Dynamics of automatic weapon mounted on the tripod

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Abstract: - The paper deals with the analysis of the automatic weapon firing stability mounted on the tripod. The dynamic model has eight degrees of freedom. Three degrees of freedom represent translation motion of the weapon and three degrees of freedom belong to the rotational motion with the gravity centre. The last motions are shooter displacement and the vibration of the elevation parts. The experimental assessment has been made on the principle of the synchronized record with two high-speed cameras and laser displacement gauges. The method is able to evaluate the possible changes of the elevation angles, firing height, weapon operation principle.

Key-Words: - Tripod, Firing stability, High speed camera, Motion equation, Automatic weapon

1 Introduction

Current automatic weapons mainly machine guns, grenade launchers and small caliber cannons are characterised by very low weight, small transport dimensions and they are carried at the most with two soldiers, see [2], [15]. 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], [4], and [5]. The firing stability is according to [4] one of the most important properties of every automatic weapon independently of its firing power. Several definitions of the firing stability exist, see [8] for example, but one of the most convenient is given in [1]. 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 equipments. 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.

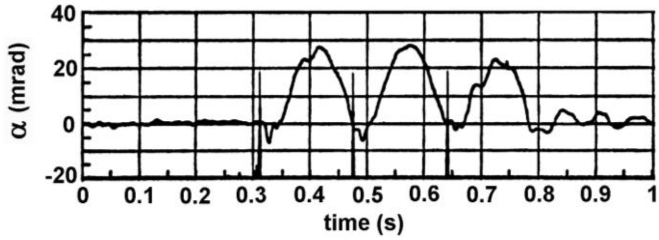

Fig.1 Stable weapon (three shots)

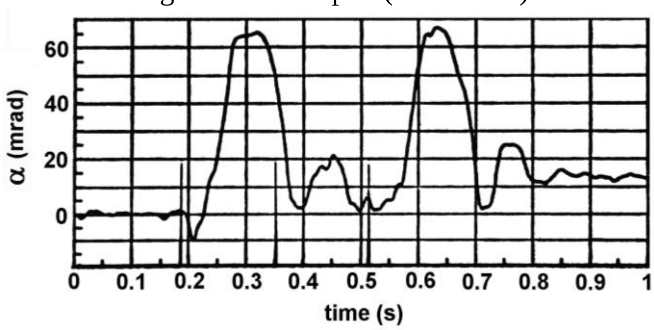

Fig. 2 Unstable weapon (three shots)

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 2[nd] shot deflection from the main aiming angle more than 40mrad.

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.

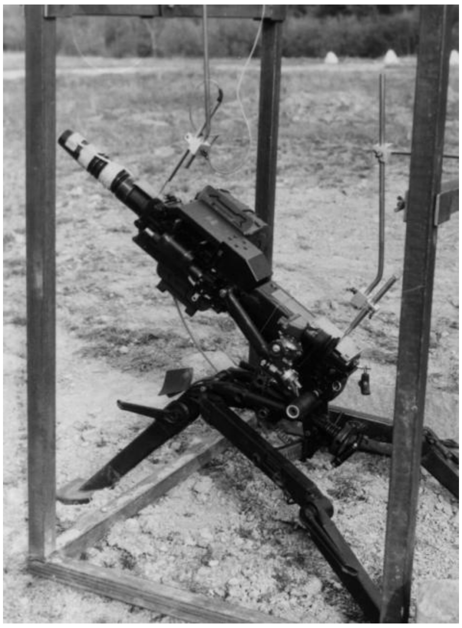

Fig. 3 Experimental way of stability investigation

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 dynamics models having one degree of freedom – rotation about A point – follow from the scheme which is portrayed in the Fig. 4, see [15].

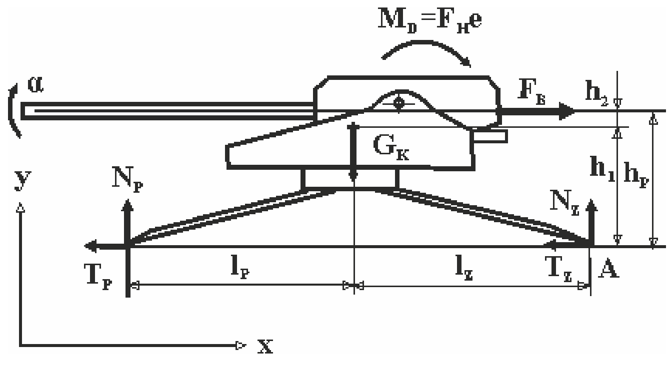

Fig.4 Simple dynamic model

The angular motion with respect to the A point, see α variable, is described by the equation (1) which does not usually include the linear displacement in x-axis.

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

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. 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.

2 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.

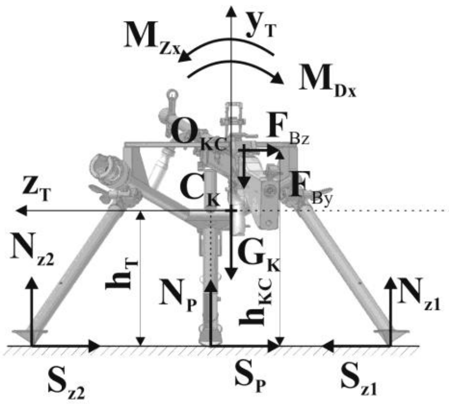

Fig.5 Dynamic model – rear view

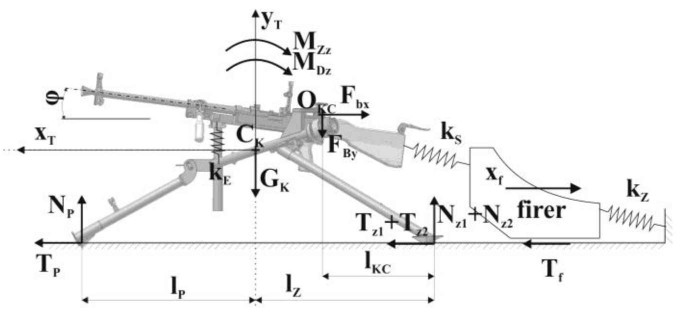

Fig.6 Dynamic model – side view

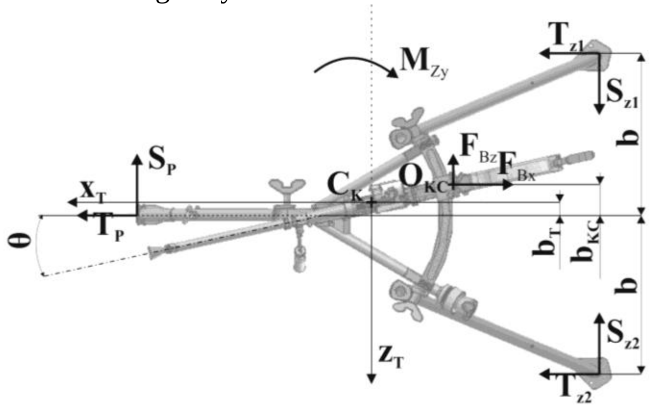

Fig.7 Dynamic model – overhead view

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

The motion equations of the whole weapon complete are:

$$ma_{\mathrm{Tx}} = \sum F_{\mathrm{ix_T}}, \tag{2}$$

$$m\,a_{\mathrm{Ty}} = \sum F_{\mathrm{iy_T}}, \tag{3}$$

$$m\,a_{\mathrm{Tz}} = \sum F_{\mathrm{iz_T}}, \tag{4}$$

$$\begin{aligned} &I_{\mathrm{x_T}}\varepsilon_{\mathrm{x_T}} - \omega_{\mathrm{y_T}}\omega_{\mathrm{z_T}}\left(I_{\mathrm{y_T}} - I_{\mathrm{z_T}}\right) - D_{\mathrm{x_Ty_T}}\left(\varepsilon_{\mathrm{y_T}} - \omega_{\mathrm{z_T}}\omega_{\mathrm{x_T}}\right) - \\ &-D_{\mathrm{z_Tx_T}}\left(\varepsilon_{\mathrm{z_T}} + \omega_{\mathrm{x_T}}\omega_{\mathrm{y_T}}\right) - D_{\mathrm{y_Tz_T}}\left(\omega_{\mathrm{y_T}}^2 - \omega_{\mathrm{z_T}}^2\right) = \sum M_{\mathrm{x_T}} \end{aligned}, \tag{5}$$

$$\begin{aligned} &I_{\mathrm{y_T}}\varepsilon_{\mathrm{y_T}} - \omega_{\mathrm{z_T}}\omega_{\mathrm{x_T}}\left(I_{\mathrm{z_T}} - I_{\mathrm{x_T}}\right) - D_{\mathrm{y_Tz_T}}\left(\varepsilon_{\mathrm{z_T}} - \omega_{\mathrm{x_T}}\omega_{\mathrm{y_T}}\right) - \\ &D_{\mathrm{x_Ty_T}}\left(\varepsilon_{\mathrm{x_T}} + \omega_{\mathrm{y_T}}\omega_{\mathrm{z_T}}\right) - D_{\mathrm{x_Tz_T}}\left(\omega_{\mathrm{z_T}}^2 - \omega_{\mathrm{x_T}}^2\right) = \sum M_{\mathrm{y_T}} \end{aligned}, \tag{6}$$

$$\begin{aligned} &I_{\mathrm{z_T}}\varepsilon_{\mathrm{z}} - \omega_{\mathrm{x_T}}\omega_{\mathrm{y_T}}\left(I_{\mathrm{x_T}} - I_{\mathrm{y_T}}\right) - D_{\mathrm{z_Tx_T}}\left(\varepsilon_{\mathrm{x_T}} - \omega_{\mathrm{y_T}}\omega_{\mathrm{z_T}}\right) - \\ &D_{\mathrm{y_Tz_T}}\left(\varepsilon_{\mathrm{y_T}} + \omega_{\mathrm{z_T}}\omega_{\mathrm{x_T}}\right) - D_{\mathrm{x_Ty_T}}\left(\omega_{\mathrm{x_T}}^2 - \omega_{\mathrm{y_T}}^2\right) = \sum M_{\mathrm{z_T}} \end{aligned}. \tag{7}$$

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

$$I_{\mathrm{E}}\left(\ddot{\alpha}_{\mathrm{E}} + \varepsilon_{\mathrm{z}}\right) + b_{\mathrm{E}}\,\dot{\alpha}_{\mathrm{E}} + k_{\mathrm{E}}\,\alpha_{\mathrm{E}} = F_{\mathrm{B}}\,r_{\mathrm{EC}}, \tag{8}$$

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,

$\ddot{\alpha}_{\mathrm{E}}$, $\dot{\alpha}_{\mathrm{E}}$, 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:

$$m_{\mathrm{S}}\ddot{x}_{\mathrm{S}} = k_{\mathrm{S}}\left(x_{\mathrm{T}} - x_{\mathrm{S}}\right) - k_{\mathrm{Z}}x_{\mathrm{S}} - T_{\mathrm{f}}\,\mathrm{sgn}(\dot{x}_{\mathrm{S}}), \tag{9}$$

where

m_{S} - shooter's mass,

k_{S} - rigidity between weapon and shooter,

k_{Z} - rigidity between firer and ground,

$\ddot{x}_{\mathrm{S}}, x_{\mathrm{S}}$ - 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.

$$\sum F_{\mathrm{ix_T}} = T_{\mathrm{P}} + T_{\mathrm{Z1}} + T_{\mathrm{Z2}} - F_{\mathrm{Bx}} \tag{10}$$

$$\sum F_{\mathrm{iy_T}} = N_{\mathrm{Z1}} + N_{\mathrm{Z2}} + N_{\mathrm{P}} - G_{\mathrm{K}} - F_{\mathrm{By}}, \tag{11}$$

$$\sum F_{\mathrm{iz_T}} = S_{\mathrm{Z1}} - S_{\mathrm{Z2}} - S_{\mathrm{P}} - F_{\mathrm{Bz}}, \tag{12}$$

$$\begin{aligned} &\sum M_{\mathrm{x_T}} = F_{\mathrm{Bz}}\left(h_{\mathrm{KC}} - h_{\mathrm{T}}\right) + F_{\mathrm{By}}\left(b_{\mathrm{KC}} - b_{\mathrm{T}}\right) + \\ &\left(S_{\mathrm{Z1}} - S_{\mathrm{P}} - S_{\mathrm{Z2}}\right)h_{\mathrm{T}} - N_{\mathrm{Z1}}\left(b - b_{\mathrm{T}}\right) + \\ &N_{\mathrm{Z2}}\left(b + b_{\mathrm{T}}\right) + N_{\mathrm{P}}\,b_{\mathrm{T}} - M_{\mathrm{Zx}} + M_{\mathrm{Dx}} \end{aligned}, \tag{13}$$

$$\begin{aligned} &\sum M_{\mathrm{y_T}} = F_{\mathrm{Bx}}\left(b_{\mathrm{KC}} - b_{\mathrm{T}}\right) - F_{\mathrm{Bz}}\left(l_{\mathrm{Z}} - l_{\mathrm{KC}}\right) - \\ &T_{\mathrm{Z1}}\left(b - b_{\mathrm{T}}\right) + T_{\mathrm{Z2}}\left(b + b_{\mathrm{T}}\right) + T_{\mathrm{P}}\,b_{\mathrm{T}} + \\ &\left(S_{\mathrm{Z1}} - S_{\mathrm{Z2}}\right)l_{\mathrm{Z}} + S_{\mathrm{P}}\,l_{\mathrm{P}} + M_{\mathrm{Zy}} \end{aligned}, \tag{14}$$

$$\begin{aligned} &\sum M_{\mathrm{z_T}} = F_{\mathrm{By}}\left(l_{\mathrm{Z}} - l_{\mathrm{KC}}\right) + F_{\mathrm{Bx}}\left(h_{\mathrm{KC}} - h_{\mathrm{T}}\right) + \\ &N_{\mathrm{P}}\,l_{\mathrm{P}} - \left(N_{\mathrm{Z1}} + N_{\mathrm{Z2}}\right)l_{\mathrm{Z}} + \\ &\left(T_{\mathrm{Z1}} + T_{\mathrm{Z2}} + T_{\mathrm{P}}\right)h_{\mathrm{T}} + M_{\mathrm{Zz}} + M_{\mathrm{Dz}} \end{aligned}. \tag{15}$$

M_{Dx}, M_{Dy}, M_{Dz} – x, y, z axis components of the dynamic couple: $M_{\mathrm{Dx}} = M_{\mathrm{D}}\cos\theta$, $M_{\mathrm{Dy}} = 0$, $M_{\mathrm{Dz}} = M_{\mathrm{D}}\sin\theta$,

M_{Zx}, M_{Zy}, M_{Zz} – x, y, z axis reaction components on the spin moment developed at the rotating band for a projectile: $M_{\mathrm{Zy}} = M_{\mathrm{Z}}\sin\varphi$, $M_{\mathrm{Zx}} = M_{\mathrm{Z}}\cos\varphi\cos\theta$, $M_{\mathrm{Zz}} = M_{\mathrm{Z}}\cos\varphi\sin\theta$.

The inertia matrix posing in equations (5) – (7) has the form [9], [12]

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

The system of the differential equations (2) – (9) has been solved using the ode45 Matlab integration software.

3 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], [6], [14].

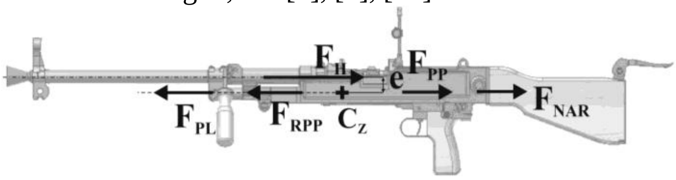

Fig.8 Forces acting onto mounting

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 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:

$$F_{\mathrm{B}} = F_{\mathrm{H}} - F_{\mathrm{PL}} + F_{\mathrm{NAR}} + F_{\mathrm{PP}} - F_{\mathrm{RPP}} \,. \tag{17}$$

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 7.62mm investigating system has the course shown in Fig. 9.

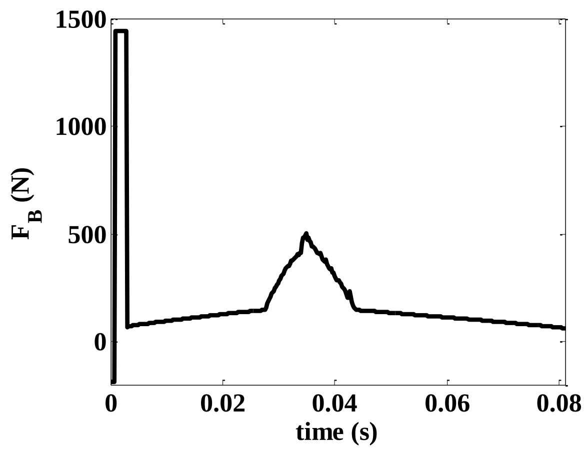

Fig.9 Exciting force F_{B}

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], [3], [4]. These forces are periodically repeated during required number of shots.

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 1.

Table 1 Main inputs for calculations

$I_{\mathrm{E}} = 0.897$ kg.m^2
$k_{\mathrm{E}} = 23100$ N.m.rad^{-1}
$b_{\mathrm{E}} = 40$ N.m.s. rad^{-1}
$r_{\mathrm{EC}} = .0465$ m
$h_{\mathrm{T}} = 0.413$ m
$m_{\mathrm{S}} = 90$ kg
$k_{\mathrm{S}} = 70000$ N.m^{-1}
$k_{\mathrm{Z}} = 4000$ N.m^{-1}
$T_{\mathrm{f1}} = 70$ N

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. 10, describes the vibration of the system rotating about z_{T} 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. 11.

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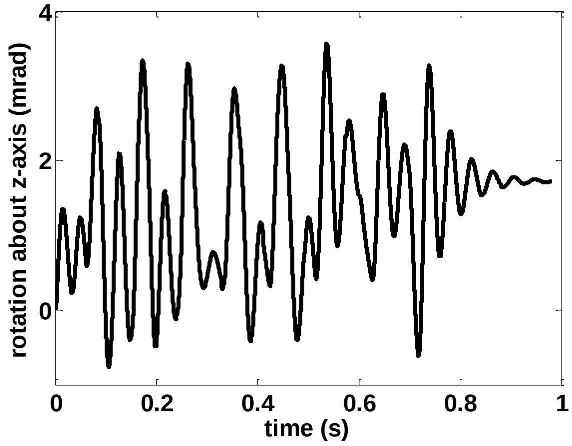

Fig.10 Vibration of elevation parts

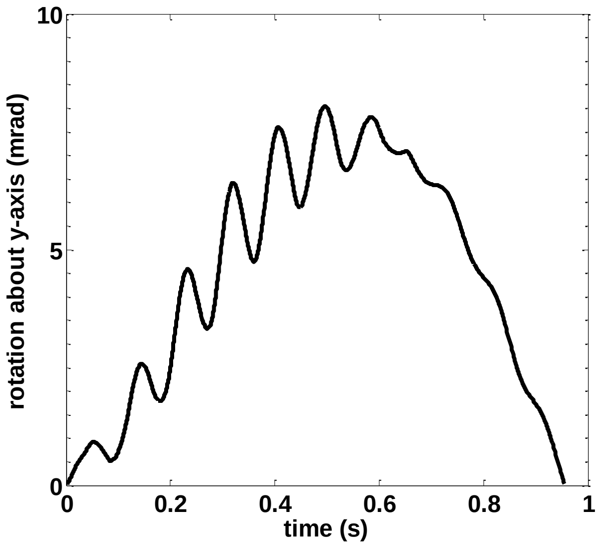

Fig.11 Rotary motion in the horizontal plane

The results of the linear displacement (in x_T axis), see Fig. 12, 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.

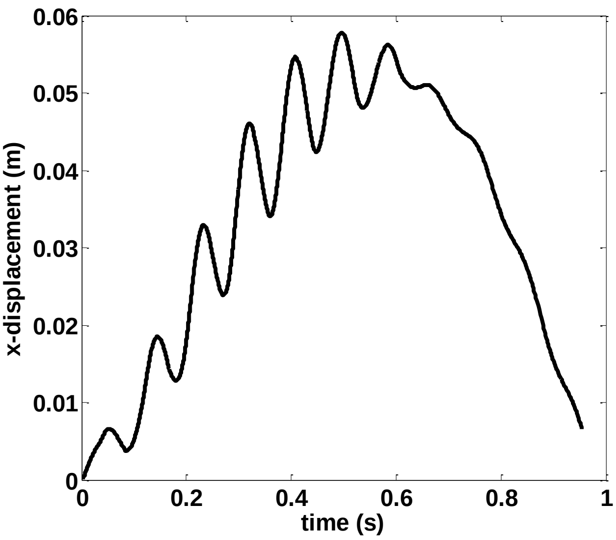

Fig.12 Weapon linear displacement

The shooter behaves as 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.

During the experimental part of the research have been used the contactless measurement techniques of the weapon displacement both the weapon 1 and tripod 2 using two high-speed cameras, see positions 3 and 4 in Fig. 13 and Fig. 14 and laser sensors in Fig. 15.

The first of them, cameras system, consists of the two parts: 3 – Olympus I-speed located upward the weapon in the 1.7m height scanning the motion in the horizontal plane, 4 - Redlake MotionXtra® HG-100K placing on the stand in the 4m distance scanning the motion in the vertical plane. Due to the different characteristics of both cameras the special trigger device on the acoustic base generates the signal starting the start of the records. Both cameras scanned with the same frequency due to the synchronization because they have diverse characteristics and they are not the same generation. It rebounded on the various resolutions both records for every snapshot. The data processing procedure is published in [7] and [13].

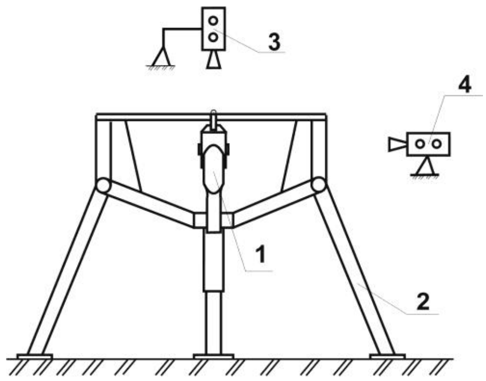

Fig. 13 Weapon and cameras – rear view

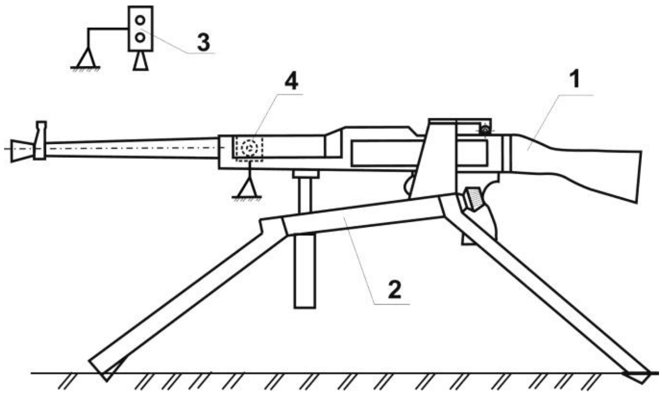

Fig.14 Weapon and cameras – side view

The laser gauges, Fig. 15 positions 4 and 5, have been used for comparing of the measuring with cameras. They have seemed to be very reliable because quick preparation. The strain gauge 3 registered the time when projectile exited the barrel muzzle. The signals have been stored in computer 7 via measuring system DEWE.

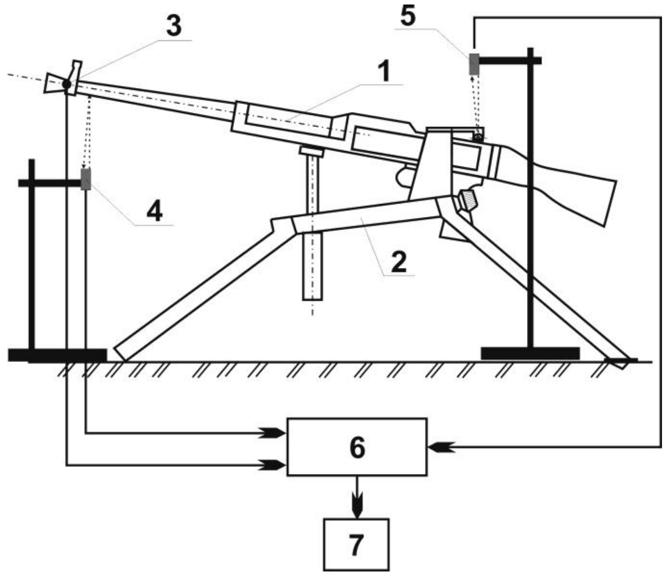

Fig.15 Weapon and laser gauges

4 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 7.62mm 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 (Objectice Crew Served Weapon) using larger calibers up to 35mm.

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