THEORY OF HIGH RATE OF FIRE AUTOMATIC WEAPON WITH TOGETHER BOUND BARRELS AND BREECHES

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Abstract: - The paper decribes the principle of the weapon with together bound of barrels and breeches at first. Then the kinematics and dynamics of the weapon mechanism with the crank mechanism inserted between the breech block and breech block carrier is discussed. Equations enabling the theoretical solution of the gas operated drive of the weapon mechanism are explained. The imagination about the utilization of the theory mentioned gives the results of the solution of the real weapon at the end of the paper.

Key-Words: - Crank mechanism, Breech, Gas flow, Equation of motion, Pressure in barrel, Discharge coefficient

1 Introduction

In addition to two formerly known high rate of fire weapon principles – the revolver principle and the Gatling principle, see [1], [2] and [7], the third high rate of fire principle with together bound barrels and breeches has been created. The first weapon of this principle has been designed by the German designer Gast at the end of the World War I.

After the World War II this principle has been redesigned by Russian designers and thus the automatic cannons of the caliber 23 mm and 30 mm have been created. On the base of this principle Czech designers have designed 20mm aircraft cannon ZPL-20 and the cannon was accepted in the armament of Czech Air Forces. Main advantages of the cannon are the low weight and relatively small dimensions at the high power of fire.

Basic design features of the cannon, see Fig. 1 and Fig. 2, are the gas operated drive accelerating the breech block carriers of both barrels, functional link of both carriers by a pinion ensuring their alternate motion (i.e. if the breech block carrier of the right barrel moves backwards, the carrier belonging to the left barrel moves forwards) and the utilization of the crank mechanism between the breech block and its carrier belonging to each barrel.

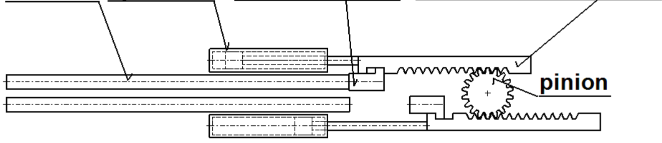


Fig. 1 Principle of design features

This crank mechanism together with the functional curve in the weapon casing ensures the continuous motion (without impacts) of the breech block when firing. The influence of the functional curve is transferred on the breech mechanism by means of the roller placed on the crank. This roller meshes with the curve.

2 Kinematics and dynamics of weapon

At the beginning of the dynamic analysis of the weapon it is necessary to find the primary geometric relations between links, velocities, transmission functions and accelerations or derivatives of the transmission functions. Found reduced mass and its derivative enter into the equation of motion whose form can be written as

$$m_{\mathrm{red}}\,\ddot{x} + 0{,}5\,\dot{x}^2\,\frac{\mathrm{d}m_{\mathrm{red}}}{\mathrm{d}x} = Q_{\mathrm{red}} \tag{1}$$

or

$$m_{\mathrm{red}}\,\ddot{x} + 0{,}5\,\dot{x}\,\frac{\mathrm{d}m_{\mathrm{red}}}{\mathrm{d}t} = Q_{\mathrm{red}}\,. \tag{2}$$

First of all, the kinematic relations have to be determined in every integration step when solving the differential equations (1) or (2).

Since weapon kinematics depends on the stroke of the main functional element and it is the breech block carrier, the equation in the form (1) is mostly used, see [1], [10] and [19].

According to [4] or [17] we apply to the vector method on the kinematic relations between main parts of the weapon mechanisms as it follows from the Fig. 2, where

x - breech block carrier displacement (measured from point A),

φ_2 - rotation angle of crank (ABC),

φ_3 - rotation angle of connecting rod (CD),

x_b - breech block displacement (measured from point D).

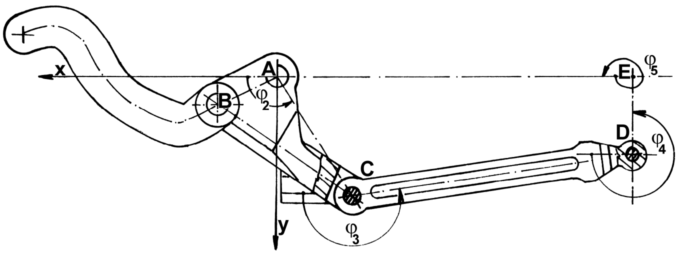


Fig. 2 Eccentric crank mechanism of weapon

Let us write on the quadrangle ACDE as independent loop, the equations describing the mechanism geometry

$$r\cos\varphi_2 + l\cos\varphi_3 + x_b - x = 0 \tag{3}$$

$$r\sin\varphi_2 + l\sin\varphi_3 - e = 0\,. \tag{4}$$

The known values are $r = AC,\ l = CD,\ \ x = x_A, \varphi_2$, where φ_2 angle is set in the analytical form following from the used cam

$$\varphi_2 = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + a_5 x^5\,. \tag{5}$$

The Newton's iteration method, known as method of corrections in [4], was applied to obtain two unknowns φ_3 and x_b suitable for the required precision ε. Mostly two or three iteration procedures were applied in every integration step.

Differentiation of the preceding equations (3) and (4) with respect to time yields the following equations for the velocities – equations (6) and (7) – result:

$$-r\sin\varphi_2\frac{d\varphi_2}{dt} - l\sin\varphi_3\frac{d\varphi_3}{dt} + \frac{dx_b}{dt} - v = 0\,, \tag{6}$$

$$r\cos\varphi_2\frac{d\varphi_2}{dt} + l\cos\varphi_3\frac{d\varphi_3}{dt} = 0\,. \tag{7}$$

The reduced mass m_{red} in equations (1) or (2) is determined from the kinetic energy of the system,

$$E_K = 0.5v^2\,(2m_{bbc} + I_{SP}\frac{\Omega_{SP}^2}{v^2} + 2I_{KL}\frac{\Omega_{KL}^2}{v^2} + 2m_{KL}\frac{v_{KL}^2}{v^2}$$
$$+ 2I_{OJ}\frac{\Omega_{OJ}^2}{v^2} + 2m_{OJ}\frac{v_{OJ}^2}{v^2} + 2m_b\frac{v_b^2}{v^2} + m_P\frac{v_P^2}{v^2}) \tag{8}$$

where

v - breech block carrier velocity,

m_{bbc} - breech block carrier mass,

I_{SP} - tooth wheel mass moment of inertia,

Ω_{SP} - angular velocity of tooth wheel,

I_{KL} - crank mass moment of inertia,

Ω_{KL} - angular velocity of crank,

v_{KL} - velocity of crank gravity centre,

m_{KL} - crank mass,

I_{OJ} - connecting rod mass moment of inertia,

Ω_{OJ} - angular velocity of connecting rod,

v_{OJ} - velocity of connecting rod gravity centre,

m_{OJ} - connecting rod mass,

v_b - breech velocity,

m_b - breech mass,

v_P - cartridge belt velocity,

m_P - cartridges and links belt mass.

The right-hand side (1) or (2) is reduced force Q_{red} which is given as follows:

$$Q_{red} = F_{GA} - F_{VA} - F_f - F_P - F_{ex} - F_{PP} \tag{9}$$

where

$F_{GA} = S_{pA}\,p_A$ - driving gas force,

$F_{VA} = S_{pAA}\,p_{AA}$ - braking force of air,

F_f - friction force,

F_p - resistance of the cartridge belt, depending on the mass of the belt link and cartridge, rigidity of link and velocity of the cartridge belt,

F_{ex} - cartridge extraction force from the belt,

F_{pp} - force of the breech rebound catch.

3 Gas drive of the weapon mechanism

The system of equations enabling to solve the action in the gas arrangement and thus also all the motion of the weapon mechanism consists of following kinds of equations, see [15]: equation of motion (1) and the other describing the function of the gas drive. These equations must be adapted for gases, for the air and for the other conditions (e.g. in dependence on the pressure ratio between the cylinder and the barrel).

The action of the drive system utilizing the propellant gases must be solved for two periods depending on the relation of the pressure of gases inside the barrel bore p_{bl} and the pressure of gases inside the gas cylinder „A“ p_A, see [6], [12]. If $p_{bl} > p_A$ then the propellant gases flow through the gas port from the barrel into the gas cylinder. For case $p_{bl} < p_A$ the gases flow in the opposite direction.

These two periods influence the equations of the gas flow in the following way.

For $p_{bl} > p_A$:

Equation of the energy change in the gas cylinder „A“

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(p_A V_A\right) = kR\left(G_A T_{bl} - G_A T_A\right) - \left(k-1\right) p_A S_{pA} v \quad (10)$$

Equation of the gas mass change in the gas cylinder „A“

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{V_A}{w_A}\right) = G_A - G_{cyA} \, . \quad (11)$$

For $p_{bl} < p_A$:

Equation of the energy change in the gas cylinder „A“

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(p_A V_A\right) = -kRT_A\left(G_A + G_{cyA}\right) - \left(k-1\right) p_A S_{pA} v. \quad (12)$$

Equation of the gas mass change in the gas cylinder „A“

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{V_A}{w_A}\right) = -\left(G_A + G_{cyA}\right). \quad (13)$$

Important characteristic of these equations is the magnitude of the gas mass flow G through any cross-section S from the state “1” to the state “2”. For the sub-critical flow it is given by the formula

$$G = \mu S\left(\frac{2}{k-1}\right)^{\frac{1}{2}} \sqrt{\frac{p_1}{w_1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{2}{k}} - \left(\frac{p_2}{p_1}\right)^{\frac{k+1}{k}}\right]} \quad (14)$$

and for the critical flow by the formula

$$G = \mu S\left(\frac{2}{k-1}\right)^{\frac{k+1}{2(k-1)}} \sqrt{k\frac{p_1}{w_1}} \, . \quad (15)$$

In these two formulae is:

μ - discharge coefficient,

S – cross-section through the gas flows,

k – ratio of specific heats,

p_1 – pressure in the vessel, from which the gas flows, (for $p_{bl} > p_A$: $p_1 = p_{bl}$; for $p_{bl} < p_A$: $p_1 = p_A$), where p_{bl} is the pressure in the barrel and p_A the pressure in the gas cylinder,

p_2 – pressure in the vessel into which the gas flows, (for $p_{bl} > p_A$: $p_2 = p_A$; for $p_{bl} < p_A$: $p_2 = p_{bl}$),

w_1 – specific volume of the gas in the vessel from which the gas flows.

The discharge coefficient μ influences the magnitude of the gas mass flow G (it takes into consideration the losses during the gas flow through any orifice). Generally it is possible to say that in the gas arrangement of the automatic gas operated weapon the gas flows through the gas port between the barrel and the gas cylinder and through the clearance between the piston surface and the cylinder wall. If the packing rings on the piston are used (as it is mostly used in weapons with together bound barrels and breeches) then the flow through this clearance is negligible.

The magnitude of the discharge coefficient μ for the flow of gas through the gas port depends on the state of the gas in the vessel from which the gas flows. For the period $p_{bl} > p_A$ (the gas flows from the barrel into the gas cylinder) at the instant of the gas port opening the gas in the barrel bore moves with very high velocity u what causes great losses especially at the entrance of the gas into the gas port. The magnitude of these losses depends on the velocity of the gas in the barrel bore. Thus the discharge coefficient for the flow from the barrel bore μ_{bl} can be aproximatelly chosen utilizing the formula

$$\mu_{bl} = 0.65 - 0.00016\, u \, . \quad (17)$$

(u is the velocity of the gas in the barrel, i.e. the velocity of the projectile, at the instant in which the projectile passes the gas port in the barrel bore).

At the period $p_{bl} < p_A$, i.e. at the opposite direction of the flow of the gas through the gas port, the conditions of the entrance of the gas into the gas port are more simple, because the gas in the cylinder is nearly at rest. Therefore it is possible to use the discharge coefficient according to the technical literature dealing with the flow of gases

$$\mu_A = 0.65. \quad (18)$$

If no packing rings on the piston would be used, then the discharge coefficient for the flow through this clearance μ_{cl} can be chosen

- for the coaxial position of the piston in the gas cylinder

$$\mu_{cl} = 1.123\,(\delta + 0.4)^{0.41} - 0.29 \, , \quad (19)$$

where δ is the clearance between the piston and the cylinder wall in millimeters

$$\delta = R_c - R_p \quad [\mathrm{mm}] \quad (20)$$

(R_c is the inner radius of the cylinder, R_p is the outer radius of the piston);

- for the eccentric position of the piston in the gas cylinder it is recommended to use

$$\mu_{\mathrm{cle}} = 1.25\,\mu_{\mathrm{cl}} \,. \tag{21}$$

But as it was mentioned before, for the weapon with together bound barrels and breeches the packing rings are used mostly and therefore the flow of gases through the clearance is not supposed.

The influence of the air being in the cylinder on the opposite site of the piston can be taken into consideration utilizing also the equations of the energy change and the mass change arranged for the air.

Thus these equations for the air cylinder “A” are

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(p_{\mathrm{AA}}V_{\mathrm{AA}}\right) = -k_{\mathrm{A}}R_{\mathrm{A}}T_{\mathrm{AA}}\left(G_{\mathrm{AAch}}+G_{\mathrm{AAcl}}\right) + \left(k_{\mathrm{A}}-1\right)p_{\mathrm{AA}}S_{\mathrm{pAA}}v \tag{22}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{V_{\mathrm{AA}}}{w_{\mathrm{AA}}}\right) = -\left(G_{\mathrm{AAch}}+G_{\mathrm{AAcl}}\right). \tag{23}$$

Let us mention, that the motion of the piston is influenced not only by the flow of gases through the gas port between the barrel and the gas cylinder and by the pressure of the air acting on the opposite side of the piston but also by the period of the exhaust of the air from the air cylinder into the atmosphere and after that by the period of the exhaust of the gas from the gas cylinder into the atmosphere (depending on the position of the piston during its backward motion).

In addition to previous equations the solution of the action of gases in the gas cylinder “A” utilizes following equations:

- instantaneous volume of the gas cylinder “A” is

$$V_{\mathrm{A}} = V_{\mathrm{A0}} + S_{\mathrm{pA}}x\,, \tag{24}$$

- instantaneous pressure of gases in the gas cylinder “A”

$$p_{\mathrm{A}} = \frac{\left(p_{\mathrm{A}}V_{\mathrm{A}}\right)}{V_{\mathrm{A}}}\,, \tag{25}$$

- instantaneous specific volume of gases in the gas cylinder “A”

$$w_{\mathrm{A}} = \frac{V_{\mathrm{A}}}{\left(\dfrac{V_{\mathrm{A}}}{w_{\mathrm{A}}}\right)}\,, \tag{26}$$

- instantaneous temperature of gases in the gas cylinder “A”

$$T_{\mathrm{A}} = \frac{p_{\mathrm{A}}\,w_{\mathrm{A}}}{R}\,. \tag{27}$$

The solution of the action of the air in the air cylinder “A” utilizes similar equations:

$$V_{\mathrm{AA}} = V_{\mathrm{AA0}} - S_{\mathrm{pAA}}x\,, \tag{28}$$

$$w_{\mathrm{AA}} = \frac{V_{\mathrm{AA}}}{\left(\dfrac{V_{\mathrm{AA}}}{w_{\mathrm{AA}}}\right)}\,, \tag{29}$$

$$T_{\mathrm{AA}} = \frac{p_{\mathrm{AA}}w_{\mathrm{AA}}}{R_{\mathrm{A}}}\,, \tag{30}$$

$$p_{\mathrm{AA}} = \frac{\left(p_{\mathrm{AA}}V_{\mathrm{AA}}\right)}{V_{\mathrm{AA}}}\,. \tag{31}$$

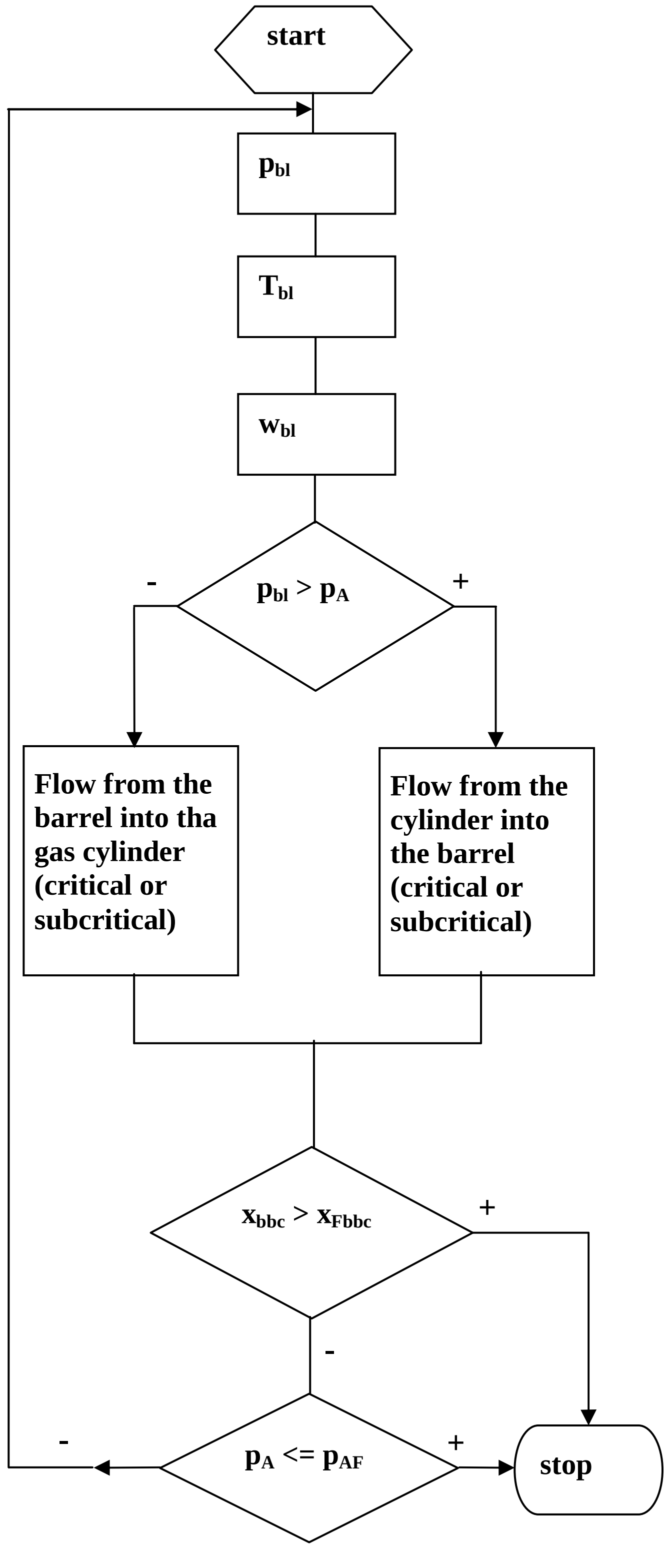
Symbols used in previous equations are:

p_{bl} - pressure of gases in the barrel bore,
p_{A} - pressure of gases in the gas cylinder “A”,
t - time,
V_{A} - instantaneous volume of the gas cylinder “A”.
V_{A0} - initial volume of the gas cylinder “A”
R - gas constant of propellant gases,
G_{A} - gas mass flow through the gas port,
T_{bl} - temperature of gases in the barrel bore,
G_{cyA} - gas mass flow from the gas cylinder through the exhaust orifice,
T_{A} - temperature of gases in the gas cylinder “A”,
S_{pA} - area of the piston in the gas cylinder “A”,
v - velocity of the piston,
$x = x_{\mathrm{bbc}}$ - displacement of the piston,
w_{A} - specific volume of gases in the gas cylinder “A”,
p_{AA} - pressure of the air in the air cylinder “A”,
V_{AA} - instantaneous volume of the air cylinder “A”,
V_{AA0} - initial volume of the air cylinder “A”,
k_{A} - ratio of specific heats of the air,
R_{A} - gas constant of the air,
G_{AAch} - air mass flow from the air cylinder through the exhaust orifice,
G_{AAcl} - air mass flow from the air cylinder through the clearance of the piston rod,
$S_{p\mathrm{AA}}$ - area of the piston in the air cylinder “A”,
w_{AA} - specific volume of the air in the air cylinder “A”.

The substance of the solution procedure is shown in the flow diagram Fig. 3. The system of differential equations was solved using the extrapolation method, published in [15] together with the equation of kinematics and the other additional equations.

The integration step 0.0001s looked to be well-chosen for the specific purpose. The choice has been made with recommendation in works such as [7], [12] and [19] and on the base of the technical experiments during the developmental stage.

The oncoming results have been gained with comparison of calculations and measurements on the 23mm aircraft cannon GSh-23 before [13] and 20mm cannon ZPL-20 [14] when the software was debugged.



p_{AF} – final value of the pressure p_A
w_{bl} – specific volume of gas in the barrel
T_{bl} – temperature of ga in the barrel
x_{Fbbc} – final value of the breech block carrier diplacement

Fig. 3 Flow calculation diagram

4 Results

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. Due to very large numbers of inputs only the most important there are mentioned hereto. First of all, the significant kinematic values are:
r = 0.065m, l = 0.138m, e = 0.0388m, m_{bbc} = 2.4kg, m_b = 0.18kg, m_{OJ} = 0.14kg, I_{KL} = 0.0005304kg.m2, I_{OJ} = 0.001166kg.m^2.

The inputs belonging to the gas drive were chosen according to design of the weapon and they were corrected with respect to the technical experiments.

The main gas drive values are:

S_{pA} = 0.000706858 m^2, k = 1.26, p_{bl} = 161 MPa (beginning of the drive), R = 350,
T_{bl} = 2529 K, k_A = 1.4, R_A = 287.

Discharge coefficients μ have been chosen according to (17), (18) as follows: μ = 0.524 if $p_{bl} > p_A$ and μ = 0.01 if $p_{bl} < p_A$.

The pressure/time history curve in the barrel p_{bl} including the aftereffect of the propellant gases for the cartridge 20x102 mm is in Fig 4.

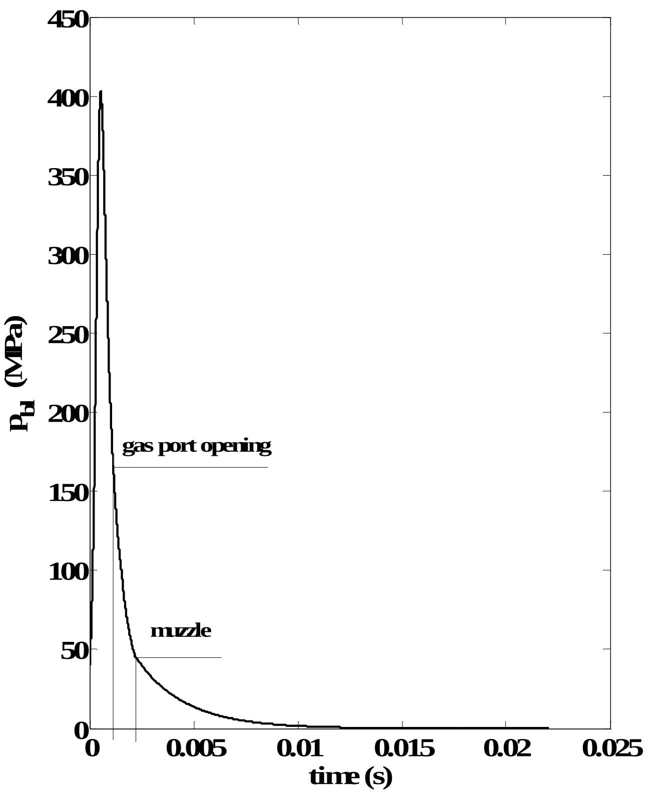


Fig. 4 Pressure in the barrel – cartridge 20x102mm

The courses of the gas pressure and the temperature in the barrel were set using their interpolations by means of polynomials so that to simplify the procedure of calculation.

Beginning from the instant of the gas port opening, see Fig.4 as well, when the bottom of the projectile passes the gas port in the barrel bore the courses of the pressure in the barrel p_{bl} = f(t) and the calculated pressure in the gas cylinder p_A = f(t) are in Fig 5. The periods of two gas flow directions through the gas port are shown. First of all it is the stage when $p_{bl} > p_A$ and afterwards the stadium $p_{bl} < p_A$.

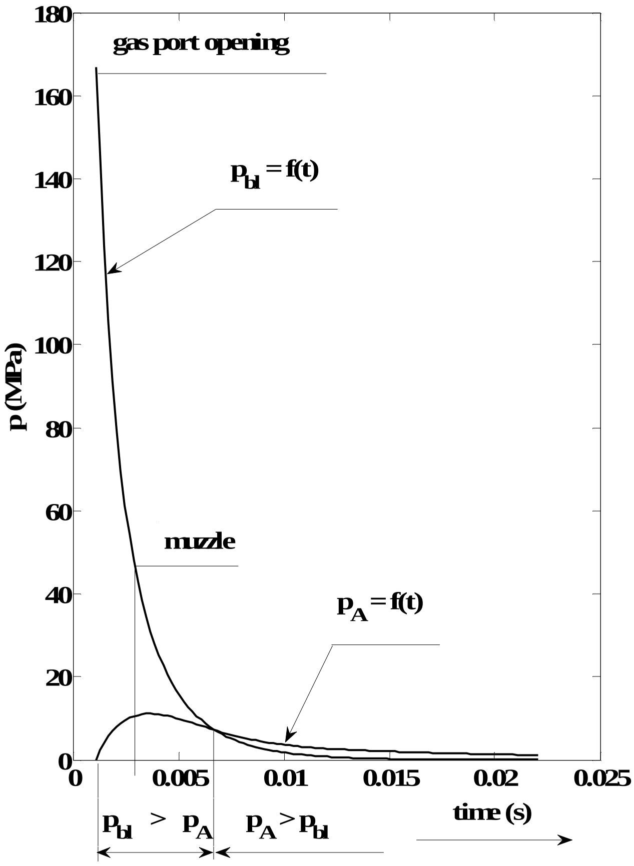


Fig. 5 Gas pressure in cylinder and barrel

During the first period of the operation small amounts of the propellant gases flow into the cylinder accelerating all reduced mass to required velocity. Only all of the 0.0002 kg of the powder enables to reach demand operation of the weapon mechanism.

The Fig. 6 (gas flow from the barrel into the cylinder) and Fig. 7 (gas mass obtaining after integration of the gas flow according to time) confirm this fact. The explaining is clear. The powder heat energy of the one kilogram is 923kJ. The calculated gas mass yields the 184J and with 35% efficiency it is approximately 65J. Afterwards the gases flow from the barrel into the cylinder in the opposite direction.

The temperature of the gas in the cylinder goes down in compliance with the Fig. 8. After its rising from temperature of the surroundings 288K to over 3000K it drops to average value approximatelly 1500K.

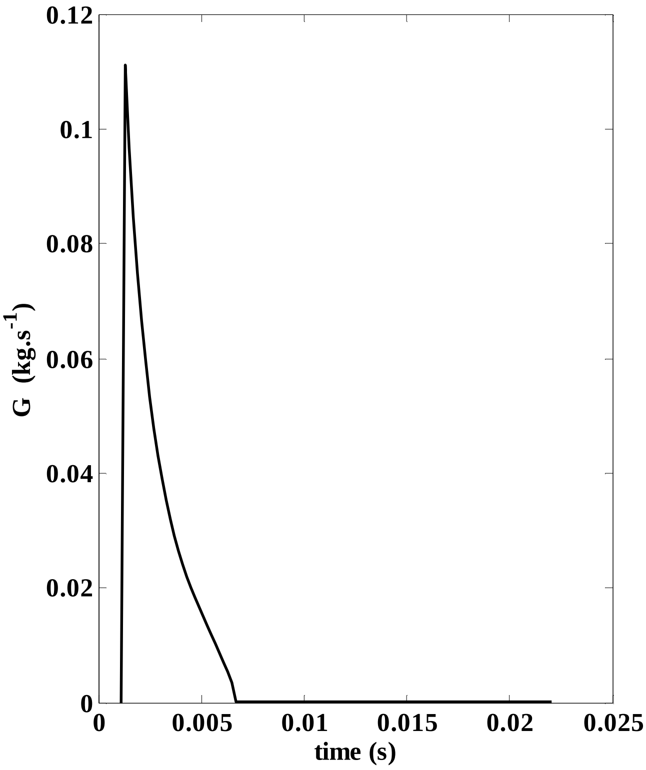


Fig. 6 Gas flow from barrel into cylinder

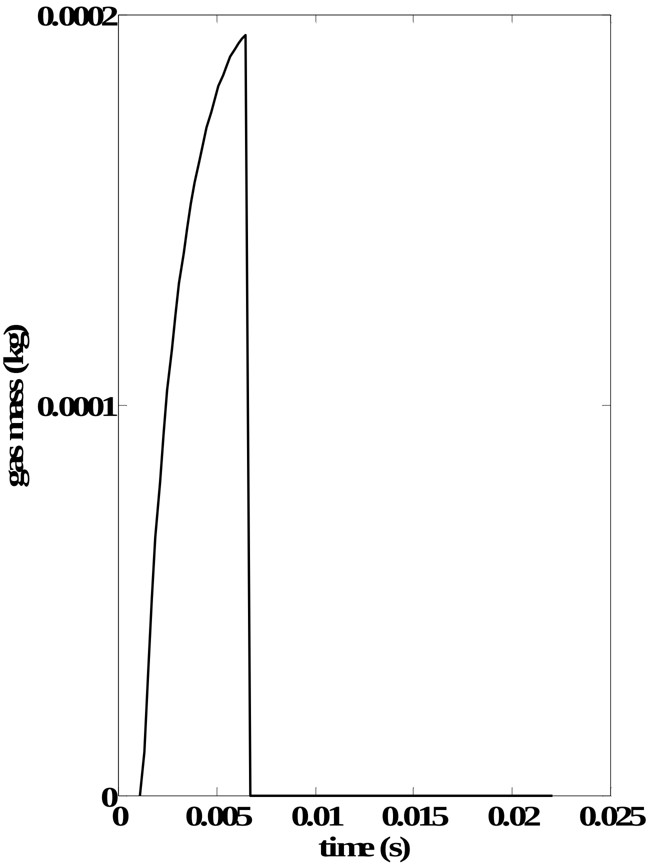


Fig. 7 Gas mass flowing from barrel into cylinder

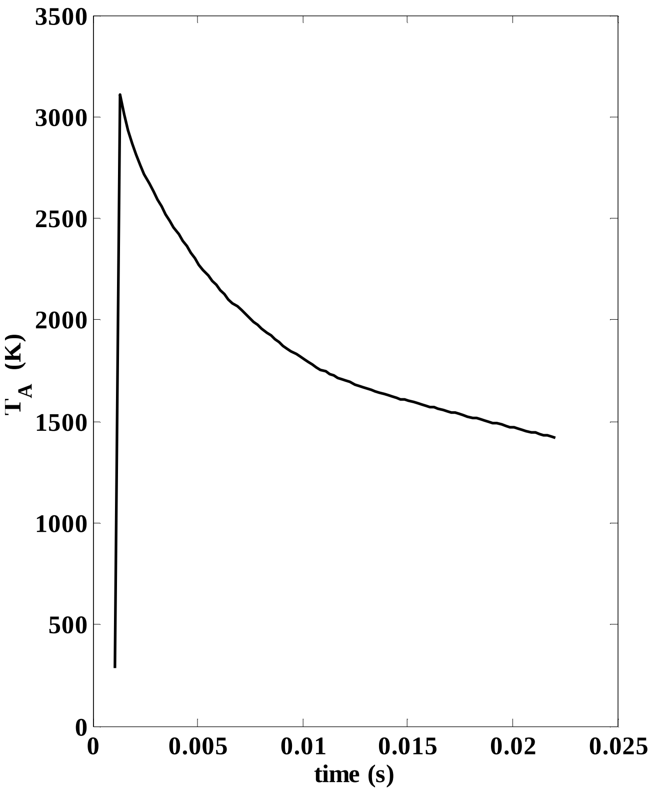


Fig. 8 Gas cylinder temperature

The dependence of the input angle φ_2 on the breech block carrier displacement x_{bbc} is drawn in the Fig. 9 and corresponds to arrangement of the cam and size of the main parts of the mechanism.

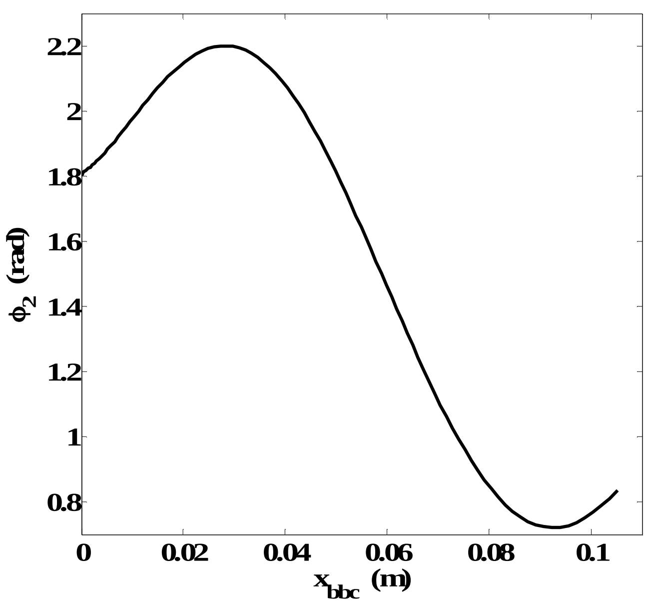


Fig. 9 Input angle φ_2

The curve course of the breech block carrier displacement on the time represents the Fig. 10.

The time starts from the time when the projectile overpasses the gas vent. Therefore the true time does not begin from zero. The course of the breech block carrier velocity is depicted in Fig. 11. There is very interesting the velocity boost after half period of the motion caused by the returning of the kinetic energy of the breech to the breech block carrier.

This phenomenon is representative of these mechanisms as it is introduced in [1], [2] or [16]. In contradistinction to small arms operated using of the classical cycles, where velocity of the main functional element slopes down, here with respect to short time of the cycle, the breech block carrier is accelerated at the second half of its cycle.

The breech block displacement versus breech block carrier displacement is visualized in Fig. 12. The overall stroke is 165 mm and depends on the cartridge size loading into the barrel. The idle period at the beginning is necessary to exclude a random event in course of the shot when the projectile or the high gas pressure is in the barrel. This dwell is known as under slide, see [1], [19].

Knowledge of that period is needful for design of the trigger mechanism as it is indicated in [11] and [16].

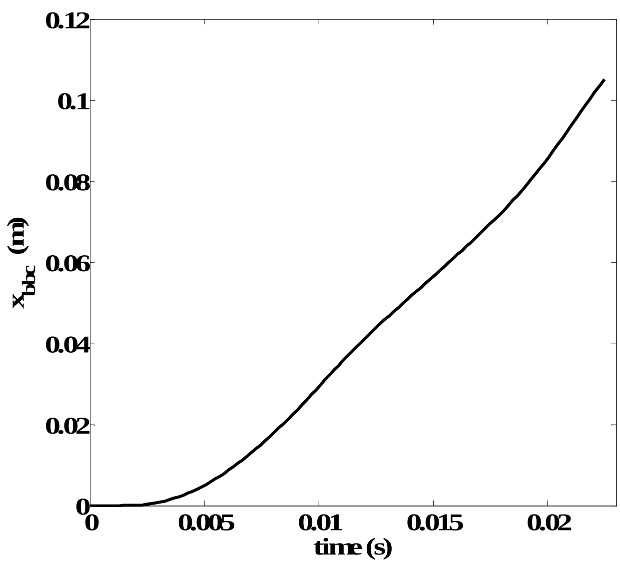


Fig. 10 Breech block carrier displacement

The additional result following from the kinematic analysis is connecting rod angle of rotation φ_3 in Fig. 13. According to breech displacement varies its velocity as it points to in the Fig. 7, where the maximum velocity is approximately in the half of the breech block carrier displacement.

The insertion of the crank mechanism between the breech block carrier and the breech block ensures the longer displacement of the breech block with respect to the displacement of the breech block carrier in the same time (see Fig. 14).

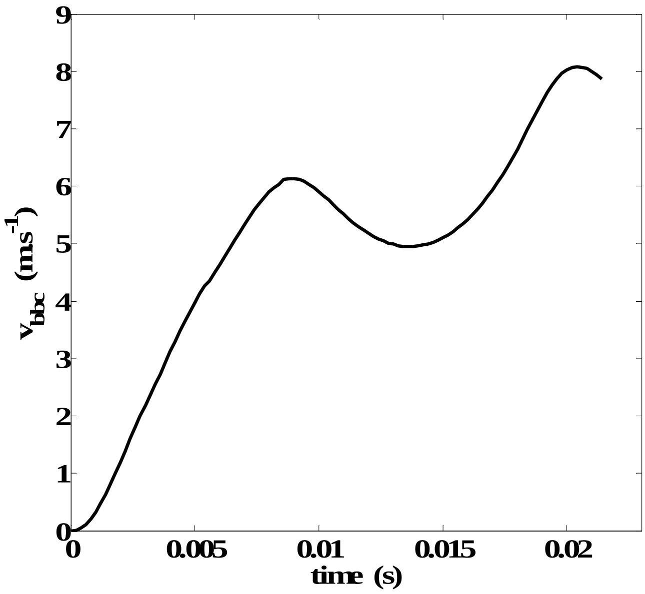


Fig. 11 Breech block carrier velocity

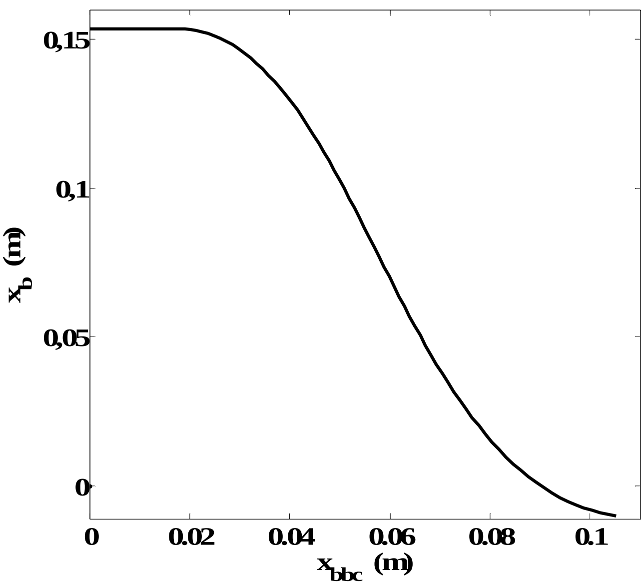


Fig. 12 Breech block displacement

Thus the velocity of the breech block is substancially increased with respect to the velocity of the breech block carrier. To prevent the shocks in limit positions of the of the breech block, the crank mechanism is completed by the functional curve in the weapon casing. The shape of this curve consists of the accelerating and the decelerating sections. The roller placed on the crank meshes with this functional curve. This design feature ensures that during the motion of the breech block carrier the velocity of the breech block changes continuously from zero to its maximum value (nearly at the half of the functional stroke) and then it decreases to zero as it is shown in the graph in Fig 15.

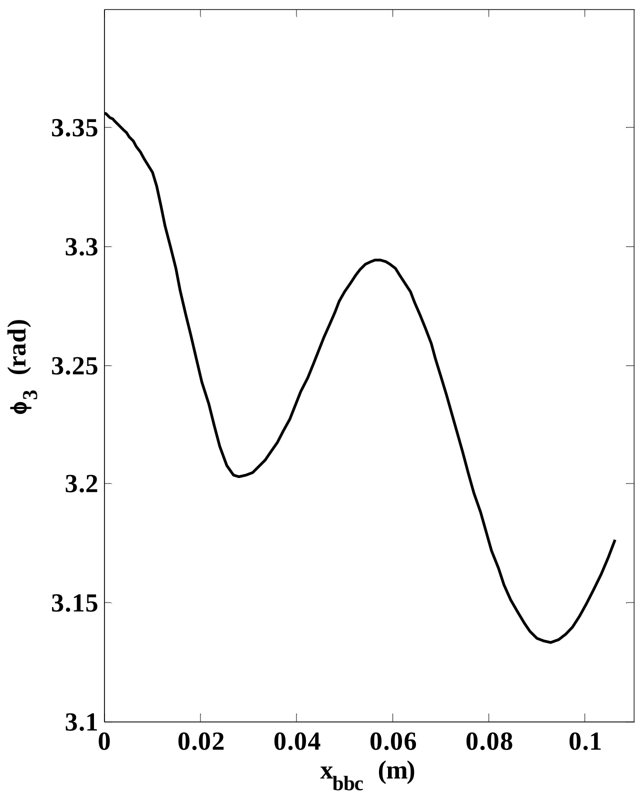


Fig. 13 Connecting rod angle φ_3

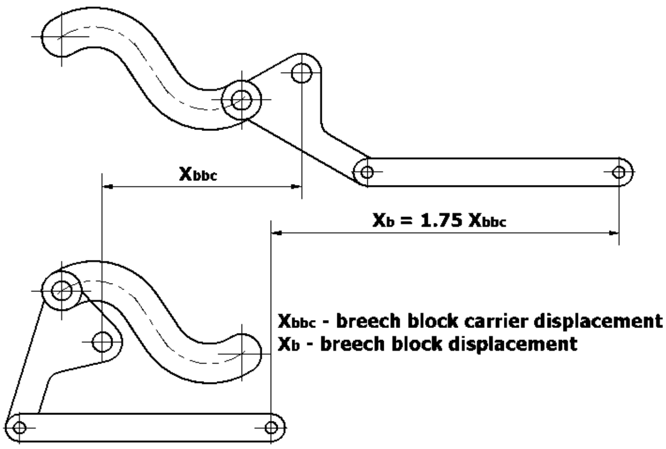


Fig. 14 Explanation of breech block and breech block carrier displacements

At the end of the cycle the breech strikes in the rear position on the weapon casing and in accordance with the shape of the cam changes the final velocity. This small impact has an advantage ensuring the termination of the movement into the rear position of the breech in case of conditions worsening, for example when friction boosts for surface contamination reasons.

The Figure 16 represents the reduced mass course versus the breech block carrier displacement as it is written in the bracket of the equation (8). The maximal value of the reduced mass matches to the minimal breech block carrier velocity, see Fig. 11 as well.

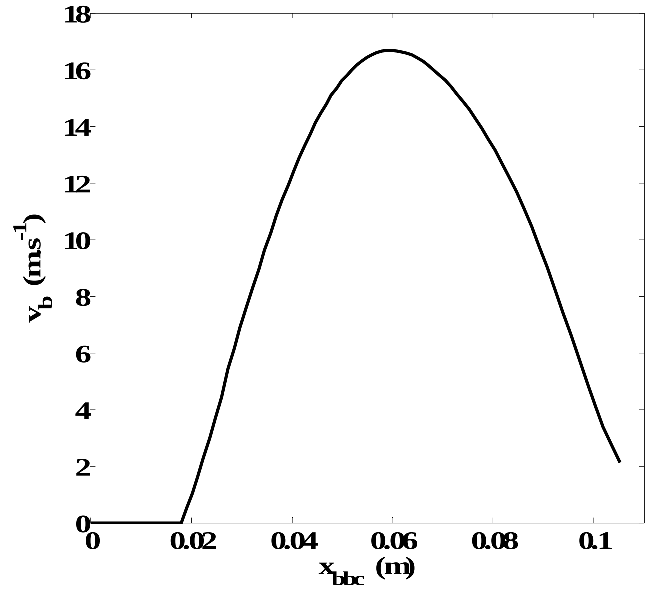


Fig. 15 Breech block velocity

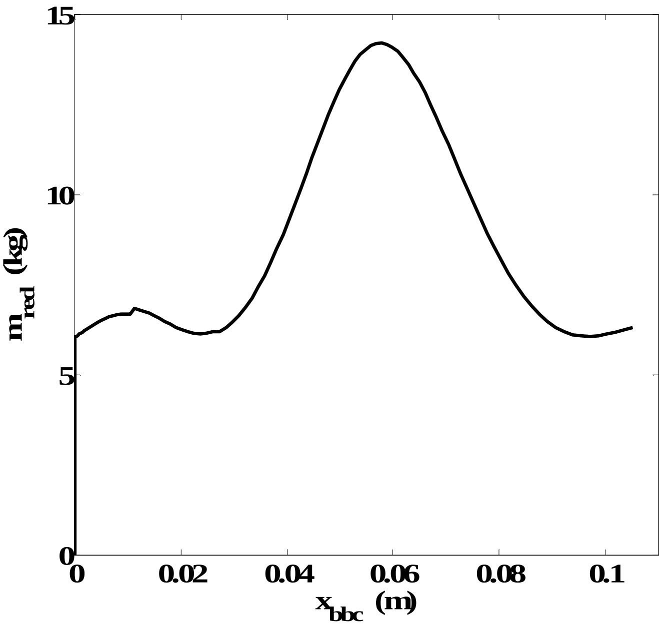


Fig. 16 Reduced mass

The differentiation of the reduced mass according to x was calculated numerically in every integration step. The course of the gas pressure in the gas cylinder itself (and it is the pressure on the driven piston connected with the breech block carrier) drawn according to Fig. 5 in changed scale is in Fig. 17.

The pressure is much lower than the initial gas pressure in the barrel when the mechanism operation begins. The force driving the whole mass creates during functional cycle the impulse equals to the momentum whereby all parts obtain the required velocities. The impulse course is drawn in the Fig. 18.

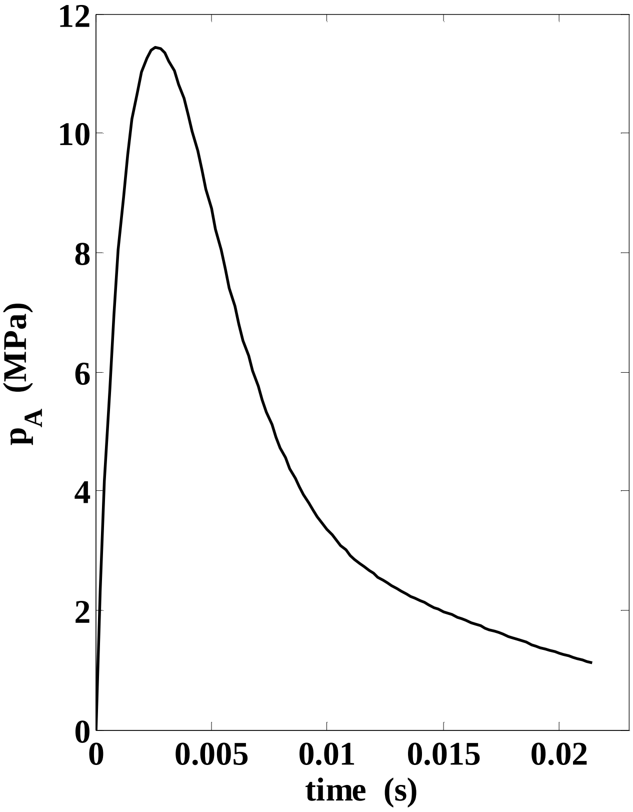


Fig. 17 Gas pressure in gas cylinder

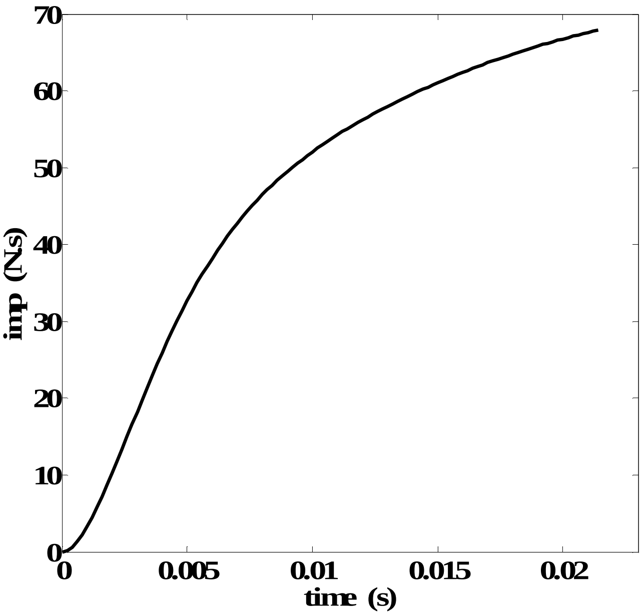


Fig. 18 Impulse of gas force in cylinder

At the end the system gains the maximal value. However, it is interesting that this high rate of fire weapons are driven within entire cycle in contrast to weapons whose rate of fire under 1000 rounds per minute. These weapons have the main functional elements accelerated in shorter time in consideration of the total functional cycle.

5 Conclusion

The results given in the figures reflect a good coincidence with the real weapon which was designed according to presented theory. The theory was verified on the other examples of weapons patterns as it is published in [2] for example.

The course of input angle φ_2 depending on the cam curve, see Fig. 3 and the equation (5), seems to be more suitable than the cam curves used in the Gatling systems, which are presented in [2] or [7]. 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.

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