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SOLUTION OF THE PYRO-RECOCKING SYSTEM OF THE AUTOMATIC CANNON

Reviewer: Stanislav BEER

A b s t r a c t :

The paper deals with the problem of the recocking of the automatic cannon (e.g. in the aircraft in case of its stoppage). Pyrocartridges are utilized for this case. The theory enabling the theoretical solution of this case is presented. It consists of three periods including the only burning of the propellant, the burning combined with the flow of gases into the gas cylinder and this flow after the end of propellant burning. The losses during the gas flow are discussed. The comparison of the theoretical solution with results of experiments is shown. Problems of propellant burning have been solved by the first author, the flow of gases into the cylinder and the acceleration of the weapon mechanism by the second author.

1. Introduction

To ensure the recocking of the automatic cannon in case of the misfired cartridge the pyro-recocking system is often utilized. This system used in the new Czech 20mm two barrel aircraft automatic cannon ZPL-20 is schematically shown in Fig. 1. It consists of a box with three cartridge chambers (for pyrocartridges), the channel with two sliding sleeves with holes in their center and a gas port. This gas port (its cross-section is S_A) connects the channel with the gas cylinder. The function of this

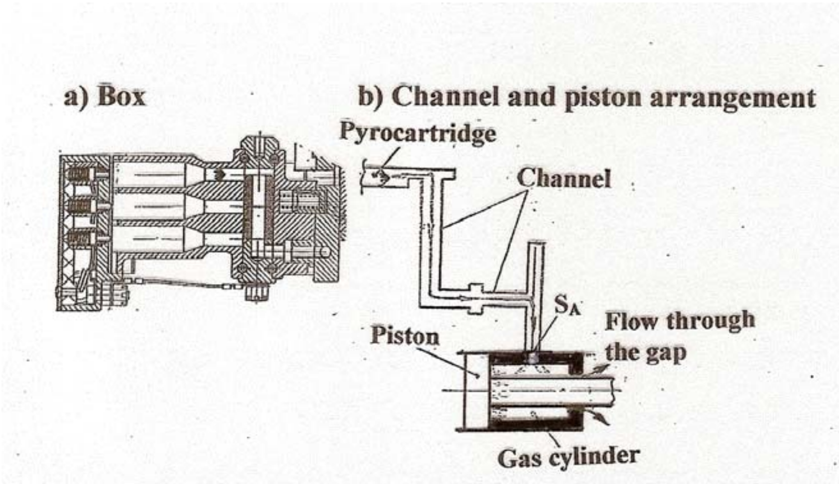

Figure 1 Scheme of the pyro-recocking system

system begins by the initiation of the electrical capsule of the pyro-cartridge and by the burning of the propellant charge. The propellant gases flow from the cartridge case through the channel and the gas port to the gas cylinder in which they act on the piston which accelerates the weapon mechanism. During this motion of the weapon mechanism the misfired cartridge is extracted and ejected, a new cartridge is shifted into the barrel and the firing in burst continues.

The function of this system consists of three periods:

- **1st period** deals with the function before entering the propellant gases into the channel,
- **2nd period** describes the burning of the propellant after the opening of the cartridge case neck, the flowing of gases into the channel, then the flow from this channel through the gas port S_A into the gas cylinder and the action of gases on the piston in this cylinder,
- **3rd period** deals with the flow of gases through the gas port between the channel and the gas cylinder (in both directions) after the end of the propellant charge burning and with the action of gases on the piston inside the cylinder.

The theory belonging to these periods is represented in following chapters.

2. Theory for the Solution of the 1st Period

The first period is limited by the opening of the cartridge case (its volume is c_1) at the pressure p_1 when the portion of the propellant charge ω_1 has been burnt according to the equation

$$\omega_1 = \frac{c_1 - \dfrac{\omega}{\delta}}{\dfrac{f}{p_1} + \alpha - \dfrac{1}{\delta}} \quad . \tag{1}$$

This portion corresponds with relative quantity of burnt out propellant

$$\psi_1 = \frac{\omega_1}{\omega} \tag{2}$$

and the relative burned thickness of the propellant grain is

$$z_1 = \frac{-\alpha_1 + \sqrt{\alpha_1^2 + 4\beta_1\psi_1}}{2\beta_1} \quad . \tag{3}$$

The dependences of the ballistic characteristics on the time $z(t)$, $\psi(t)$, $p(t)$ are given by the equations

$$\frac{dz}{dt} = \frac{p}{I_k} \tag{4a}$$

$$p = \frac{f\omega\psi}{c_1 - \dfrac{\omega}{\delta} - \omega\psi(\alpha - \dfrac{1}{\delta})} \tag{4b}$$

$$\psi = \alpha_1 z + \beta_1 z^2 + \gamma_1 z^3 \tag{4c}$$

which are usually solved by a numerical method.

For the analytic solution it is necessary to simplify the third previous equation (4c) using $\gamma_1 = 0$. Thus we obtain the expressions

$$t(z) = -\frac{M}{\alpha_1}\ln\frac{k_z(\alpha_1 + \beta_1 z)}{z} - Nz + k_t \tag{5}$$

$$\psi(t) = \alpha_1 e^{\frac{t-a}{b}} + \beta_1 e^{\frac{z(t-a)}{b}} \tag{6}$$

$$p(t) = \frac{f\omega\psi(t)}{(c_1 - \frac{\omega}{\delta}) - \omega(\alpha - \frac{1}{\delta})\psi(t)} \tag{7}$$

where

$$M = \frac{I_k(c_1 - \frac{\omega}{\delta})}{f\omega}$$

$$k_t = N.z_{10} + t_{10}$$

$$k_z = \frac{z_{10}}{\alpha_1 + \beta_1 z_{10}}$$

$$N = \frac{I_k(\alpha - \frac{1}{\delta})}{f}$$

z_{10} - chosen initia condition
t_{10} - initial condition corresponding with z_{10}
a, b - constants obtained from logarythmic linear regression $t = a + b.\ lnz$ of the equation (5)

Final values of ballistic characteristics at the end of the first period are obtained from the equations (5), (6) and (7) after the substitution $z = z_1$ utilizing the equations (1), (2), (3).
At the opening of the cartridge case the adiabatic expansion into the channel decreases the pressure of gases from the value p_1 to the initial pressure in the channel including the cartridge case p_{C0} according to the equation

$$p_{C0} = p_1 (\frac{c_{1op}}{c_{1\exp}})^k \ , \tag{8}$$

where

$$c_{1op} = c_1 - \frac{\omega}{\delta} - \omega_1(\alpha - \frac{1}{\delta})$$

is the free volume at the opening of the cartridge case and

$$c_{1\exp} = c_{1op} + c_2 \ .$$

Remark:
In following solution the symbol c_2 (i.e. the volume of the channel) is replaced by a symbol V_C .

Additional symbols in the equations used for the solution of the first period (1) to (8):

f - specific energy of propellant
ω - mass of propellant charge
α - covolume of propellant gases
δ - density (specific mass) of propellant
$\alpha_1, \beta_1, \gamma_1$ - geometric characteristics of propellant grain
t - time
I_k - pressure impulse of propellant gases.

3. Theory for the Solution of the 2nd and 3rd Periods

These periods begin by the entering of gases into the channel and continue by the flow of gases through the channel and the gas port into the gas cylinder. This flow causes the increase of the pressure inside the cylinder which accelerates the piston connected with the weapon mechanism. The magnitude of the pressure is also influenced by the losses of propellant gases flowing from the gas cylinder through the gap around the piston rod into the atmosphere. The solution of this action utilizes following equations:

Main equations for the solution of the 2nd and 3rd period

Pressure of gases in the channel in the **2nd period ($t < t_{bur}$)** after the time interval ***dt***

$$p_{Cn} = p_{C(n-1)} + \frac{Z_p f \dfrac{(m_{\omega 0} - m_{\omega 1b}).dt}{t_{bur}}}{V_{Ct}} - \frac{R.T_C.G_A.dt}{V_{Ct}} \qquad (9)$$

Pressure of gases in the channel in the **3**[rd] **period (t > t$_{bur}$)** after the time interval ***dt***

- if $p_C > p_A$ gases flow through the gas port S_A from the channel into the gas cylinder

$$p_{Cn} = p_{C(n-1)} - \frac{R.T_C.G_A.dt}{V_{Ct}} \tag{10}$$

- if $p_C < p_A$ gases flow through the gas port S_A from the gas cylinder into the channel

$$p_{Cn} = p_{C(n-1)} + \frac{R.T_C.G_{AR}.dt}{V_{Ct}} \tag{11}$$

General equations for the mass flow G through any cross-section:

- for the **critical flow** for $k = 1.26$ is

$$\frac{p_2}{p_1} < \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} = 0.553$$

and the mass flow is

$$G_{CR} = \mu.S\left(\frac{2}{k-1}\right)^{\frac{k+1}{2(k-1)}} \sqrt{k\frac{p_1}{w_1}} \tag{12}$$

- for the **subcritical flow** ($p_2/p_1 > 0.553$ for $k = 1.26$)

$$G_{SCR} = \mu.S\sqrt{\left(\frac{2}{k-1}\right).\frac{p_1}{w_1}.}\left[\left(\frac{p_2}{p_1}\right)^{\frac{2}{k}} - \left(\frac{p_2}{p_1}\right)^{\frac{k+1}{k}}\right]^{0.5} \tag{13}$$

Equations of the gas energy change in the gas cylinder

- if $p_C > p_A$:

$$\frac{d}{dt}(p_A V_A) = kR(G_A T_C - G_{GA} T_A) - (k-1)p_A S_P v \tag{14}$$

- if $p_C < p_A$:

$$\frac{d}{dt}(p_A V_A) = -kRT_A(G_A + G_{GA}) - (k-1)p_A S_p v \tag{15}$$

Equations of the gas mass change in the gas cylinder:

- if $p_C > p_A$:

$$\frac{d}{dt}\left(\frac{V_A}{w_A}\right) = G_A - G_{GA} \tag{16}$$

- if $p_C < p_A$:

$$\frac{d}{dt}\left(\frac{V_A}{w_A}\right) = -(G_A + G_{GA}) \tag{17}$$

Equation of motion of the piston

$$m_r a = m_r \frac{d^2 x}{dt^2} = S_p(p_A - p_{at}) - F_f - iF_R \tag{18}$$

Equation of the instantaneous volume of the gas cylinder:

$$V_A = V_{A0} + S_{cyl} x \tag{19}$$

Equation of the piston velocity:

$$v = \frac{dx}{dt} \tag{20}$$

Formula for the pressure in the cylinder:

$$p_A = \frac{(p_A V_A)}{V_A} \tag{21}$$

Formula for the specific volume of gases in the gas cylinder:

$$w_A = \frac{V_A}{\left(\frac{V_A}{w_A}\right)}. \qquad (22)$$

The symbols used in these equations and in the flow diagram representing the procedure of the solution (Fig. 2):

a	- acceleration of the piston and components connected
f	- specific energy of propellant
F_f	- friction force
F_R	- resistance of the cartridge belt
G	- mass flow
G_A	- mass flow from the channel into the gas cylinder
G_{AR}	- mass flow from the gas cylinder into the channel (reverse flow direction)
G_{GA}	- mass flow from the gas cylinder into the atmosphere through the piston rod gap
i	- transmission ratio of the feed mechanism
k	- ratio of specific heats
m_r	- reduced mass of the piston with weapon mechanism
$m_{\omega 0}$	- initial mass of the propellant charge in the pyrocartridge
$m_{\omega 1}$	- mass of the propellant charge at the instant of the opening of the cartridge case neck
p_C	- pressure of gases in the channel
$p_{C(n-1)}$	- pressure of gases in the channel at the beginning of the time interval dt
p_{Cn}	- pressure of gases in the channel at the end of the time interval dt

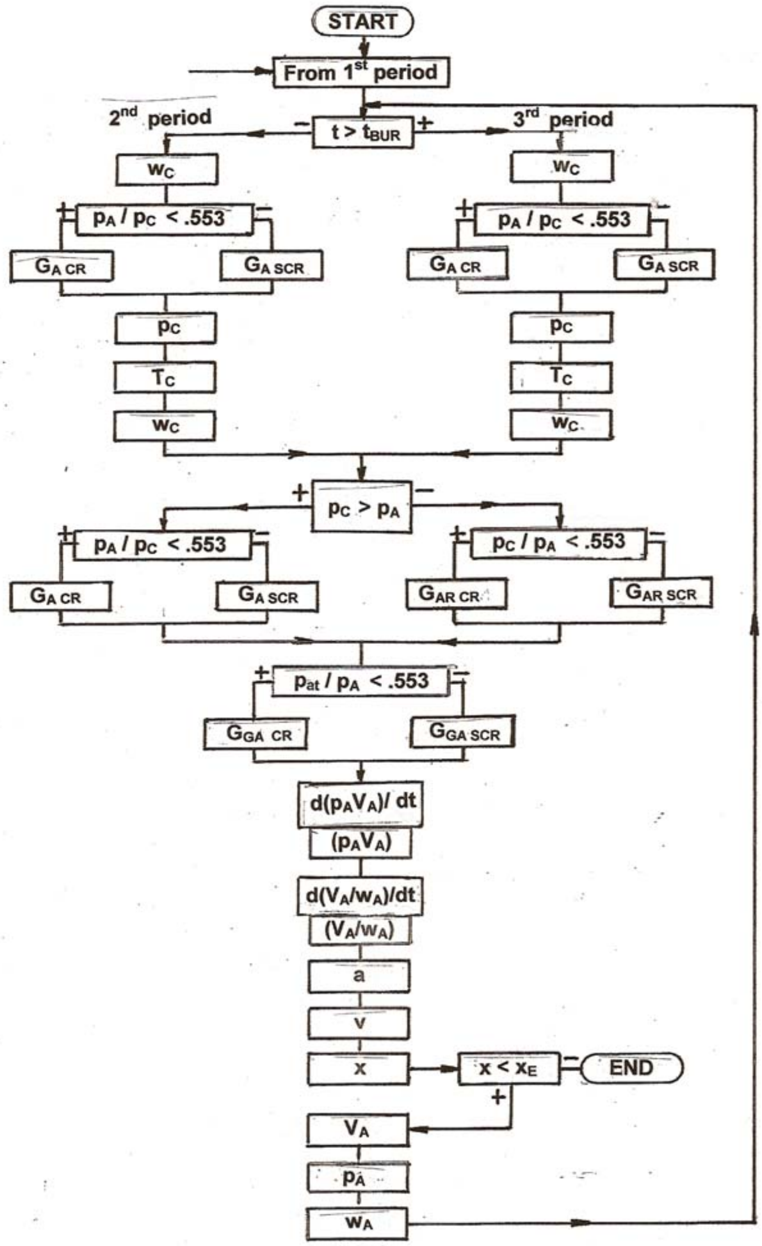

Figure 2 Flow diagram for the solution of the 2nd and the 3rd periods

p_1	- pressure in the vessel from which the gases flow
p_2	- pressure in the vessel into which the gases flow
p_A	- pressure in the gas cylinder
p_{at}	- pressure of the atmosphere
R	- gas constant
S	- cross-section of the orifice
S_A	- cross-section of the gas port connecting the channel with the gas cylinder
S_{GA}	- cross-section of the piston rod gap
S_p	- acting area of the piston
S_{cyl}	- cross-section of the cylinder
t	- time measured from the beginning of the 2nd period
t_{bur}	- time of the end of propellant charge burning in the 2nd period
dt	- time interval of the numerical solution of the system of equations
T	- temperature
T_A	- temperature of gases in the gas cylinder
T_C	- temperature of gases in the channel
V_A	- volume of the gas cylinder
V_{A0}	- initial volume of the gas cylinder
V_{cc}	- volume of the cartridge case
V_{Ct}	- total volume of the channel (including the volume of the cartridge case)
v	- velocity of the piston
w_1	- specific volume of gases in the vessel from which the gases flow
w_A	- specific volume of gases in the gas cylinder
x	- displacement of the piston
Z_p	- coefficient of pressure losses in the channel
μ	- discharge coefficient
μ_A	- discharge coefficient for gases flowing through the gas port S_A from the channel into the gas cylinder
μ_{AR}	- discharge coefficient for gases flowing through the gas port S_A from the gas cylinder into the channel (reverse flow)
μ_{GA}	- discharge coefficient for gases flowing through the piston rod gap from thegas cylinder into the atmosphere.

The solution of the mentioned system of equations gives the dependences

$$p_A = f(t),\ v = f(t),\ x = f(t).$$

To ensure correct solution it is necessary to know the magnitude of losses when flowing of gases through the channel, from the channel into the gas cylinder (and in the opposite direction) and also from the cylinder through the gap into the atmosphere.

So it is necessary to know the values of the **coefficient Z_p** and of the **flow cofficients $\mu_{A,}$, μ_{AR}** and **μ_{GA}**.

4. Comparison of Results of Calculations with Experiments

To obtain correct results of the solution it was necessary to compare the theoretical results with the results of experiments. We have obtained the results of corresponding experiments from Prof. Dipl. Eng. Jan Kusák, Ph.D. (the scientist of Prototypa-ZM, Ltd. Brno). We want to express him many thanks for this help.

The experiments have been realized directly on the pyro- recocking system of the 20mm aircraft automatic cannon ZPL-20 only it was completed by the arrangement for the measuring of the pressure of gases inside the gas cylinder. The pyrocartridges PYR-20 were tested at the **temperature –60^{o}C.** At this temperature the mean value of the maximum pressure of gases inside the cartridge case in the instant of opening of the cartridge case neck was **169.4 MPa** (measured value). This result was taken into consideration when solving the **1st period.**

For the solution of **next two periods** following characteristics of the recocking system have been used:

- mean value of the piston reduced mass $m_r = 5$ kg
- total volume of the channel $V_{Ct} = .000005047$ m^3
- cross-section of the gas port $S_A = .000028274$ m^2
- cross-section of the channel at the place of S_A is equal to S_A
- initial volume of the gas cylinder $V_{A0} = .000015974$ m^3
- magnitude of the piston rod gap is given by the radii
  - of the piston rod D_{pr} = 16f9 mm
  - of the opening for the piston rod D_{op} = 16.5H9 mm

4.1 Solution of the 1st Period

The equations (1) up to (8) have been utilized for the solution of this period. With respect to the fact, that the temperature at the measuring was –60^{o}C, it was necessary to correct characteristics of the propellant charge known for the temperature 20^{o}C [2]. These new characteristics **for –60^{o}C** are:

- specific energy of propellant $f = 983000$ J.kg^{-1}
- propellant grain unit rate of burning $u_1 = 7.02.10^{-10}$ m.s^{-1}.Pa^{-1}
- pressure impulse of propellant gases $I_k = 329000$ Pa.s
- covolume of propellant gases $\alpha = 1.015.10^{-3}$ m^3.kg^{-1}

The solution of mentioned equations with new characteristics **for –60°C** gives the results shown in the pressure diagram in Fig. 3. This diagram represents the change of the pressure in the closed cartridge case (at the end the pressure is p = 169.4 MPa) and after the opening of the cartridge case neckthe gases fill the channel and therefore the pressure decreases instantaneously to the value p_{C0} = 23.7 MPa. This is the initial pressure for the solution of **the 2nd period.**

4.2 Solution of the 2nd and the 3rd Periods

As it was mentioned the results of the solution are influenced by the losses during the flow of gases from the pyrocartridge into the gas cylinder – i.e. by the coefficient Z_p and by the flow coefficients $\mu_{A,}$, μ_{AR} and μ_{GA}. The flow coefficients can be chosen utilizing [4].

First of all the **flow coefficient μ_A** for the entrance of gases from the channel into the gas cylinder. The cross-section of the channel and the cross-section of the gas port S_A are equal (both diameters are 6 mm) and therefore it is possible to choose

the flow coefficient μ_A = 1.

For the opposite flow of gases (from the gas cylinder into the channel) according to [4] it is recommended

the flow coefficient μ_{AR} = 0.6.

The **flow coefficient for the flow of gases through the gap** between the piston rod and the sleeve in the gas cylinder can be determined according to the formula - see [4]:

$$\mu_{GA} = 1.123.(\delta + 0.04)^{0.41} - 0.29 \tag{23}$$

(the radial clearance in the gap δ is substituted in mm)

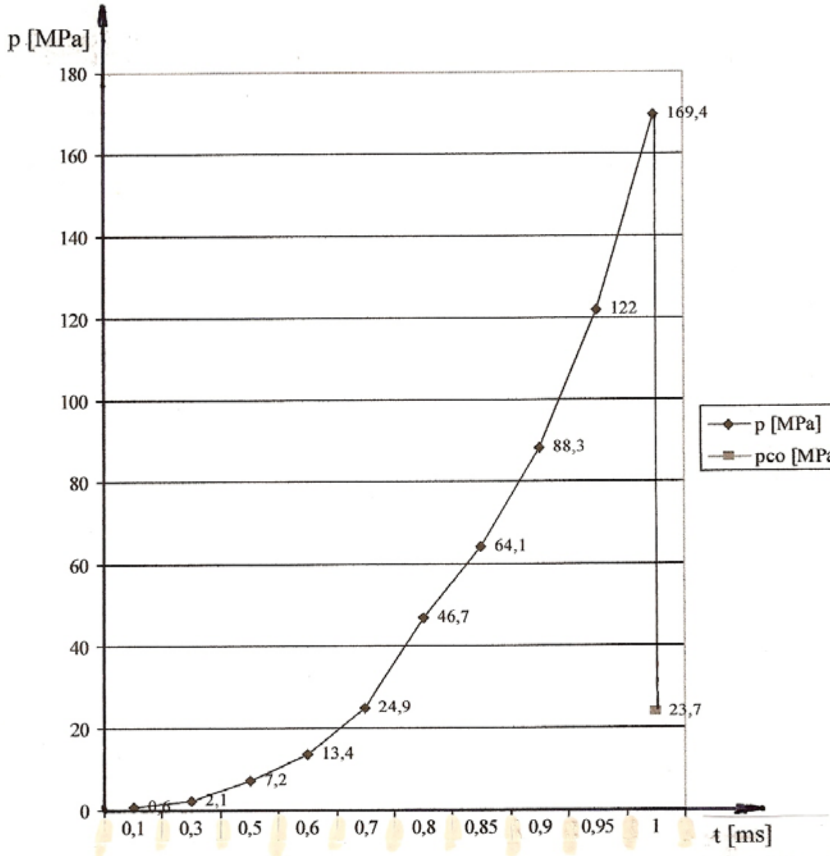

Figure 3 Pressure- time curve for the 1st period

As it was mentioned, the diameter of the piston rod is 16f9 and the diameter of the opening in the sleeve is 16.5H9. The mean dimensions of these two components give mean value of the clearance δ = 0.2795 mm and for this value the flow coefficient for the gap according to (23) is μ_{GA} = 0.4134. With respect to the fact, that the relative motion of the piston rod in the sleeve has the opposite direction than the flow of gases i.e. it decreases the flow coefficient. Therefore the value of this coefficient in calculation was chosen 80% of the value according to (23)

$$\mu_{GA} = 0.3307.$$

The cross-section of the gap determined from the mean dimensions of both corresponding components (the piston rod and the opening in the sleeve) is

$$S_{GA} = 0.000014261 \text{ m}^2 .$$

The last important value **– the coefficient of pressure losses in the channel Z_p –** has been chosen on the base of the comparison of the calculation with results of the experiment. The used value of this coefficient is

$$Z_p = 0.39 \, .$$

The total time of the **propellant burning** has been determined 3 ms. Because the time of the 1st period is 1 ms (see chapter 4.1 and Fig. 3) the time of the propellant burning in the 2nd period is

$$t_{bur} = 2 \text{ ms.}$$

Utilizing all these values and the equations (9) up to (22) the action of the system was calculated according to the flow diagram shown in Fig. 2. The results of this calculation are shown in Fig. 4. The curves represent the change of the pressure in the gas cylinder p_A with respect to the time for the second and the third periods (full line was obtained from the experiment and the dashed line has been calculated). **The comparison of the calculation with the experiment** shows good coincidence of the maximum pressure

experiment…………..30.00 MPa,
calculated……………30.14 MPa.

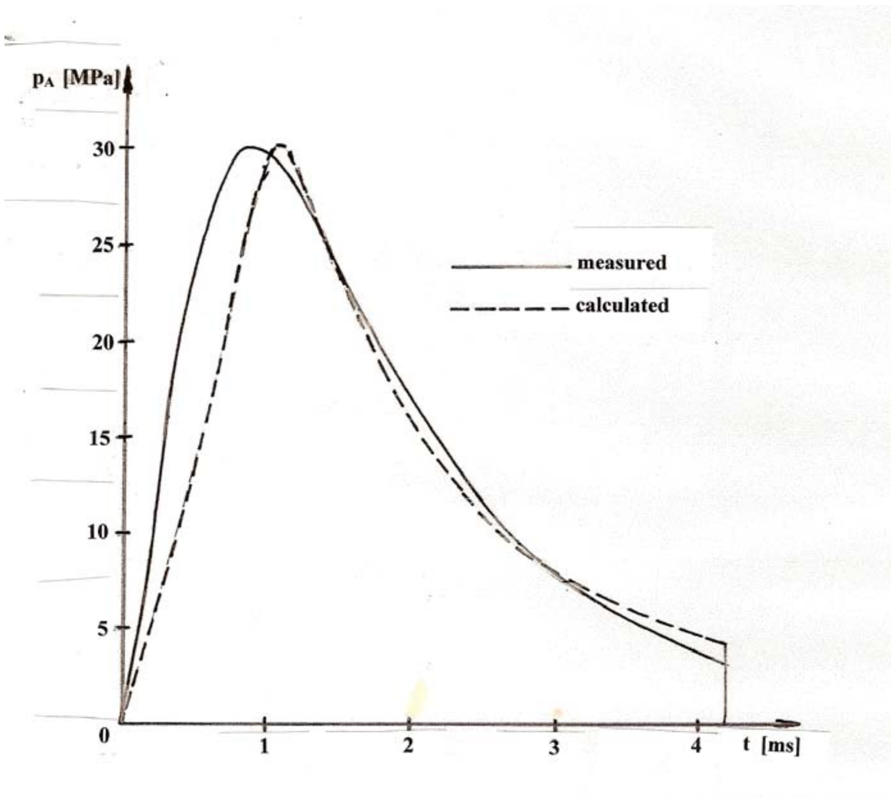

Figure 4 Comparison of measured and calculated curves $p_A = f\,(t)$

The pressure impulse represented by the area bellow corresponding curves is slightly different for the for the calculated curve in comparison with the measured curve. The values of this impulse are:

experiment…………..0.062 MPa,s
calculated……………0.055 MPa.s.

The **difference** between these two values represents **–11.26 %**. Complicated ballistic calculations permit such a difference < 20 %. Therefore this result **is acceptable**. The difference is visible mainly in the initial portion of curves. So it is possible to assume, that it is caused by the formula (9), where linear burning of the propellant is assumed. In a real case i.e. in case of the nonlinear burning the difference between the calculation and the experiment would be smaller.

5. Conclusion

The task of this paper was to find the theoretical solution of the pyro-recocking system which is used in automatic cannons and to compare it with experiments. On the base of the reached results it is possible to say, that this method can be used for preliminary calculations e.g. for the preparation of experiments.

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