PROBLEMS OF MECHATRONICS
ARMAMENT, AVIATION, SAFETY ENGINEERING

ISSN 2081-5891 5, 4 (18), 2014, 21-32

Shooting Errors Simulations Initiated by Barrel Jumping of 40 mm Turret Guns

Aleksandar KARI[1*], Olivera JEREMIĆ[2], Momčilo MILINOVIĆ[2],
Damir JERKOVIĆ[1], Miloš MARKOVIĆ[2]

[1]University of Defence in Belgrade, Military Academy,
33 Pavla Jurisica Sturma St., 11000 Belgrade, Serbia
[2]University in Belgrade, Faculty of Mechanical Engineering,
Kraljice Marije 16, 11000 Belgrade, Serbia
[*]corresponding author, e-mail: karial@ptt.rs

Manuscript received August 18, 2014. Final manuscript received December 3, 2014

DOI: 10.5604/20815891.1138362

Abstract. Model considered estimations of isolated shooting errors initiated by barrel jumping after each particular bullet as the research of particular characteristic important for gun mounting on the mobile platforms. Sequential influences of barrel disturbances are included in the initial ballistics derivations independent of vehicle turret and undercarriage. Expected disturbance magnitudes are analyzed during and beyond shooting for the particular bullet in the ripple. Shooting ripple errors are analyzed according to the angular disturbances transposed to the projectile initial ballistic elements. Rate of barrel impeachments during firing is taken as the element of projectile spin disturbance. Barrel system with appropriate recoil equipment is taken as the rigid body model in the first approximation. Behaviour of 40 mm automatic gun as the possible concept aimed at the shooting with small elevation angles, as mounted on the mobile combat platforms was tested.

This paper is based on the work presented at the 10th International Armament Conference on „Scientific Aspects of Armament and Safety Technology", Ryn, Poland, September 15-18, 2014.

Ballistic testing of real projectiles on the proving ground is used as reference to selected gun particular errors. Further extended research was directed to the system's acceptable accuracy and stability in the cases of gun mounting on the Armour Personal Carrier (APC).

Keywords: mechanics, shooting errors, barrel jumping, oscillations, APC, accuracy

1. INTRODUCTION

The most of papers, which consider, directly or conditionally, influenced parameters for the mounting of the low calibre guns are noted last time in literature [1-4]. The reason is continual request for improving firepower of land and air combat fleets, especially personal carriers and helicopter units aimed at direct support of clashes in the first line. Improving firepower, means improving ammunition terminal efficiency, but in balance with the requests regarding calibre, shooting precision, and rate of fire. In that sense of meaning, it is useful to test different calibre types of automatic guns for implementation as a turret mounted weapons on combat vehicles. It means namely to know behaviour of weapon precision regarding mechanical influences of weapon, mounted platform, and mounted undercarriage of mobile system, as separately subsystems influencing the projectile initial errors. Barrel jumping and its influences on the projectile initial disturbances are the errors transposed to the exterior ballistic and included in the final shooting errors on the target.

Disturbances of barrel jumping, after the projectile leave a barrel, depend on platforms, as the referred oscillatory system, by damping response time and could be avoided if it integrates into the modified rate of automatic fire. It means that influences of platform undercarriage on the projectile disturbances have been eliminated because each of a platform corresponds to appropriate rate of fire which provides gun mounting with total system damping before firing each projectile in the ripple. Ripple cadence for each of the platforms is chosen variably depending on total damping time for the same mounted gun. Also, new redesigning of ammunition aimed at the new targets and shooting conditions, which could be required, could make new affects on the gun and platform mechanical responses during firing and gun recoil period.

Antiaircraft gun of 40 mm calibre is not aimed at the direct fire on the ground targets. The possibility of integration of this weapon on the mobile platforms has different constrains depending on platforms and their applications. Ground vehicles or helicopters very probably could have respectable redesigning requests for the ammunition and the structure of the gun recoil and automatic firing system, too. The aim of this work is to discover the basic isolated influences, made by barrel jumping, affecting the projectile and also the initial ballistic shooting elements, caused by recoil system initial part of motion during full interior ballistic cycle.

2. MATHEMATICAL AND MECHANICAL MODEL

To discover gun disturbances data valid to affect projectile at initial motion on the ballistic trajectory, with small elevation angles of shooting, simplified mechanical model is developed. Mechanical – oscillatory model of gun with appropriate moving subsystems is shown in Figure 1a for un-disturbing equilibrium level and Figure 1b for disturbing – jumping level. Disturbing variables are observed as a function of the disturbance barrel-jumping angle φ around zero angle initial elevation as the referent equilibrium state. In the paper, it is accepted general approach of Lagrange analytical mechanics considered by 3-D, analytical equations of gun system states with appropriate generalized forces and moments which initiate generalized coordinates, the system jumping angle φ, the external recoil displacement x, and the interior ballistic projectile displacement s taken as relative motion.

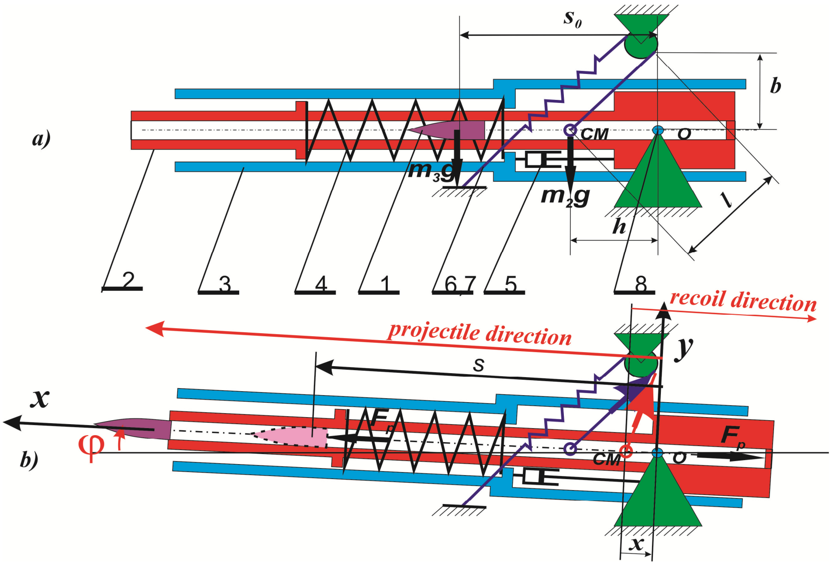

Fig. 1. Mechanical model:
a) system position at the zero point moment $t = 0$,
b) system position at the disturbing time $t = t_k$
1 – projectile, 2 – barrel, 3 – cradle, 4 – barrel spring, 5 – recoil brake,
6, 7 – equilibrators, 8 – shoulder of gun cradle

Mathematical model is accepted as simplified one, based on initiated system motion made by projectile motion and its firing in the barrel.

The linearization of the model is realized based on assumption that articles in equations of higher orders, which could be important for the affection of undercarriage gun mounted mechanics, do not affect as the disturbances of projectile initial exterior ballistic data because response of complete gun system on the bullet firing is much longer then interior ballistic cycle.

In that sense of meaning, it is considered the small time interval t_k of recoil and jump of the system, which overlaps with interior ballistics period. The process of weapon damping after projectile leaves the barrel is considered as free damping oscillations important for the automatic rate of fire as variable cadence dependent on a type of mobile platform undercarriage and underlies the different model of linearization. According with explanations and assumptions, the part of system disturbances by the angle φ and the part of recoil displacements x are valid for the total projectile motion along the barrel s, in considerations of this paper.

The general equation of system equilibrium (Fig. 1b), based on the generalized coordinates $q_1 = \varphi$, $q_2 = x$, $q_3 = s$ is the following:

$$\frac{d}{dt}\left(\frac{\partial E_k}{\partial \dot{q}_i}\right) - \frac{\partial E_k}{\partial q_i} = Q_i\,, \qquad i = 1,2,3 \tag{1}$$

Model encircled next inertial and stiffness potential coefficients:

m_1 – mass of gun cradle (Fig. 1a, position 3) with appropriate moment of inertia $I_{Oz}^{(1)}$ around axes of gun cradle shoulder (equilibrium axes);

m_2 – reduction mass of barrel (Fig. 1a, position 2), with appropriate gun recoil system (Fig. 1a, position 4 and 5) and their moment of inertia $I_{Cz}^{(2)}$ round centre of gravity (CM) m_2;

m_3 – mass of projectile (Fig. 1a, position 1).

The total potential energy sources represented in these considerations (Fig. 1b) are the following:

c_3 – spring stiffness, which affected system motion, as potential energy sources for the barrel (Fig. 1a, position 4);

$c_1 = c_2$ – stiffness of springs as the equilibrators independent of the cradle and the barrel as joint functional systems (Fig. 1a, position 6 and 7);

β – damping coefficient of recoil hydraulics.

Regarding system approach after derivation of energies and appropriate, generalized forces (moments), next equations designed Lagrange approach from (1):

Kinetic energies of subsystems motion:

$$\begin{aligned} E_{k1} &= \frac{1}{2} I_{Oz}^{(1)} \dot{\varphi}^2 \\ E_{k2} &= \frac{1}{2} I_{Cz}^{(2)} \dot{\varphi}^2 + \frac{1}{2} m_2 \left(\dot{x}^2 + x^2 \dot{\varphi}^2 \right) \\ E_{k3} &= \frac{1}{2} m_3 \left(\dot{s}^2 + s^2 \dot{\varphi}^2 \right) \end{aligned} \tag{2}$$

And generalized forces are

$$\begin{aligned} Q_{\varphi} &= c_1 \Delta l_1 \frac{bh}{l_{10}} + c_1 \Delta l_2 \frac{bh}{l_{20}} - m_2 gh - m_1 gh - m_3 g s_0 \\ Q_x &= -c_1 \Delta l_2 \frac{h}{l_{20}} - c_3 \Delta l_3 \\ Q_s &= -m_3 g \varphi \end{aligned} \tag{3}$$

respecting that:

$\sin\varphi = \varphi$;

$b = b_1 = b_2$ – radial distance from barrel CM;

h – axial distance from barrel CM;

$\Delta l_j = l_j - l_{j0}$– deformations of appropriate springs j = 1, 2, 3 (Fig. 1a) during disturbing motion;

s_0 – initial projectile distance from CM.

Using initial conditions linearization by Mac Loren order around CM value $\varphi = 0$, geometrical values shown in Fig. 1a and their functional relations imaged in Fig. 1b, after replacing (2) and (3) in equation systems (1), generate next final form of equations for disturbing kinetic energy are:

$$\begin{aligned} \ddot{\varphi}\left(I_{Oz}^{(1)} + I_{Cz}^{(2)} + m_2 x^2 + m_3 s^2 \right) + 2\dot{\varphi}\left(m_2 x \dot{x} + m_3 s \dot{s} \right) &= \\ = -c_1 b^2 \left(\frac{1}{l_{10}^2} + \frac{1}{l_{20}^2} \right) h^2 \varphi + m_3 g \left(s_0 - s \right) &+ \\ + \left(-c_1 \frac{h^2 b}{l_{20}^2} + m_2 g \right) \left(h - x \right) & \\ m_2 \ddot{x} - m_2 x \dot{\varphi}^2 = \left(c_1 \frac{h^2 b}{l_{20}^2} - m_2 g \right) \varphi + \left[c_1 \frac{h^2}{l_{20}^2} + c_3 \right] \left(h - x \right) - \beta \dot{x} - F_p & \\ m_3 \ddot{s} - m_3 s \dot{\varphi}^2 = F_p - m_3 g \varphi & \end{aligned} \tag{4}$$

where F_p – gun propulsion force.

In that sense of meaning, equations of motions (4) represent only behaviour required in the mentioned above assumptions for the very beginning of recoiling motion and very beginning of gun barrel jumping which transposes into the disturbances of projectile initial ballistic values as it vector projectile muzzle velocity, launching elevation angle and projectile impeachment rate influenced on total spin vector. These values are taken into the 2D vertical plane and affecting projectile ranges errors.

Simulation model of (4) provides next final kinematical performances as the values affecting the projectile:

- disturbances of initial elevation angle, caused by the barrel jumping $\varphi(t_k)$ at the moment of projectile launching,
- angular velocity of the barrel jump $\dot{\varphi}(t_k)$ disturbing projectile impeachment and full spin vector,
- initial velocity of projectile $|\vec{v}_0| = v_x = \dot{s}(t_k)$, disturbed by relative motion of the barrel axial recoil velocity $\dot{x}$,
- lateral component of the muzzle velocity vector $\vec{v}_0$, as the impeachment disturbance v_φ, caused by relative motion of a barrel into the vertical direction (rotational jumping), influenced on projectile initial angle of attack.

The model does not consider transient (interior to exterior) ballistic effects on projectile motion.

Final conditions at the instant t_k generated on the interval $t \in (0, t_k)$, are taken as initial disturbances of projectile flight after launching. In that sense of meaning, simplified and linearized equations of system motions (4), confirmed particular influences of weapon transposed directly only on the projectile trajectory.

3. EXTERIOR BALLISTICS CONSIDERATIONS AND EVOLVED PARTICULAR WEAPON INFLUENCES

Exterior ballistic testing of initial conditions' influences, developed in mathematical and mechanical model, was divided into three steps:

- Step 1 is combined proving ground testing and data simulation of the appropriate real projectiles' trajectories. Trajectories generated in these tests are used into the considering of particular influences in the next steps.
- Step 2 – elimination of axial and lateral wind along appropriate experimental trajectories influencing the projectile aerodynamics. This proving ground clearing of experimental trajectories design, the reduced trajectories by ranges for the different tested elevations.

These trajectories are experimental ones with the real ammunition and interior ballistic errors but with eliminated exterior ballistic proving ground conditions.

- Step 3 – elimination of the recoil and barrel jump weapon effects, derived in this paper, by the redesigning of initial trajectory data on the reduced trajectories made in step 2. This could represent ideal exterior ballistic weapon's study state launching trajectories but with real aerodynamics and real ammunition and barrel's interior ballistics.

By this method, separation of the particular weapon influences caused by influences of barrel vertical jump is considered, into 2-D space.

4. RESULTS OF SIMULATION AND DISCUSSION

The simulation of equations (4) is realized by the geometrical data of gun design and in the time interval $t \in (0, 4.8)$ ms [5, 6], which was appropriated to the interior ballistic cycle for 40 mm automatic gun. Also, software for the gun propulsion force F_p has been used based on literature as standard interior ballistic package [6]. Projectile aerodynamics and exterior ballistics is referred in the former papers of scientific literature [1, 6, 7].

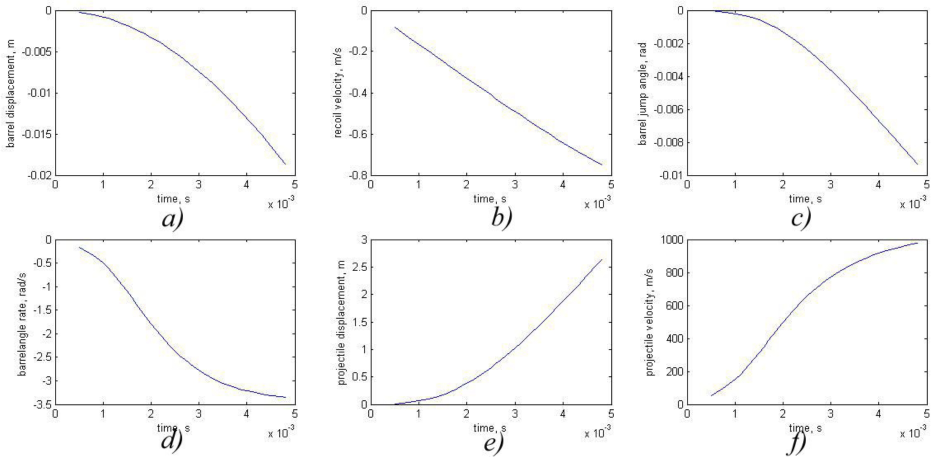

Fig. 2. Results of simulation of disturbing gun motion

Data in Figures 2a and 2b represent recoil displacements and recoil velocities evaluation during projectile motion in the barrel. Barrel jump angle and angular rate for the same interval are shown in Figures 2c and 2d. Projectile displacement and velocity evaluation are shown in Figures 2e and 2f.

Based on appropriate assumptions, final disturbances referred to transposing effect on projectile motion are given in Table 1.

Table 1. Final gun system disturbances

standard muzzle velocity v_0	axial disturbance velocity $\dot{x}(t_k)$	projectile impeachment disturbance $v_\varphi = L\dot{\varphi}(t_k$	angular rate of barrel (projectile disturbance peach rate $\dot{\varphi}(t_k)$	barrel elevation angular disturbance $\varphi(t_k)$	initial disturbances of projectile attack angle $\Delta\alpha(t_k) = atg\frac{v_\varphi}{v_o}$	relative projectile velocity $\dot{s}(t_k)$
978 m/s	0.8 m/s	8.2 m/s	3.4 rad/s	0.95 mrad	8.4 mrad	975.8 m/s

Experimental and reducing exterior ballistic research was developed based on proving ground trajectories testing, measured by Doppler radar of projectile flight to the self-destruction point (SDP).

Ballistic ($x_1 - y_1$) and weapon disturbances $(x - y)$ frames, shown in Figure 3, represent image which describes the way of transformation of projectile scalar velocity components v_0, and v_φ from gun barrel frame $x - y$, onto the projectile trajectory frame $x_1 - y_1$, and its velocities v_{x1} and v_{y1}. This was required to involve real weapon disturbances into the exterior ballistic frame with disturbances to make reduced trajectories, clear of proving ground exterior conditions. Proving ground exterior temperature was about normal standard temperature 15°. Reduced wind effect is given in Table 2.

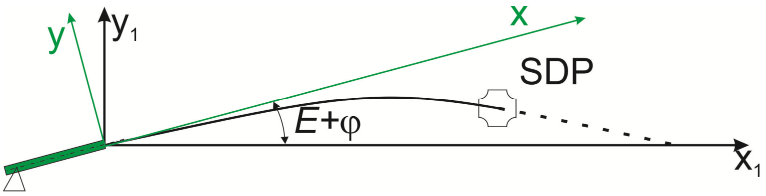

Fig. 3. Weapon disturbing and ballistic coordinate frames

Variable elevations are used for the same weapon disturbances, noted in Table 2 with assumption that small angles of elevations do not affect equations linearization made around zero equilibrium angles supposed in the mechanical model. This provides approximate estimations of separated effects of weapon on trajectory ranges.

Figure 4 represents two experimental tests with characteristic elevations used for numerical method of designing the reduced trajectories based on particular experimental data. Each of trajectories was tested with two firing experiments. The reduced trajectories recalculated range D_{red} from the average values between two experiments under the same elevation and proving ground conditions. The data are selected in Table 2.

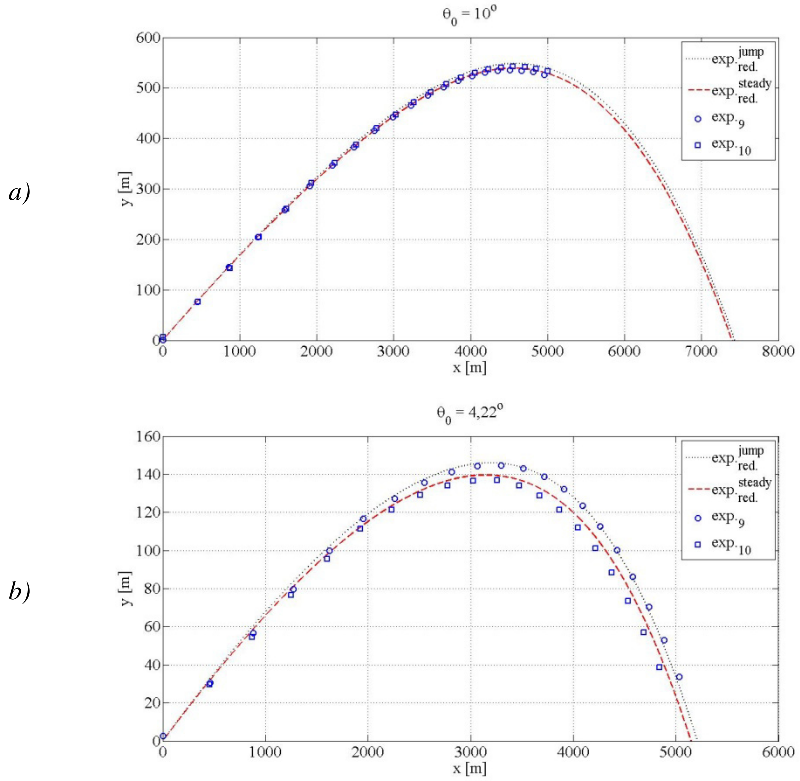

Fig. 4. Representative trajectories of experimental and simulation tests:
a) elevation angle – θ_0,
b) maximum shooting expected elevation angle on the ground targets

The set of reduced experimental trajectories and expected steady state trajectories (Table 2, range D_{ss}), which do not include weapon mechanics jump influences, which are given in Table 1, are represented in Figure 5. The range differences ΔD of these two types of trajectories (Table 2) are taken as the weapon generated errors, considered in this paper.

All sets of data are shown in Table 2. Negative and zero angles are considered by the range errors on the ranges with fixed depression value of target position. Positive elevations are considered on the appropriate topographic ranges without local target angles (depression $h = 0$).

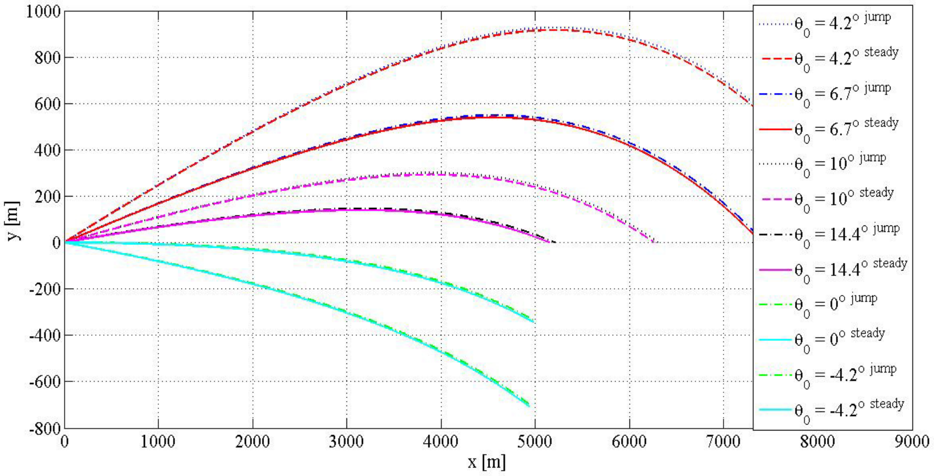

Fig. 5. Representative trajectories of simulation tests

Table 2. Elevation exterior ballistic test

Elevation [mrad]	Wind reduced W_{x1} = 2.7 m/s W_{x1} = 0 m/s	Range study state	Range difference influenced by weapon	Position target depression	Percentage relative target miss
	Range reduced D_{red} (W_{x10}, W_{y10}) [m]	D_{ss} [m]	$\Delta D = D_{red}$-D_{ss} [m]	h [m]	$\bar{D} = \frac{\Delta D}{D_{red}} \cdot 100$ [%]
–75	3013	2970	43	–300	1.4
0	4820	4772	48	–300	1.0
75	5210	5148	62	0	1.2
120	6306	6260	46	0	0.7
178	7430	7395	35	0	0.5
250	8575	8547	28	0	0.3

Regarding the exposed data, it could be useful to note that the influenced parameters of weapon jump in the fire have all been fixed for the considered angles of elevation. Percentage influences of range errors (Table 2) are always positive if weapon is used for shooting with small elevations. Maximum errors generated by weapon appear if weapon is used on the ranges of about 5000 m with elevation angles between 0 to 4.5 degrees (75 mrad).

All values of percentage range errors, caused by weapon jump effects transposing to the projectile trajectory, are about 1%, with expectation to decrease at higher elevations but for the cases of less than 45 degrees.

This directed conclusion that ranges of 5000 m, expected as maximum for the ground shooting of the 40 mm guns, could have much less relative percentage of targets range misses at the higher elevation angles.

5. CONCLUSION

This research is the small study of the real questions of technical adaptability of 40 mm guns mounted for use against ground targets. The paper successfully used simplified gun subsystem mechanical model as the first approach to test exterior ballistic transient influences based on tunnel and proving ground verified and tested projectiles aerodynamics. Lagrange's analytical system approach, based on energy and their equations linearization in equilibrium area of disturbances, shows fixed weapon jump disturbances as approved for different small positive and negative angles of elevation less than 10 degrees. For the first time, in the paper it was used so called reduced experimental trajectory as a kind of laboratory reference range measured numerically, cleaned on proving ground conditions as a comparative set of data to test weapon jumping effects, influenced separately on the range. Generation of trajectories which do not have weapon jump effects (steady state weapon conditions), but include all effects of real firing made by interior ballistic disturbances and ammunition influences, are also, methodology contribution made in this paper. Further research will consider the effects of rate of fire redesigned by full oscillations and damping effects of gun mounted on the applicant platforms, and testing different types of absorbing systems to improve rate of fire and combat platform stability.

Acknowledgements

This paper is the part of research on the project III 47029 of the Ministry of Education, Science and Technological Development of Republic of Serbia funded in 2011-2015 years.

REFERENCES

[1] Milinovic M., Jerkovic D., Jeremic O., Kovac M., Experimental and Simulation Testing of Flight Spin Stability for Small Calibre Cannon Projectile, *Journal of Mechanical Engineering*, vol. 58, no. 6, pp. 394-402, 2012.

[2] Štiavnický M., Lisý P., Influence of barrel vibration on the barrel muzzle position at the moment when bullet exits barrel, *Advances in Military Technology*, vol. 8, no. 1, June 2013.

[3] Kari A., Milinović M., Jeremić O., New stiffness variator of recoil gun systems, *Proceedings of the 9th International Armament Conference on Scientific Aspects of Armament & Safety Technology*, pp. 380-394, 25-28.09.2012, Pułtusk, Poland, 2012.

[4] Kari A., Jerković D., Milinović M., Ilić S., Launching recoil dumping improvement for MLRS by using a ring wire rope absorber, *15th International Conference on Applied Mechanics and Mechanical Engineering*, Cairo, Egypt, 2012.

[5] Tancic L.J., *Exercises Collection of Interior Ballistic* (in Serbian), Military Academy, Belgrade, 1997.

[6] Cvetkovic M., *Interior Ballistic* (in Serbian), Military Academy, Belgrade, 1996.

[7] Jerkovic D., *The Influence of Aerodynamic Coefficients on the Movement of the Axisymmetric Body*, Master thesis, FTN Novi Sad, 2009.