculating the kinematic characteristics of weapons. It includes the presentation of the short recoil operated 9 mm PW INKA pistol numerical model. The model was created in the MCS Adams software which uses the multibody systems. The boundary conditions for each part were specified and their implementation was determined. As the preliminary results of numerical investigations, the slide and barrel velocity and displacement curves were obtained.

Comparison of a numerical solution with the literature data allowed for its qualitative verification.
Keywords: mechanics, weapon design, short recoil operation, numerical model, multibody systems.

1. INTRODUCTION

There are a few of operation systems in firearms. The most common are gas-operation [1, 2], blowback [3-5], short recoil [6-8], and delayed blowback system [9]. In papers [6-8] the authors focused on the NR-30 and NS-23 short recoil operated aircraft cannons with a bolt accelerator. The available sources show a shortage of studies on this operation system, especially in the area of weapons without a recoil accelerator. This solution is commonly used in pistols, particularly feed with 9 × 19 mm Parabellum round, due to the high muzzle energy of the projectile. For this reason, it would be beneficial to conduct the research on this system, which would be especially useful for development of new weapon types or modification of existing constructions.

The best solution to achieve the stated objective is to use the latest simulation techniques based on CAD/CAE software. As reported in the literature, the multibody system (MBS) [1, 3, 10, 11] and the finite element method (FEM) [1, 12] are the most often used in the simulations of firearms operation. For the calculation of kinematic characteristics of weapon, it is more convenient to use the MBS. This method allows calculating a more complex numerical model than FEM with less computational costs. Therefore, it was decided to use MCS Adams software [13].

The aim of the ongoing works is to broaden the knowledge of short recoil operated weapons. Additional benefit of selecting PW INKA pistol [14] as a model weapon is that it will be possible to better test and optimise this construction for further development works.

2. DESCRIPTION OF SHORT RECOIL OPERATED WEAPON WORK CYCLE

The simplest system of weapon operation is the blowback system. Its main disadvantage is the bolt mass, which must be of a sufficiently large value to ensure the safety conditions. For this reason, this system is applied in pistols firing ammunition with projectile muzzle energy up to approx. 350 J or with more powerful ammunition in submachine guns, where a heavier bolt can be used. Implementation of so heavy slide to use higher power cartridges in a pistol, would make this system inapplicable, so other solutions should be used [15]. In 9 × 19 mm pistols with the muzzle energy from 542 J to 814 J (when firing a standard ballistic barrel) [16], the most common is a short recoil operation.

Recoil operated weapon is characterized by the fact that a barrel is locked and it starts to move together with a bolt. There is known long and short recoil operation. In the first variant, a barrel moves the same distance as a bolt. In the second case, its movement is shorter than movement of the bolt [15].

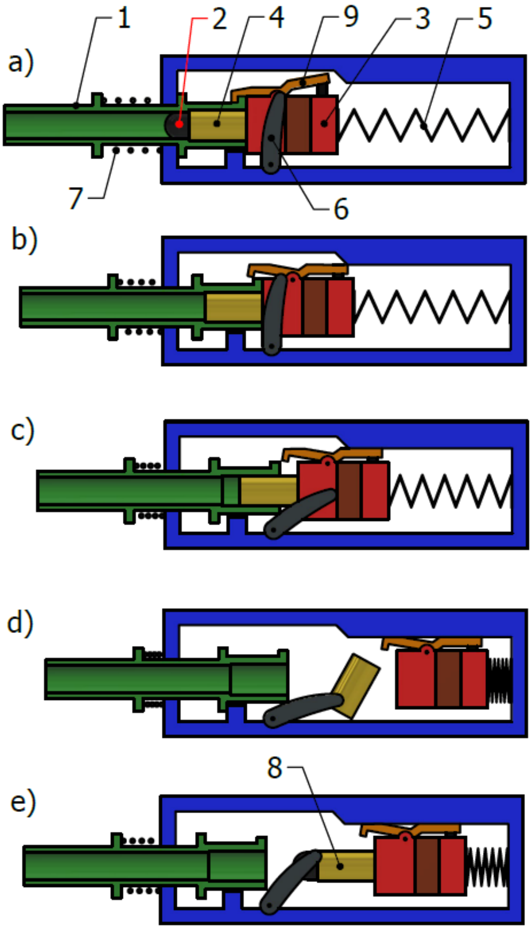

Fig. 1. Scheme of work of short recoil operated weapon: 1 – barrel, 2 – projectile, 3 – bolt, 4 – case, 5 – recoil spring, 6 – bolt accelerator, 7 – barrel spring, 8 –next cartridge, 9 – locking lever

The short recoil system cycle (Fig. 1) consists of the following stages:

a) After ignition of the propellant, pressure in the barrel (1) moves the projectile (2) toward the muzzle and the bolt (3) with the barrel in the opposite direction, acting through the bottom of the case (4) on the front of the bolt (Fig. 1a).
b) After a relatively short movement of the bolt with the barrel, the projectile leaves the barrel and the pressure decreases to the value of atmospheric pressure or close to atmospheric pressure and the bolt is unlocked (Fig. 1b).

c) The barrel with the bolt continues the rearwards movement by inertia, compressing the recoil spring (5). In case of the accelerator (6) presence, the movement of the bolt starts accelerating in relation to the barrel (Fig. 1c). The accelerator is used for heavy bolts.
d) The barrel is stopped when it reaches the rearmost position, or in case of the barrel spring (7) presence, it starts to return to the front. During the backward bolt motion, the striking mechanism is cocked and the case is ejected. After the bolt reaches the rearmost position, it begins to return under the recoil spring force (Fig. 1d).
e) During the forward bolt motion, the next cartridge (8) is fed to the chamber (Fig. 1e). Bolt starts to lock the barrel and returns to the forward position with it, provided that the barrel did not return earlier under its own spring force [15].

Locking and unlocking the barrel can be done by tipping down or rotating the barrel, locking lever or using a toggle lock. This process schematically is shown in Fig. 1. In this case, this process is carried out by the locking lever (9).

3. DEVELOPMENT OF THE PRELIMINARY NUMERICAL MODEL

Development of the numerical model began from the preparation of 3D models in the CAD environment and exporting them to MCS Adams software [13]. During building the numerical model, the following assumptions were made: a real system is the multibody system, real parts of the pistol are described by rigid elements, parts are connected by kinematic pairs of different classes and they are subjected to specific forces and torques [17].

The numerical model (Fig. 2) consists of sixteen parts: the slide (1), grip module (2), barrel (3), frame (4), magazine tub (5), magazine follower (6), cartridge (7), case (8), hammer (9), sear (10), main spring strut (11), barrel disconnector (12), takedown pin (13), disconnector (14), trigger bar detent (15) and extractor (16). The model contains the most important parts of the weapon that affect its work cycle.

Apart from the interaction forces between the weapon parts, the system is loaded by the following forces (Fig. 2):

- F_p – force of gas pressure acting on the bottom of the case,
- F_{rs} – force of recoil spring,
- F_m – force of mainspring,
- F_{ms} – force of magazine spring,
- F_{tb} – force of trigger bar spring,
- F_{es} – force of extractor spring,
- F_{bc} – force extracting bullet from case,
- F_{bb} – force of bullet engraving into barrel.

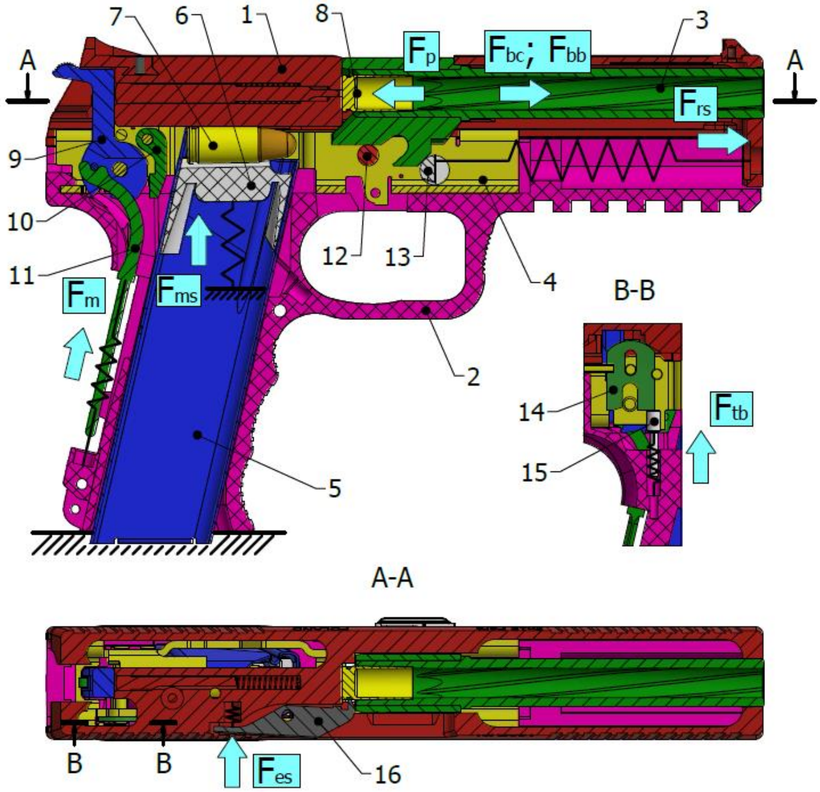

Fig. 2. The initial position of the parts of the numerical model at the time $t = 0$ and the forces acting on the moving elements: 1 – slide, 2 – grip module, 3 – barrel, 4 – frame, 5 – magazine box, 6 – magazine follower, 7 – cartridge, 8 – case, 9 – hammer, 10 – sear, 11 – main spring strut, 12 – barrel disconnector, 13 – takedown pin, 14 – disconnector, 15 – trigger bar detent, 16 – extractor

The following initial and boundary conditions were specified:

- parts of the pistol (rigid elements) are stationary at the initial moment $t = 0$,
- material parameters were defined for the parts,
- the forces acting on the system were defined,
- at the initial moment $t = 0$, the gas pressure starts to increase (which is equivalent to an ignition of propellant), the gas pressure is the input for the system and it forces the motion of parts,
- stationary parts during a shot were fixed in the numerical model: the grip module, frame, magazine box, barrel disconnector and takedown pin,
- degrees of freedom were determined to the parts,
- contact pairs were defined.

The force of gas pressure was measured during a shot with a ballistic test barrel using an experimental method. Average course of pressure, applied in simulations was presented in Fig. 3. The tests were performed for 9 × 19 mm Parabellum pistol ammunition with lead core made by Mesko S.A. (Poland). In Adams software, discrete measurement data were interpolated using the cubic spline (CUBSPL function) [13].

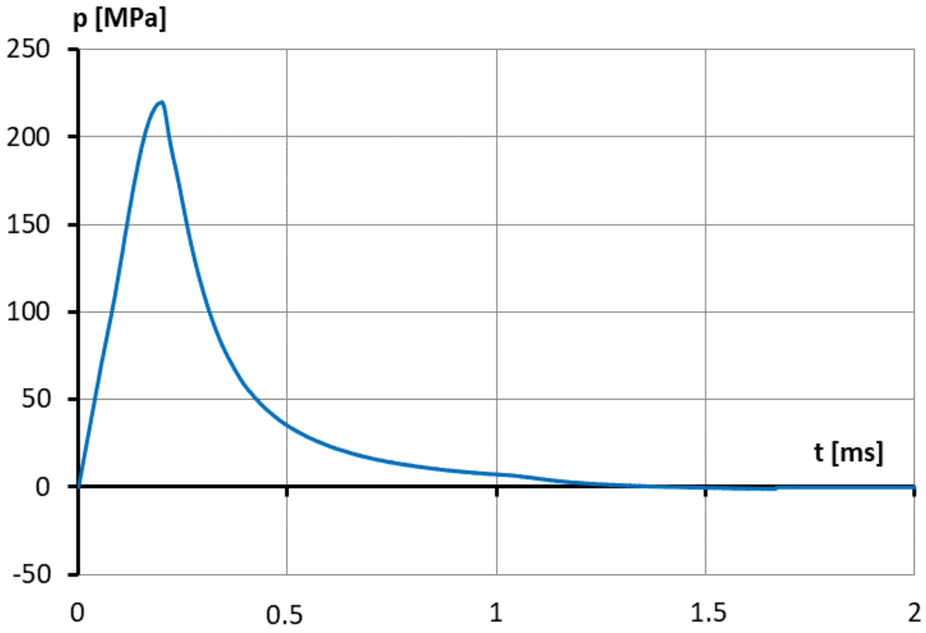

Fig. 3. Experimentally obtained pressure time diagram of 9 × 19 mm Parabellum pistol ammunition with lead core made by Mesko S.A. (Poland)

The stiffness and force of springs and mass of parts was determined on the basis of the technical documentation of the weapon and the actual measurements, which confirmed the compliance of the stiffness and forces (Table 1) and masses (Table 2).

Fixed barrel, considered in the model presented in [1, 3], allowed for omission the bullet engraving force in kinematics simulations. In case of the model presented in this paper, during the initial phase of the slide motion, the barrel moves back together with the slide parts due to their connection (locking). This fact and bullet engraving force order of magnitude [3] impose the necessity of this force application in the kinematics model.

Table 1. Stiffness and preload of the most important springs

Spring type	Stiffness [N/mm]	Spring preload [N]
Recoil spring	0.8	26.0
Main spring	3.7	46.6

Table 2. Materials and masses of main moving parts

Part	Material	Weight [g]
Slide	Steel	340.1
Barrel	Steel	109.5

The force extracting the bullet from the case is not taken into account in the work [1], because the barrel is locked, and the unlocking takes place after this force action, so it does not affect the operation. The situation is different in the thesis [3] and in case of the model presented in this paper, where the force extracting the bullet from the case was taken into account due to its influence on the slide motion.

The force of interaction between the case and the chamber in the thesis [3, 4] is important, because the case starts its movement at the same time as the projectile, that is during acting of the force of gas pressure. The case is subjected to plastic deformation, which causes a significant increase in the axial force (friction) of the interaction between the case and the chamber. In the work [1] this force was left out because the bolt and barrel unlock after the pressure drops to atmospheric pressure or close to atmospheric pressure. For the same reason, in this work, the force of interaction between the case and the chamber is represented as ordinary friction (Coulomb friction model).

Contact forces in the numerical model can be represented by Impact, Restitution or User Defined function. In this case, the IMPACT function was used which determines the contact force based on the following formula [18]:

$$F = \begin{cases} 0 & \text{for } q > q_0 \\ k(q_0 - q)^e - c_{max}\dot{q} * STEP(q, q_0 - d, 1, q_0, 0) & \text{for } q \leq q_0 \end{cases} \tag{1}$$

where:

F – normal contact force, k – contact stiffness, q_0 – displacement followed by contact of the members, q – relative displacement of contact surfaces, e – exponent of the force deformation characteristic, c_{max} – maximum damping coefficient, $\dot{q}$ – relative velocity of contact surfaces, d – boundary penetration with full damping.

First part of formula 1 is contact stiffness (F_k):

$$F_k = k(q_0 - q)^e \tag{2}$$

Second part of formula 1 is damping (c):

$$c = c_{max}\dot{q} * STEP(q, q_0 - d, 1, q_0, 0) \tag{3}$$

The graphic interpretation of formula 1 is presented in Fig. 4.

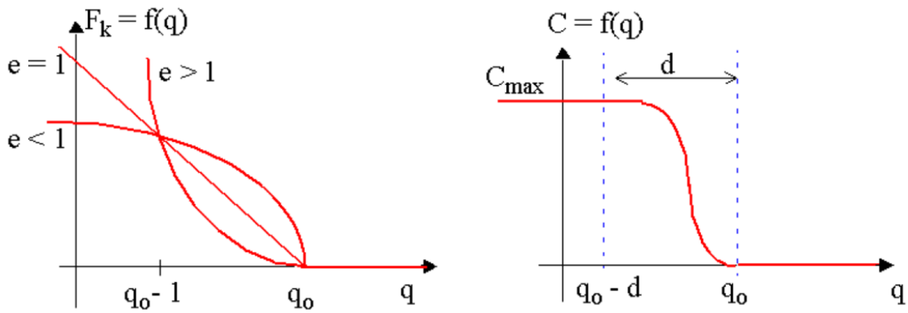

Fig. 4. On the left – graph of the contact stiffness (F_k) versus displacement (q) with the presentation of different exponent (e), on the right - the relationship between damping (c) and penetration depth [18]

In this case the Coulomb friction model was adopted. According to this theory, friction is divided into static and dynamic friction (also known as kinetic or sliding). The graphical interpretation of this resistant force model was presented in Fig. 5. The static friction (T_s), which depends on the static friction coefficient (μ_s), and the normal force (N), reach their maximum values just before the beginning of the movement, increasing with the increase in the displacement force (P) to the limit value:

$$T_s = N\mu_s \tag{4}$$

After starting the movement, the static friction becomes the dynamic one (T_d). This value decreases until a constant value is reached as a consequence of the displacement force increase (relative velocity of the rubbing surfaces). It depends on the dynamic friction coefficient (μ_d) and the normal force [19]:

$$T_d = N\mu_d \tag{5}$$

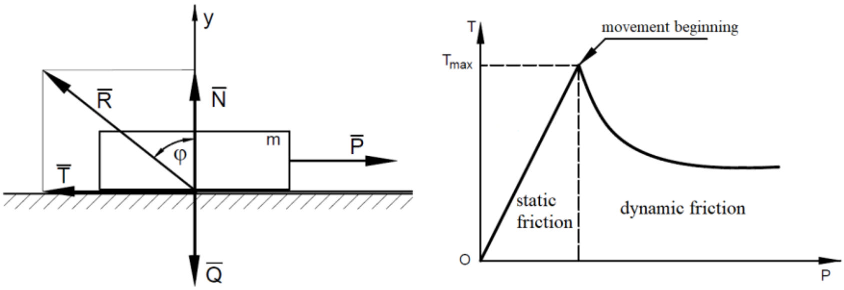

Fig. 5. Coulomb friction model [19]

The Coulomb model was used in the MCS Adams software (Fig. 6). The static friction coefficient (μ_s) reaches its maximum value for the stiction transition velocity (V_s) or its minimum ($-\mu_s$) for the negative value of the stiction transition velocity ($-V_s$). A positive value of the dynamic friction coefficient (μ_d) is achieved for a velocity higher than or equal to the friction transition velocity ($V \geq V_d$), and the negative value ($-\mu_d$) for a velocity lower or equal to the negative value of the friction transition velocity ($V \leq -V_d$). The user enters four parameters into the software: μ_s, μ_d, V_s, and V_d. The dependence of the friction coefficient on speed is interpolated by the cubic step function [18].

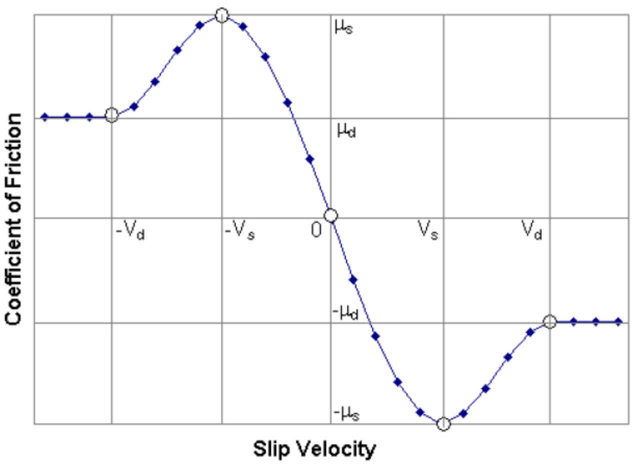

Fig. 6. Graph of the friction coefficient versus the relative velocity of two rigid elements: μ_s - static friction coefficient, μ_d - dynamic friction coefficient, V_s - stiction transition velocity, V_d - friction transition velocity [18]

The time step was 31.5 µs. Values of parameters from all above equations was determined from the literature [18].

4. PRELIMINARY RESULTS OF NUMERICAL INVESTIGATIONS

The results of numerical investigations of the slide and barrel displacement and velocity courses are shown in Fig. 7 and 8. The slide velocity with positive values means the rearwards movement. Comparing the curves obtained by numerical investigation and examples from literature [20], there is a qualitative similarity, which can partially suggest the correctness of applied methods and stated assumptions.

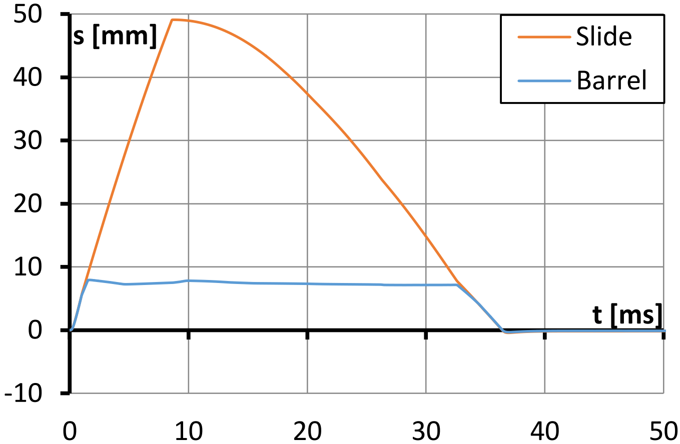

Fig. 7. Displacement of slide and barrel versus time obtained using numerical investigation

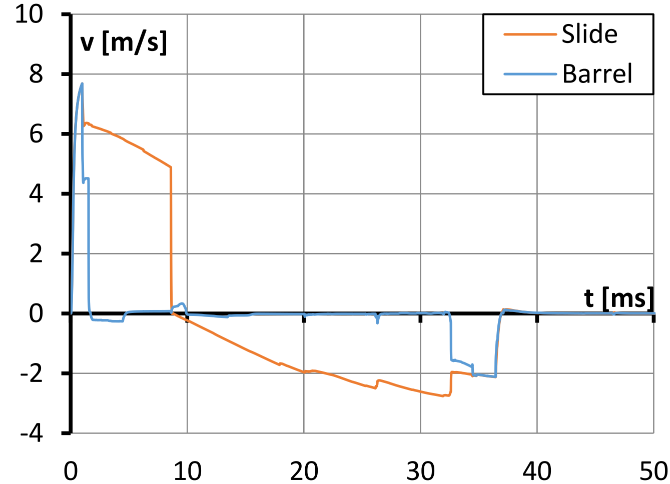

Fig. 8. Velocity of slide and barrel versus time obtained using numerical investigation

5. CONCLUSIONS

The paper is aimed at presentation of the literature review in the area of weapon operation numerical simulations, which allowed us for formulation and analysis of the preliminary numerical model for short recoil operated pistol.

The obtained results are preliminary, because the model requires further improvements, e.g.: selection of better match friction coefficients, better selection of material characteristics, better selection of the time step, and investigation of the model sensitivity to the parameters selection. Determining the exact forces of extracting the bullet from the case and bullet engraving into barrel requires further literature review. These forces currently were only pre-selected.

The developed numerical model is extensive and should accurately reflect the weapon. The model includes: friction between the parts, the forces of the springs, the forces of extraction and ejection of case and feeding of the next cartridge to the chamber, the interaction between the parts, etc. Possible discrepancies between the results of numerical investigation and the real values may result from the imperfection of the adopted method of numerical modelling, which assumes the rigidity of parts or from uncertainty of measurement of gas pressure.

The developed model requires validation. Therefore, the further works are going to be focused on experimental measurements of the pistol kinematic characteristics.

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Opracowanie wstępnego modelu numerycznego broni działającej na zasadzie krótkiego odrzutu lufy z zastosowaniem metody układów wieloczłonowych

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Streszczenie. W artykule zawarto przegląd literaturowy opracowań dotyczących różnych zasad działania broni strzeleckiej oraz przegląd artykułów dotyczących nowoczesnych metod obliczeń kinematyki broni. Przedstawiono sposób budowy modelu numerycznego 9 mm pistoletu PW INKA działającego na zasadzie krótkiego odrzutu lufy. Model stworzono w programie komputerowym MCS Adams, który korzysta z metody układów wieloczłonowych. Opisano warunki początkowo brzegowe przyjęte dla modelu. Przedstawiono wstępne wyniki obliczeń w postaci wykresów drogi oraz prędkości w funkcji czasu i porównano je z danymi literaturowymi w celu ich weryfikacji jakościowej.

Słowa kluczowe: mechanika, konstrukcja broni, krótki odrzut lufy, metody numeryczne, metoda układów wieloczłonowych.