Firing stability of mounted small arms

Jiri Balla, Marek Havlicek, Ludek Jedlicka, Zbynek Krist, Frantisek Racek

***Abstract*—**The article[1] focuses on the motions of the automatic weapons on the tripod during a burst fire. The presented dynamic model has got eight degrees of freedom. The calculated results were verified on the real weapon. The excitation force as the input data was obtained analysing of measured data from the functional diagram in course of the functional cycle. The main components of the excitation force are discussed for their using in calculations. The experimental determination of the motions of the weapon has been obtained using of two high-speed cameras and laser displacement gauges. The procedure can be used in the process of the evaluation or assessment of the weapon system during procurement process, during military testing, etc.

***Keywords*—**Automatic weapon, Excitation force, Firing stability, High speed camera, Inertia matrix.

I. Introduction

CURRENT automatic weapons mainly machine guns, grenade launchers and small caliber cannons are characterized by very low weight, small transport dimensions and they are carried at the most with two soldiers, see [2], [8]. These weapons are mounted either on wheeled and track carriages or on the bipods or tripods. Both transmit forces from the firing weapon to the ground via their own parts. Structures have to be able to ensure stable operation in all elevation and bearing angles. Requirements on the stable function are more demanded for the carried weapons. Use of new materials and technologies enables to achieve suitable firing stability which could not be obtained before. If at the end of the WWII the ratio between a single weapon and its mounting were 0.4, nowadays this proportion is more than 2, see [3], [5], [8] and [12]. The firing stability is according to [1], [3], [14] or [19] one of the most important properties of the automatic weapon despite of its firing power.

Several definitions of the firing stability exist, see [2], [7] for example, but one of the most convenient is given in [3]. The weapon is stable when it forms the battery at the time projectile leaves muzzle of the barrel. Further the weapon must have such velocities and accelerations that ensure appropriate working conditions of a crew and equipment's. It means that the weapon can move and oscillate when firing. But the changes of the aiming angle at the time when projectile leaves the barrel reduce the hit probability mainly in case of burst firing. The aiming errors achieve according to the fire power values from several mrad (light machine guns) to tens of mrad (automatic grenade launcher).

Knowledge of automatic weapon properties and its influence on the stability are important to suitable weapon operation. The examples of the stable weapon represent the Fig. 1 and Fig. 2. The stability evaluation criterion is the angle of the weapon jump in the vertical plane of the weapon. This angle has been the main stability criterion for a long time.

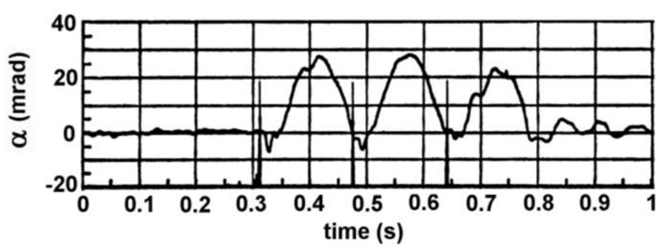

Fig. 1 Stable weapon (three shots)

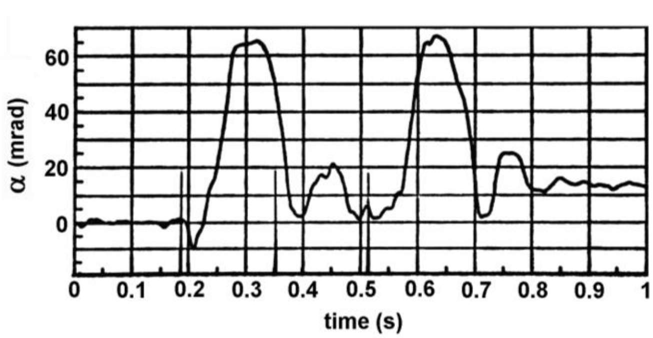

Fig. 2 Unstable weapon (three shots)

The case whilst the weapon is stable is evident: the weapon holds the same position in every shot, but the unstable weapon has in the 2nd shot deflection from the main aiming angle more than 40 mrad.

[1] Manuscript received December 3, 2010. This work was supported by the the research projects: VZ MO0FVT0000402.

J. Balla is with the University of Defence, Kounicova 65, 662 10 Brno, Czech Republic (corresponding author to provide phone: 00 420 973 44 5013; fax: 00 420 973 44 5318; e-mail: jiri.balla@ unob.cz).

M. Havlicek is with the University of Defence, Kounicova 65, 662 10 Brno, Czech Republic (corresponding author to provide phone: 00 420 973 44 5013; fax: 00 420 973 44 5318; e-mail: loshados@ centrum.cz).

L.Jedlicka is with the University of Defence, Kounicova 65, 662 10 Brno, Czech Republic (corresponding author to provide phone: 00 420 973 44 5230; fax: 00 420 973 44 5318; e-mail: ludek.jedlicka@ unob.cz).

Z. Krist is with the University of Defence, Kounicova 65, 662 10 Brno, Czech Republic (corresponding author to provide phone: 00 420 973 44 5011; fax: 00 420 973 44 5011; e-mail: zbynek.krist@ unob.cz).

F. Racek is with the University of Defence, Kounicova 65, 662 10 Brno, Czech Republic (corresponding author to provide phone: 00 420 973 44 5013; fax: 00 420 973 44 5176; e-mail: frantisek.racek@ unob.cz).

The experimental way of the determination whether weapon is stable or not includes designing the special frame where the gauges are fixed and weapon can move, as it is shown in Fig. 3. The gauges are fixed to the frame and enable to determine the linear vertical displacements of the weapon on the two places and then the skewing with respect to the rear spade. The time when the projectile leaves the barrel is determined by means of the strain gauge. The results in Fig. 1 and Fig. 2 correspond to the 30 mm grenade launcher depicted in Fig. 3. Drawbacks of this procedure follow from the somewhat unwieldy measuring assembly which was necessary to use for given purpose. The other disadvantage was the use of cable connection between the measuring gauge and the amplifier in the device causing unforeseeable changes of electrical characteristics when they have to be longer due to protection and security of the measuring team.

The computational methods were retrenched to the calculations only in the vertical plane. The horizontal plane was studied using purely with the statics methods. The dynamic models having one degree of freedom – rotation about A point – followed from the scheme which is portrayed in the Fig. 4, see [15]. Experts very often used theorem on conservation of energy and theorem on conservation of momentum.

The angular motion with respect to the A point, see α variable, was described by the ordinary differential equation (1) which does not usually include the linear displacement in x-axis. The solution was possible using simpler procedures without more exact approach that is at the present time in disposition.

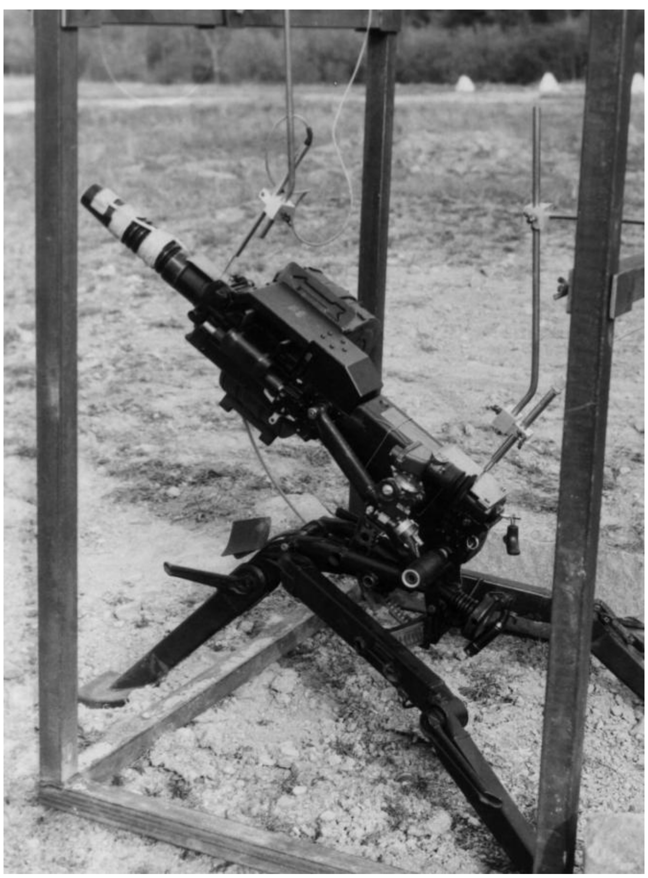

Fig. 3 Experimental way of stability investigation

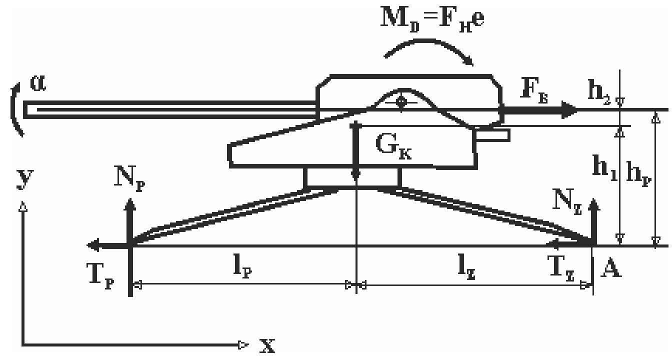

Fig. 4 Simple dynamic model

$$I_A\ddot{\alpha} = F_B h_1 + (T_Z + T_P)h_2 + N_P l_P - N_Z l_Z + F_H e\,, \qquad (1)$$

where

I_A - system mass moment of inertia with respect to the A point,

F_B - force acting onto system when operates,

T_Z - axial reaction at rear support,

T_P - axial reaction at front support,

N_P - vertical reaction at front support,

N_Z - vertical reaction at rear support,

F_H - force of shot,

h_P - command height,

h_1 - gravity center height,

h_2 - axis bore height over gravity center,

l_P - horizontal distance between front spade and gravity center,

l_Z - horizontal distance between rear spade and gravity center,

e - vertical distance between F_B and F_H forces.

The least favourable instance is when weapon fires with zero or negative elevation angle. The presented model does not include the shooter's and ground properties as their rigidities, masses etc. In the next part there will be suggested how to improve the calculation quality by taking the other proprieties when the weapon fires with different elevation and traverse angles φ and θ.

II. Problem Formulation

The new approach to the determination of the firing stability is creation of the dynamic model with more degrees of freedom and its verification using the high-speed cameras and laser gauges in the technical experiments.

The dynamic model, see Fig. 5, Fig. 6 and Fig.7, has eight degrees of freedom. Six degrees of freedom belong to the own tripod, one degree belongs to the vibration of the elevation parts and the last, eights, goes with the shooter's motion.

The input parameters have been obtained using CAD model of the weapon system, mainly the inertial characteristics and its combination with measuring of some elastic properties as the rigidity of the elevating gear is.

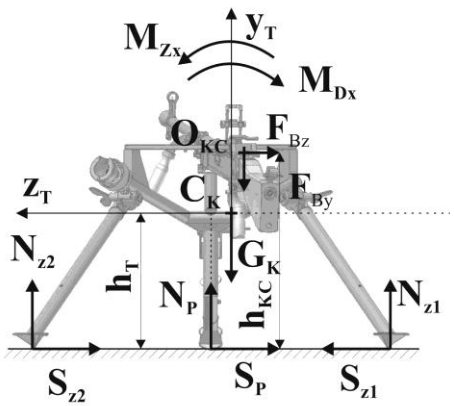

Fig. 5 Dynamic model – rear view

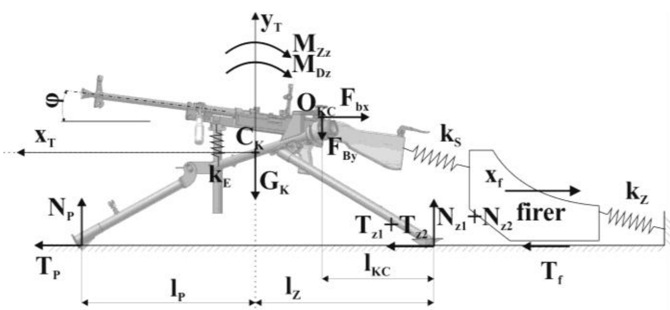

Fig. 6 Dynamic model – side view

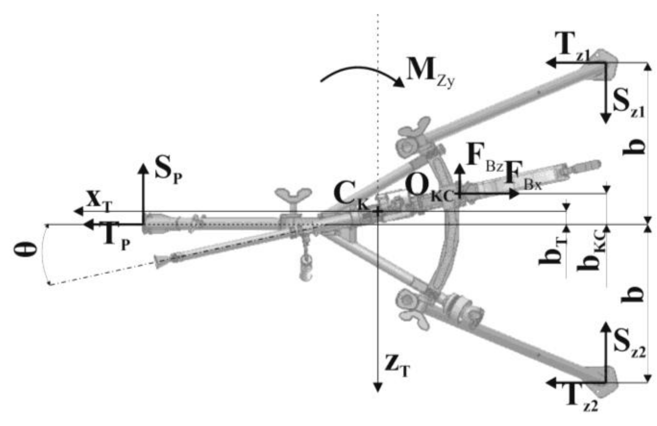

Fig. 7 Dynamic model – overhead view

The motion equations are written by means of the following formulas.

The motion equations of the whole weapon complete are:

$$ma_{Tx} = \sum F_{ix_T} , \qquad (2)$$

$$m\,a_{Ty} = \sum F_{iy_T} , \qquad (3)$$

$$m\,a_{Tz} = \sum F_{iz_T} , \qquad (4)$$

$$I_{x_T}\varepsilon_{x_T} - \omega_{y_T}\omega_{z_T}(I_{y_T}-I_{z_T}) - D_{x_Ty_T}(\varepsilon_{y_T}-\omega_{z_T}\omega_{x_T}) - D_{z_Tx_T}(\varepsilon_{z_T}+\omega_{x_T}\omega_{y_T}) - D_{y_Tz_T}(\omega_{y_T}^2-\omega_{z_T}^2) = \sum M_{x_T} , \qquad (5)$$

$$I_{y_T}\varepsilon_{y_T} - \omega_{z_T}\omega_{x_T}(I_{z_T}-I_{x_T}) - D_{y_Tz_T}(\varepsilon_{z_T}-\omega_{x_T}\omega_{y_T}) - D_{x_Ty_T}(\varepsilon_{x_T}+\omega_{y_T}\omega_{z_T}) - D_{x_Tz_T}(\omega_{z_T}^2-\omega_{x_T}^2) = \sum M_{y_T} , \qquad (6)$$

$$I_{z_T}\varepsilon_{z} - \omega_{x_T}\omega_{y_T}(I_{x_T}-I_{y_T}) - D_{z_Tx_T}(\varepsilon_{x_T}-\omega_{y_T}\omega_{z_T}) - D_{y_Tz_T}(\varepsilon_{y_T}+\omega_{z_T}\omega_{x_T}) - D_{x_Ty_T}(\omega_{x_T}^2-\omega_{y_T}^2) = \sum M_{z_T} . \qquad (7)$$

The motion of the elevation part is described by the equation, in [15] as well

$$I_E(\ddot{\alpha}_E+\varepsilon_z) + b_E\dot{\alpha}_E + k_E\alpha_E = F_B r_{EC} , \qquad (8)$$

where

I_E - mass moment of inertia with respect to the trunnion,

k_E - rigidity of the elevation gear,

b_E - damping coefficient of the elevation parts,

$\ddot{\alpha}_E$, $\dot{\alpha}_E$, α_E - angular acceleration, velocity and rotation angle of the elevation parts,

r_{EC} - F_B force arm (distance between C_Z and O_{KC}).

Finally the last equation belonging to the shooter's motion is:

$$m_S\ddot{x}_S = k_S(x_T-x_S) - k_Z x_S - T_f\,\mathrm{sgn}(\dot{x}_S) , \qquad (9)$$

where

m_S - shooter's mass,

k_S - rigidity between weapon and shooter,

k_Z - rigidity between firer and ground,

$\ddot{x}_S, x_S$ - shooter's acceleration and displacement.

Next formulas give the additional forces and moments in the main motion equations with helping the figures 5, 6, 7 and 8.

$$\sum F_{ix_T} = T_P + T_{Z1} + T_{Z2} - F_{Bx} , \qquad (10)$$

$$\sum F_{iy_T} = N_{Z1} + N_{Z2} + N_P - G_K - F_{By} , \qquad (11)$$

$$\sum F_{iz_T} = S_{Z1} - S_{Z2} - S_P - F_{Bz} , \qquad (12)$$

$$\sum M_{x_T} = F_{Bz}(h_{KC}-h_T) + F_{By}(b_{KC}-b_T) + (S_{Z1}-S_P-S_{Z2})h_T - N_{Z1}(b-b_T) + N_{Z2}(b+b_T) + N_P b_T - M_{Zx} + M_{Dx} , \qquad (13)$$

$$\sum M_{y_T} = F_{Bx}(b_{KC}-b_T) - F_{Bz}(l_Z-l_{KC}) - T_{Z1}(b-b_T) + T_{Z2}(b+b_T) + T_P b_T + (S_{Z1}-S_{Z2})l_Z + S_P l_P + M_{Zy} , \qquad (14)$$

$$\sum M_{z_T} = F_{By}(l_Z-l_{KC}) + F_{Bx}(h_{KC}-h_T) + N_P l_P - (N_{Z1}+N_{Z2})l_Z + (T_{Z1}+T_{Z2}+T_P)h_T + M_{Zz} + M_{Dz} . \qquad (15)$$

The dynamic couple $M_D = F_H e$ has the x, y, z axis components:

$$M_{Dx} = M_D\cos\theta,\ M_{Dy} = 0,\ M_{Dz} = M_D\sin\theta.$$

The spin moment developed by the rotating projectile M_Z has the x, y, z axis reaction components: $M_{Zy} = M_Z\sin\varphi$, $M_{Zx} = M_Z\cos\varphi\cos\theta$ and $M_{Zz} = M_Z\cos\varphi\sin\theta.$

The inertia matrix posing in equations (5) – (7) has the form as it is presented in [17], [21] or [22]:

$$I=\begin{pmatrix} I_{x_T} & -D_{x_Ty_T} & -D_{x_Tz_T} \\ -D_{y_Tx_T} & I_{y_T} & -D_{y_Tz_T} \\ -D_{z_Tx_T} & -D_{z_Ty_T} & I_{z_T} \end{pmatrix}. \quad (16)$$

The system of the differential equations (2) – (9) has been solved using the ode45 Matlab integration software, see [11] or [12]. The software changes the integration step according to the errors of numerical calculations and setting of the procedure before the simulation beginning. One of the drawbacks of the Matlab standardized procedures (as ode45, ode23, etc. are) is the impossibility barely to change the integration step from experience with simulations of the nonlinear systems.

III. Problem solution

The force acting in the weapon and causing the motion of all weapon parts depends on the type of operation. During burst firing they are periodic in nature. Let us explain the gas operation system case which is very often used in the military small arms. The following forces act on the mounting when the gun fires are visualized in Fig. 8, see [1], [5], [6] and [13]:

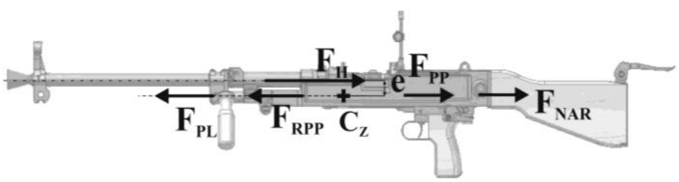

Fig. 8 Forces acting onto mounting

F_H - force of shot depending on the barrel gas pressure,
F_{PL} - force on the gas chamber,
F_{NAR} - buffer force when breech is in the rear position,
F_{PP} - return spring force,
F_{RPP} - impact force when breech is in the front position.

The main meaning regarding of the weapon force loading has the force of shot F_H whose course is shown in Fig. 9.

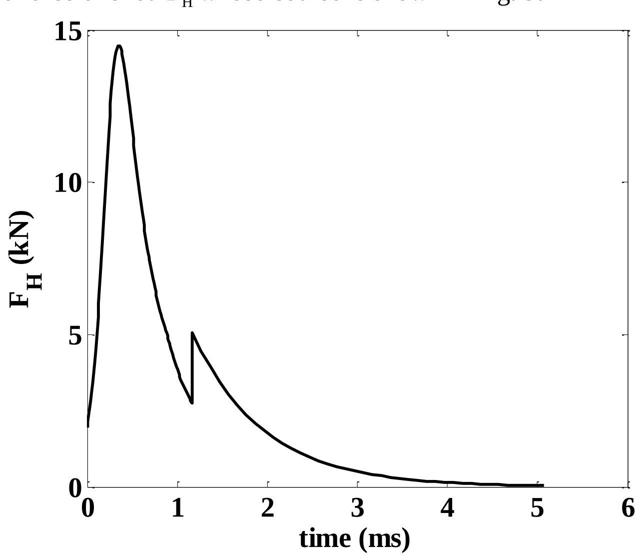

Fig. 9 Force of shot

The force of shot defined for example in [1], [3] or [9] the following formula

$$F_H = p_{dh}S - F_{fh}, \quad (17)$$

where

p_{dh} is the pressure on the head of the barrel chamber in course of the projectile movement in the barrel.

This force summarizes the forces on the head of the barrel chamber, on the conical part of the barrel chamber and resistances against the projectile motion acting in the opposite direction to the recoil.

The bore area, which depends on the caliber, is:

$S = \frac{\pi}{4}d^2$ for smooth bore and $S = \frac{\pi}{4}d^2 + nah$ for barrel with rifling, where:

d - caliber,

n - number of grooves,

a - width of groove,

h - depth of groove,

p_{dh} - pressure on the chamber head.

The relationship between forces on the projectile and on the bore area corresponding to the caliber in the chamber head is, see [3], [9] or [18]

$$F_{dq} = F_{dh}\frac{m_q}{m_q + \frac{m_\omega}{2}}, \quad (18)$$

where $F_{dq} = p_{dq}S$ is force on the projectile,

p_{dq} - pressure on the projectile head,

m_q - the projectile mass,

m_ω - the powder charge mass.

The barrel reaction on the resistances against the projectile movement are expressed with the following expression

$$F_{fh} = fF_t + F_t\tan\alpha, \quad (19)$$

where $F_t = \left(\frac{2i}{d}\right)^2 F_{dq}\tan\alpha$ is total peripheral force,

i - the radius of gyration of the projectile,

f - friction coefficient between the projectile and the internal surface of the barrel,

α - rifling angle.

The rifling torque on the tube is given as

$$M_Z = F_t\frac{d}{2}. \quad (20)$$

It has the same value and it acts in the opposite direction of the projectile rotation. The reaction on the rifling torque causes the non-uniform additional loading of the right and left trunnions and the right and left sliding surfaces of the cradle see Fig. 10, see [18].

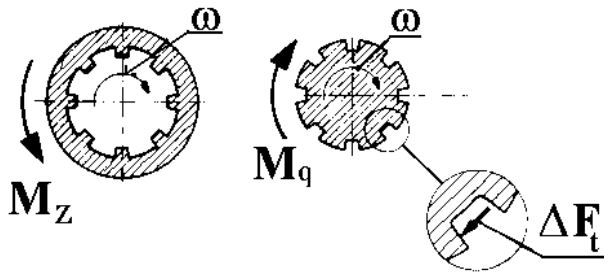

Fig. 10 Rifling torque

It is clear, see [3] as well, that the force of shot is possible to set equal to the force on the barrel chamber head with 2% accuracy. Then we can write the calculating formula as

$$F_H = 0.98 p_{dh} S. \tag{21}$$

When the projectile exits the barrel, the force of shot can be considered like rocket engine, whose the thrust is determined from the following known expression, see [15], [20] or [25],

$$F_H = \xi_R S p = \frac{dm_\omega}{dt} w + S(p_u - p_a), \tag{22}$$

where are

ξ_R - the reactivity coefficient of the barrel muzzle depending on the adiabatic coefficient κ. Its value is 1.24 for the weapon without a muzzle device,

p_u - pressure at the outlet area (muzzle) of the barrel during aftereffect time,

p_a - atmosferical pressure,

$\frac{dm_\omega}{dt}$ - gases mass flow,

w - gases exhaust velocity.

The gases mass flow is possible to determine from next equation

$$\frac{dm_\omega}{dt} = \varphi(\kappa) S \sqrt{p_h \rho}, \tag{23}$$

where $\varphi(\kappa) = \sqrt{\kappa} \left(\frac{2}{\kappa+1} \right)^{\frac{\kappa+1}{2(\kappa-1)}}$ is adiabatical coefficient function,

$\rho = \rho_u \left(\frac{p_h}{p_{hu}} \right)^{\frac{1}{\kappa}}$ - gases density in the barrel when the projectile exits the barrel.

The exhaust velocity of the gases from the barrel muzzle is

$$w = c_{PL} \sqrt{\frac{2}{\kappa-1} \left(\frac{p_a}{p_h} \right)^{\frac{\kappa-1}{\kappa}}}, \tag{24}$$

where the sound velocity in the gases is $c_{PL} = \sqrt{\kappa r T}$.

In the given formulae there are:

κ - adiabatic coefficient,

r - gas constant,

T - temperature of gases in the barrel.

After projectile leaving the muzzle the force of shot increases due to the resistances against the projectile movement do not exist and due to the outflow discharge of the gases from the barrel. This fact is expressed with ξ_R coefficient; see for example [8].

At the end of this part there is introduced the equation for the pressure in the aftereffect period:

$$p_h = \frac{p_{hu}}{1 + A t^{\frac{2\kappa}{\kappa-1}}}, \tag{25}$$

where

p_{hu} - the pressure in the barrel when the projectile exits the barrel, and

$$A = \frac{\kappa - 1}{2 m_\omega} S \, \varphi(\kappa) \sqrt{p_{hu} \rho_u}. \tag{26}$$

The easier way to obtain outlet parameters is to use of approximation methods mainly for preliminary design calculations. One example is the exponential approximation. This method uses the relation

$$p_h = p_{hu} e^{\frac{\tau}{b}}, \tag{27}$$

where

$b = \frac{\beta - 0.5}{F_{hu}} v_u m_\omega$ is the time constant,

v_u - the muzzle velocity of the projectile,

F_{hu} - the magnitude of the force of shot when the projectile exits the barrel,

$\tau = b \ln \frac{p_{hu}}{p_a}$ - is the flow time.

The results of computations are presented in Fig. 11 where are step by step displayed the pressure in the barrel, the gases mass flow and after the integration the total mass of gases corresponding to the powder charge mass. The time begins from the instant when the projectile starts to move. The exhaust of gases begins at the time 1.1 ms.

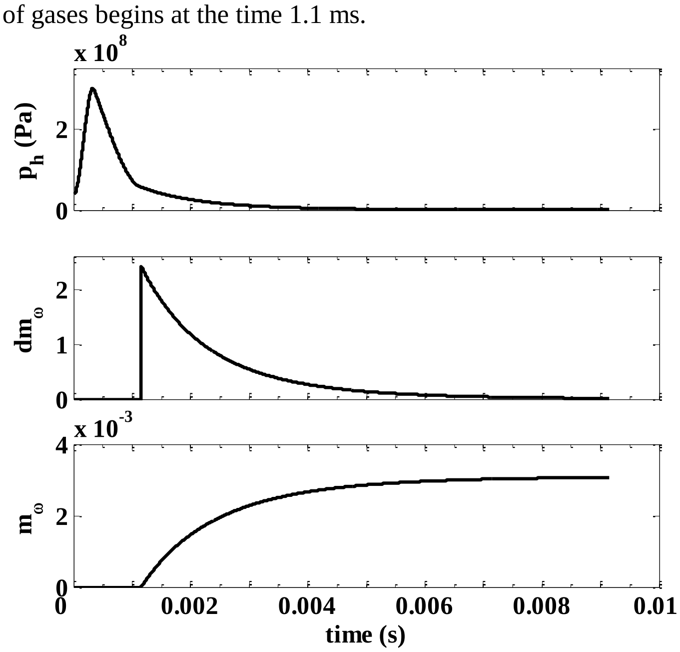

Fig. 11 Outlet parameters of 7.62 mm weapon

The second main force acting on to mounts is the F_{PL} gas force chamber which is represented in Fig. 12.

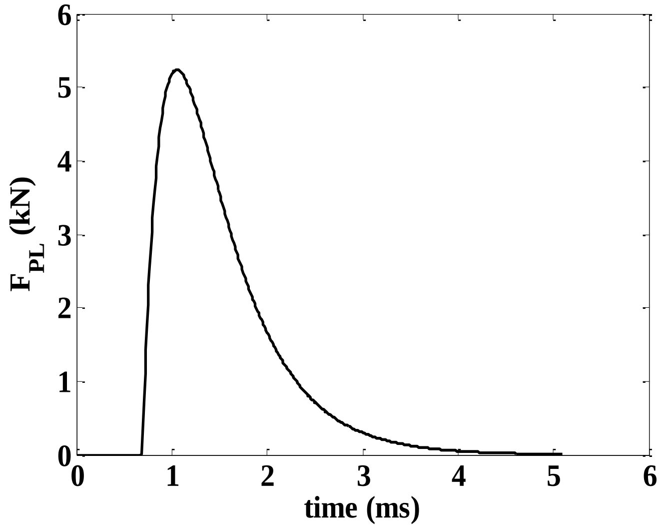

Fig. 12 Force on the gas chamber

The sum of these forces transmitted from the weapon to the mount is known as F_B weapon force action or exciting force on the mount and can be written:

$$F_B = F_H - F_{PL} + F_{NAR} + F_{PP} - F_{RPP}\,. \tag{28}$$

Independently of the caliber the F_B force course of the gas operation system is same and is unlike only in the magnitude force F_B. The forces during one shot of the 7.62 mm machine gun investigating system have the course shown in Fig.13.

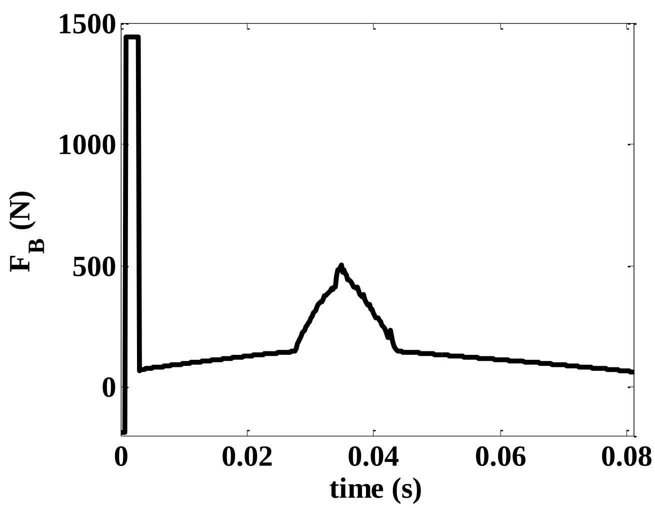

Fig. 13 Exciting force

Eight shots impulse force diagram following from Fig 13 as repeating sequence of shots has been used for on-going calculations. The entire impulse obtained by the weapon is depicted in Fig. 14. The drop at the end of every shot is caused by the impact of the breech system when it is coming to the front position. The impact velocity depends on the weapon caliber and in our case it is approximately 4 m/s. Before the first shot this velocity is lower achieving 2 m/s.

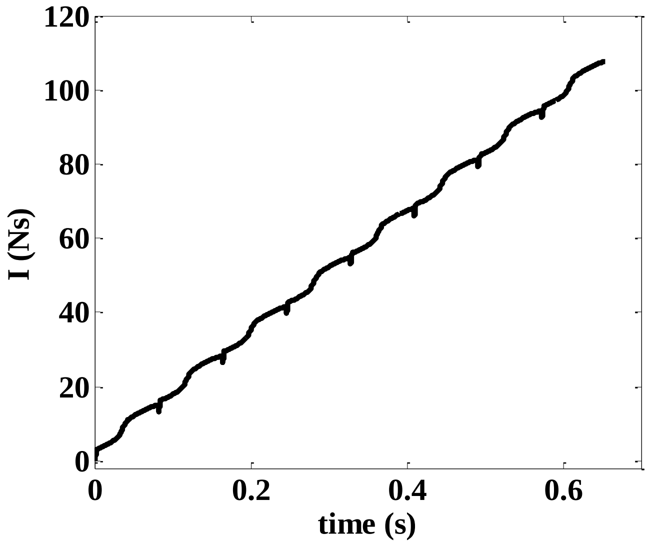

Fig. 14 Eight shot exciting force impulse

The force diagram for the weapon of known construction can be determined from the firing force acting on the barrel and by using the functional diagram of the weapon or the force and acceleration diagram. It can also be found experimentally. The detailed construction of a force diagram is described in references [1] or [8]. These forces are periodically repeated during required number of shots.

The M_Z course acts on the weapon in very short time when the projectile moves in the barrel as the Fig. 15. The main influence is on the rotation of the weapon about x_T axis because discussed small caliber weapons usually fire at low elevation angles φ and bearing θ. The torque M_Z causes the additional loading of the trunnion and guiding on the cradle.

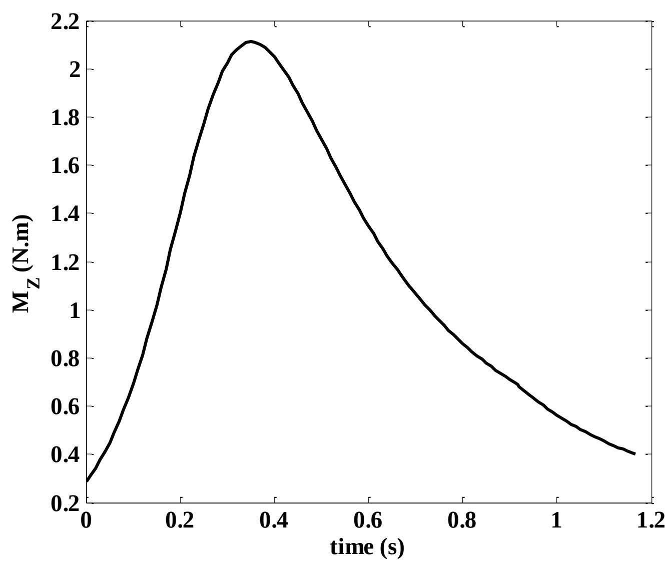

Fig. 15 Torque engraving/time history

The results of calculation are presented onward. The numerical values of the input parameters belonging to the system were obtained from technical specifications and drawings redrawn into the CAD form. The gravity centers and the inertia matrix have been determined directly from CAD software and several of them by measuring. Due to the very large numbers of inputs only the most important are mentioned hereto, see Table I, Table II and Table III.

TABLE I
WEAPON PARAMETERS

Symbol	Quantity	Value
m	weapon mass	21.5 kg

TABLE II
SHOOTER'S PARAMETERS

Symbol	Quantity	Value
m_S	shooter mass	90 kg
k_S	rigidity between weapon and shooter	70 000 N/m
k_Z	rigidity between ground and shooter	4 000 N/m

TABLE III
ELEVATION PART PARAMETERS

Symbol	Quantity	Value
I_E	elevating parts mass moment of inertia	0.897 kg.m^2
k_E	stiffness of elevating gear	23 100 N.m/rad^{-1}
b_E	dumping coefficient of angular motion	40 N.m.s/rad
r_{EC}	distance of the trunnion to the excitation force axis	0.0465 m

The inertia mass matrix values given in (5), (6), (7), and (16) are

$$I = \begin{pmatrix} 0,609 & 0,065 & -0,027 \\ 0,065 & 1,330 & 0,012 \\ -0,027 & 0,012 & 1,377 \end{pmatrix}.$$

It is clear that the discussing system can be considered as symmetrical due to small no diagonal elements with respect to the main values lying on the diagonal. The simulation results are presented farther.

The first of them, see Fig. 16, describes the vibration of the elevating parts rotating about trunnion axis. The calculations have confirmed the hypothesis that without taking the elastic coupling of the elevation gear into the consideration is not possible to get results comparable with the technical experiments.

The motion in horizontal plane (rotation about y_T axis) with shifting of the weapon on one side has been explained an action of the shooter who has pressed the weapon on one side and this phenomena has been affirmed by measuring, Fig. 17.

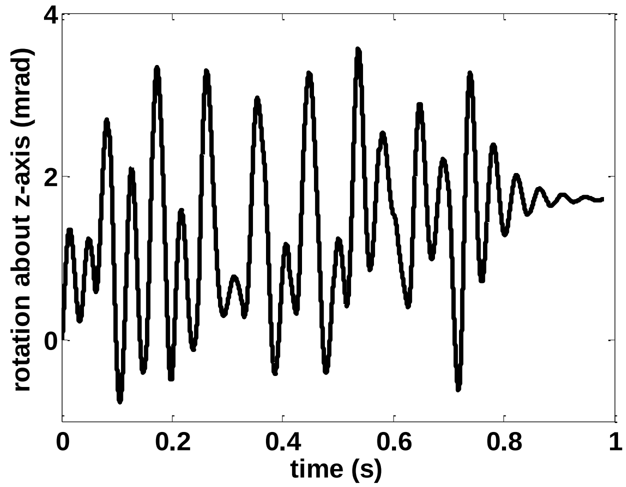

Fig. 16 Vibration of elevation parts

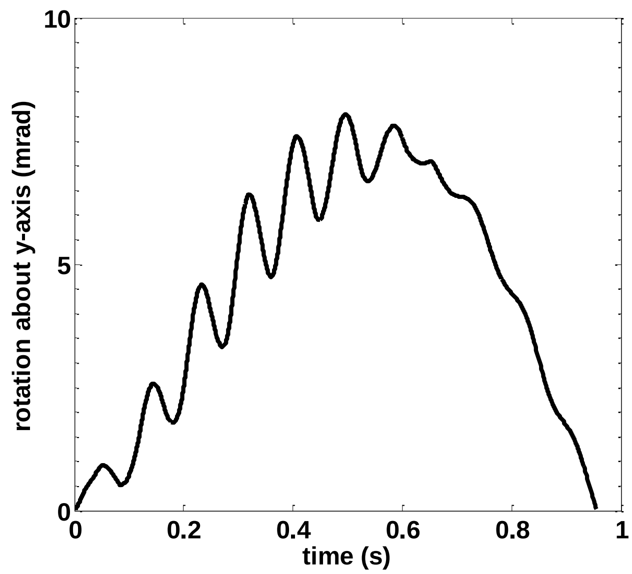

Fig. 17 Rotary motion in the horizontal plane

The results of the linear displacement (in x_T axis), see Fig. 18, is affected by the shooter action as well as it was mentioned in course of the previous figure explanation.

The both performance charts are similar.

The shooter behaves as a low frequency filter with respect to the weapon and transmits the frequency component parts until the cut frequency which is approximately 1 Hz. It is same as vibrations of the elevating parts or other parts when they are mounted on the tank chassis and burst firing.

It was the goal of the experiment to verify the behaviour of the appropriate weapon (7.62 mm UK-59 L on the tripod) with the mathematical model results. The following indicators were chosen as a criterion of dynamic firing stability:

- rotation of the weapon around z axis,
- rotation of the weapon around y axis, and
- horizontal displacement of the weapon along the x axis.

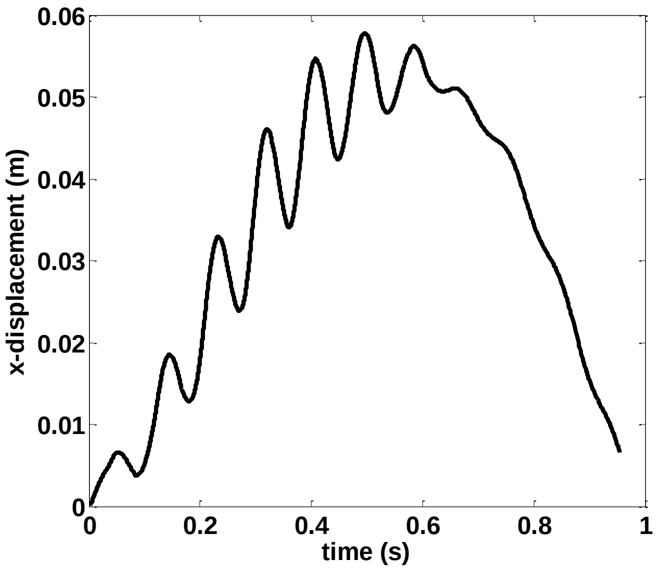

Fig. 18 Weapon linear displacement

The experiment had consisted of three independent but simultaneous experimental measurements. The fundamental method was the utilization of two synchronized high-speed cameras, the output of which allows us to encompass the spatial analyses of parameters of weapon dynamic firing stability. This main method was supplied by two another measurement methods to support the results of main high speed cameras method. Both of them were optical contactless methods. One of them was utilization of active laser measurement gauges for detection of weapon absolute movement in the vertical plane. The second one was recording of video-signal of the real target hits during the experiment by standard video-camera. All the chosen methods were optical contactless methods that cannot affect the weapon during the experimental firing.

As mentioned, the main method was utilization of the two high speed cameras; see the experimental configuration in Fig. 19 and Fig. 20, positions 3 and 4. The cameras system, consists of the two cameras: 3 – Olympus I-speed located upward the weapon in the 1.7 m height scanning the motion in the horizontal plane, and 4 - Redlake MotionXtra® HG-100K placing on the stand in the 4 m distance scanning the motion in the vertical plane. The special triggering device PTU (http://www.prototypa.cz/index.html) was used for camera record synchronization. This device sent the trigger signal to the cameras as a reaction on the initial voice event – the weapon first shot. Due to easier data processing the cameras were set to record with the same frequency. With the reference to assumed weapon movement velocity, weapon dimension and required image quality the recording frequency was chosen as 5000 frames per second. The said recording frequency allowed us to reach the image quality 704 x 432 pixels for Redlake MotionXtra® HG-100K and 320 x 240 pixels for Olympus I-speed. The chosen recording frequency defined the maximal exposition time of both cameras that reached the value less than 0.2 msec. That extremely short exposition time required usage of additional lighting systems. The three lamps of resulting wattage 2000 W were used as lighting systems for weapon illumination during the experimental firing.

The video-sequences as the output of both cameras were additionally post processed to get the spatial analyses of parameters of weapon dynamic firing stability. For determination of weapon parts movement, the contrast circle marks were situated on the specified parts of the weapon. The same marks were situated on the floor under the weapon or on the wall behind the weapon to verify the camera stability during the experimental firing. Post processing of the high speed camera video-sequences consists in valuation of the gravity center of the said contrast circle marks. In any image of the video-sequence the circle marks were found, see an example in Fig. 21. The original image A was that divided into separate sub-images B and C consisting of the said contrast circles. The centers of gravity, e.g. (XT1, YT1), has been computed for any of the circle marks using the following formulas, see [10] and [23]:

$$x_{\mathrm{T}} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{C}} e_{\mathrm{i}} x_{\mathrm{i}}}{\sum_{\mathrm{i}=1}^{\mathrm{C}} e_{\mathrm{i}}} \quad , \qquad y_{\mathrm{T}} = \frac{\sum_{\mathrm{j}=1}^{\mathrm{L}} e_{\mathrm{j}} y_{\mathrm{j}}}{\sum_{\mathrm{j}=1}^{\mathrm{L}} e_{\mathrm{j}}} \ . \qquad (29)$$

Where x_{i} is the sub-image pixel coordinate in x axis, y_{i} is the sub-image pixel coordinate in y axis, C is a number of columns in the sub-image, L is a number of lines in the sub-image and e_{i}, e_{j} are the intensity in sub-image pixel of the coordinates i, j. After the circle mark center of gravity coordinates evaluation in the sub-image, the re-computation of that in the original image was provided. The resulting circle marks center of gravity coordinates are still expressed in pixels. To get the coordinates expressed in meters the scale in the image has to be known. The scale can be evaluated from the known distance between two circle marks:

$$sc = \frac{1}{n} \sum_{\mathrm{i}=1}^{n} \frac{d_{\mathrm{i}}}{b_{\mathrm{i}}} , \qquad (30)$$

Where d_{i} is real distance of the cyclic marks (m), b_{i} is the distance of the cyclic marks in the image (px), and n is the number of used cyclic marks pairs for scale evaluation. The evaluation of the time line from frame number in the video-sequence is defined as:

$$t = kT , \qquad (31)$$

where t is a time (s), k is a frame number [-], T is a period of high speed camera image scanning (s). It is valid for the period of high speed camera image scanning that:

$$T = \frac{1}{f_{\mathrm{ps}}} , \qquad (32)$$

where f_{ps} is a high speed camera image scanning frequency (s^{-1}). The movement (displacement) of some circle mark is presented in the Fig. 22. The presented there signal was determined after the original signal filtering. The numerical 3rd order Butterworth low-pass filter with cut-off frequency 100Hz was used for signal filtering.

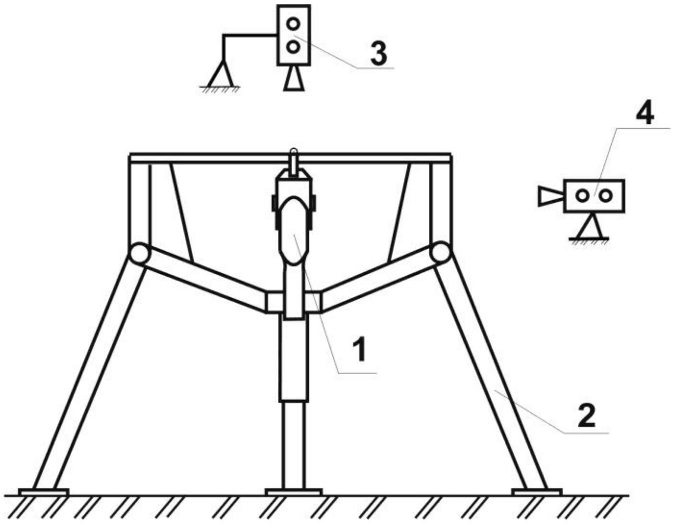

Fig. 19 Weapon and cameras – rear view

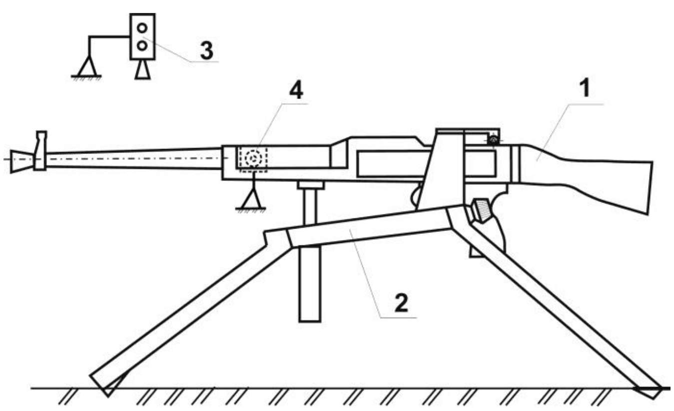

Fig. 20 Weapon and cameras – side view

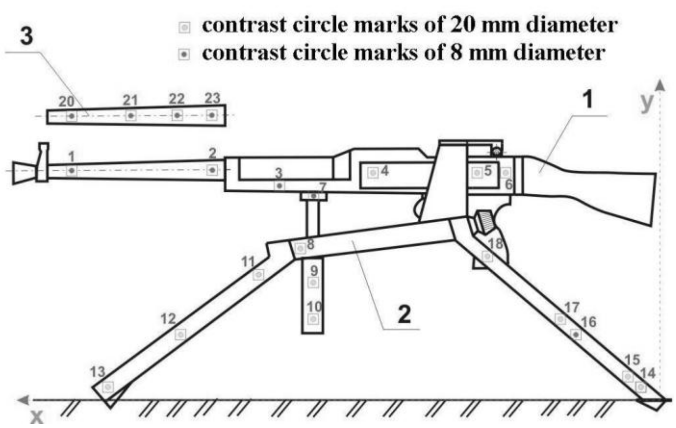

Fig. 21 Weapon and cameras – side view

The laser gauges, Fig. 23 positions 4 and 5, have been used for comparison of the result from high speed cameras measurement as the second measurement method. The first gauge (NCLDF 120/025) 4 was situated under the barrel muzzle. The second one (infraweg 300/60) was situated above the rear part of the weapon. The signals have been stored in computer 7 via measuring system DEWE. The sampling rate was 100 000 Hz. The signal processing of the signals from laser gauges consists in transformation of analogue voltage signal into the numerical signal expressed in metrical displacement. The rotational around the y axis was additionally computed from the said numerical signals.

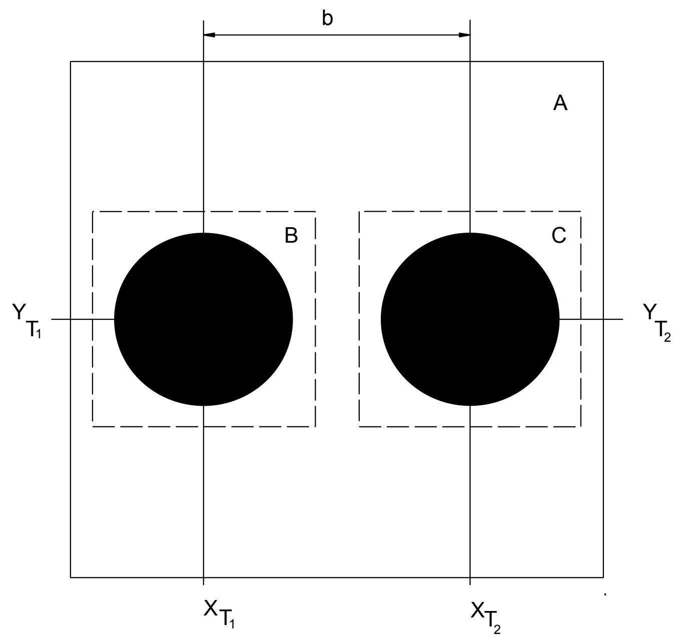

Fig. 22 Weapon and cameras – side view

Finally, the evaluation of the target hits coordinates was done. The order and hit coordinates were determined from the record of video-sequence of the Panasonic NV-MX300EG camera situated near the target. The hit coordinates were compared with the found absolute movement parameters obtained from the previous both measurement methods.

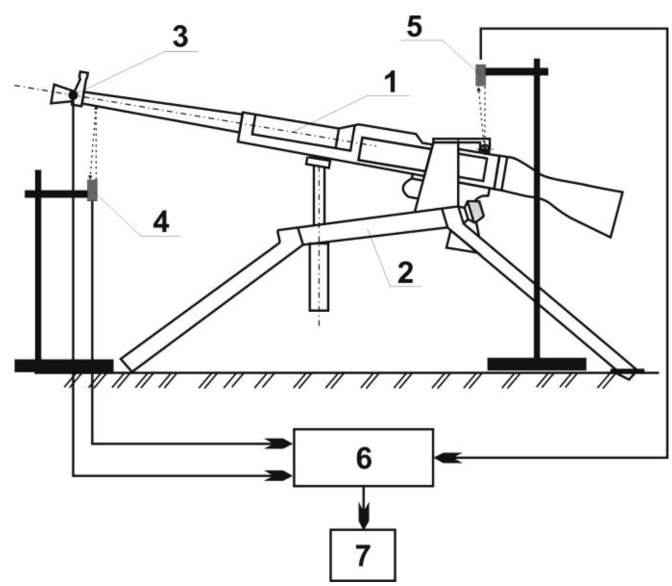

Fig. 23 Weapon and laser gauges

IV. Conclusion

The results given in the figures reflect a good coincidence with the real piece which was explored according to presented theory. The theory was verified on the 7.62 mm machine gun.

The procedure used in this article has been applied in the Czech research institutes and in the University of Defence in Brno as additional teaching material for students of weapons and ammunition branch.

In future it is supposed to study the influence of the change of shooter’s stiffness (e.g. linking between shooter and the weapon will be elastic and viscose damping with more than one degree of freedom) and the influence of the mass change throughout the firing together.

In addition to the theory will be applied in automatic grenade launchers and in OCSW (Objective Crew Served Weapon) using larger calibers up to 35 mm.

References

[1] Allsop, D. F., Balla, J., Cech, V., Popelinsky, L., Prochazka, S., Rosicky, J. Brassey´s Essential Guide to MILITARY SMALL ARMS. London, Washington. Brassey´s, 1997.

[2] Balla, J., Havlicek, M., Jedlicka, L., Krist, Z., Racek, F. Dynamics of automatic weapon mounted on the tripod. The 12th WSEAS International Conference on Mathematical and Computational Methods in Science and Engineering (MACMESE '10). Algarve (Portugal), November 2010.

[3] Cech, V. Recoil systems I. Textbook. Military academy in Brno. (Czech Republic], 1991.

[4] Celens, E., Plovie, G. Recoil of small arms. Royal Military Academy, Department of Armament and Ballistics. Brussels (Belgium).

[5] Chinn, G. The Machine Gun. Volume V. Edwards Brothers Publishing Co., Ann Arbor Michigan, 1987.

[6] Dyckmans, D. E-book in Ballistics. Theory and software [Online]. Royal Military Academy Brussels, Department of Weapon Systems & Ballistics. (Belgium). Available: http://e-ballistics.com

[7] Engineering Design Handbook. Guns Series. Automatic Weapons. Headquarters, U.S. Army Materiel Command, February, 1970.

[8] Fiser, M., Popelinsky, L. Small Arms. Textbook. Brno: University of Defence, 2007.

[9] Hayes, J., T. Elements of Ordnance. A Textbook For Use Of Cadets Of The United States Military Academy. New York. John Wiley & Sons, Inc. London: Chapman & Hall, Limited.

[10] Jedlicka, L., Beer, S., Videnka, M. Modelling of pressure gradient in the space behind the projectile. In Proceedings of the 7th WSEAS International Conference on System Science and Simulation in Engineering, Venice (Italy), November 21 – 23, 2008.

[11] Macko, M., Racek, F., Balaz, T. A determination of the significant points on sporting shooter body for comparison of the computing and measuring shooter movement. In Proceedings of The WSEAS Applied Computing Conference. Vouliagmeni Beach, Athens (Greece), September 28-30, 2009.

[12] Vibration and Shock Handbook. Edited by Clarence W. de Silva. CRC Press. Taylor & Francis Group. ISBN 0-8493-1580-8.

[13] Ogorkiewitz, R. Technology of Tanks I, II. London: UK Biddles Limited Guilford and King´s Lynn, 1991.

[14] Vitek, R. Influence of the small arm barrel bore length on the angle of jump dispersion. In The Proceedings of the 7th WSEAS International Conference on System Science and Simulation in Engineering, Venice (Italy), November 21 – 23, 2008.

[15] Peter, H. Mechanical Engineering. PRINCIPLES OF ARMAMENT DESIGN. Trafford Publishing. Suite 6E. 2333 Government St., Victoria. B.C. V8T 4P4, CANADA.

[16] Textbook of Ballistics and Gunnery. Volume One. Part I - Basic theory. Part II - Applications and Design. London. Her Majesty’s Stationnary office, 1987.

[17] Racek, F., Balaz, T., Macko, M, Cervenka, M. Measuring and modelling of initiation mechanisms of small arms. Proceedings of the 9th WSEAS International Conference on Applied Computer science (ACS´09). Genova Italy, October 17-18, 2009.

[18] Julis, K., Brepta, R. Mechanics II. Dynamics. SNTL, Prague (Czechoslovakia), 1987.

[19] Handbook on Weaponry. Rheinmetall GmbH, Düsseldorf. Second English Edition, 1982.

[20] Textbook of Ballistics and Gunnery. Volume One. Part I - Basic theory. Part II - Applications and Design. London. Her Majesty’s Stationary Office, 1987, 797 pages.

[21] Peter, H. Armament engineering. A computer aided approach. Trafford Publishing. Victoria, Canada.

[22] Stejskal, V., Okrouhlik, M. Vibrations with Matlab. Prague, CVUT (Czech Republic), 2002.

[23] Vitek, R. Measurement of the stereoscopic rangefinder beam angular velocity using the digital image processing method. The 12th WSEAS International Conference on Mathematical and Computational Methods in Science and Engineering (MACMESE '10). Algarve (Portugal), November 2010.

[24] Jedlicka, L. Requirements on the accuracy of determination of target position and movement parameters. The 12th WSEAS International Conference on Mathematical and Computational Methods in Science and Engineering (MACMESE '10). Algarve (Portugal), November 2010.

[25] Balla, J. Combat vehicle vibrations during fire in burst. The Proceedings of The NAUN/IEEEAM Conferences Mathematical Models For Engineering Science (MMES '10). Puerto de la Cruz, Tenerife (Spain), December 2010.

Jiri Balla born in Poprad (Czechoslovakia), 6th June 1954. MSc degree in mechanical engineering at Military academy in Brno 1978. Ph.D. degree in field weapons and protection against them at Military academy in Brno 1986. Assoc Prof of Military academy in Brno 1998 in field military technology, weapons and ammunition. Professor of Defence University in Brno 2006 in same field as Assoc Prof. Currently the author’s major field of study is dynamics of weapon barrel systems . He worked in military units as ordnance officer. After PhD studies he was a teacher as lecturer and associate professor. He was visiting fellow at Royal Military and Science (RMCS) in Shrivenham (UK) 1996, 1997, 1998. Currently he is a professor at University of Defence in Brno at Weapons and ammunition department.

The main book:

1. Allsop, D. F., Balla, J., Cech, V., Popelinsky, L., Prochazka, S., Rosicky, J. Brassey´s Essential Guide to MILITARY SMALL ARMS. London, Washington. Brassey´s, 1997.

Prof. Balla is member of Czech Association of Mechanical Engineers (CzAME).

Marek Havlicek born in Jihlava (Czech Republic), 29th September 1975. MSc degree in weapons and munition at Military academy in Brno 2001, PhD degree in the field of weapons and munition at University of Defence 2010. Currently he works as a fireworker of department of forensic sciences of czech military police. His main areas of interest are ballistics, gunnery, munition and IED.

Ludek Jedlicka born in Vyskov (Czech Republic), 19th August 1974. MSc degree in weapons and munition at Military academy in Brno 1997, PhD degree in the field of weapons and munition at University of Defence 2007. Currently he works as a lecturer at University of Defence in Brno at Department of Weapons and ammunition. His main areas of interest are ballistics, gunnery, and munition.

Zbynek Krist born in Kyjov (Czech Republic), 6th December 1974. MSc degree in weapons and munition at Military academy in Brno 2000, PhD degree in the field of weapons and munition at University of Defence 2008. Currently he works as a lecturer at University of Defence in Brno at Department of Weapons and ammunition. His main areas of interest are small arms, weapons mounting and gunnery.

František Racek born in Litomysl (Czech Republic), 20th May 1971. MSc degree in opto-electronical engineering at Military Academy in Brno 1994. Ph.D. Degree in field weapon and ammunition at University of Defence, Brno 2006. Lecturer in Military academy in Brno from 1998 in field of military technology, optical devices, fire control systems. Lecturer in University of Defence Brno from 2006 in same field. He worked as a senior officer at

military units. Currently, the author's major field of study is contactless measurement of weapon.

The main books:

1. Baláž, T., Racek, F., *et al*. The Sights II. Textbook, University of Defence, Brno, 2009.
2. Fischer, P., Racek. F., *et al*. Optical devices I. University of Defence, Brno, 2009.
3. Fischer, P., Racek. F., *et al*. Optical devices II. University of Defence, Brno, 2009.