PRELIMINARY ESTIMATION OF INFLUENCE OF BARREL RESISTANCE FORCE FORMULATION ON THE BALLISTIC CURVES FOR ANTI-AIRCRAFT CANNON

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Abstract: *Results of theoretical modeling of ballistic phenomena for two main approaches to formulation of barrel – projectile interaction were presented. Results of numerical simulations show serious discrepancy between results of approach applied in STANAG 4367 and classical modelling way applied in interior ballistics (described by e.g. Serebrakov or Corner). Moreover, influence of fundamental parameters describing the projectile-barrel interaction in classical approach on results of estimation of ballistic curves.*

Keywords: *barrel-projectile interaction, numerical simulations of ballistic phenomena, ballistic curves*

1. Introduction

Theoretical and experimental investigations of interior ballistics phenomena are one of the most important steps in armament systems design process. Results of these investigations provide important data on loading conditions of armament system parts and allows for estimation of investigated system ballistic capabilities. This problem was widely investigated by many authors – e.g. [1-4]. Variety of approaches applied in interior ballistics modelling provide, among others, different approaches to description of physical formulation of whole problem (lumped-parameters / distributed parameters models), propellant burning process (e.g. physical and geometrical burning law). The differences between models are also noticeable in the approach to including of barrel resistance force. In case of classical approach [1], this effect is included in, so called, start pressure and virtually increase of projectile mass. The start pressure is defined as pressure necessary to engrave the rotating band into barrel rifling (Figure 1). Projectile mass changes are possible under the assumption of linear relation between projectile energy and work made against barrel resistance. In this paper, the differences in calculation results obtained with classical approach to modeling barrel-band interaction and approach using explicit form of barrel resistance [2] were presented. The under-consideration launching system was 35 mm anti-aircraft cannon [5, 6].

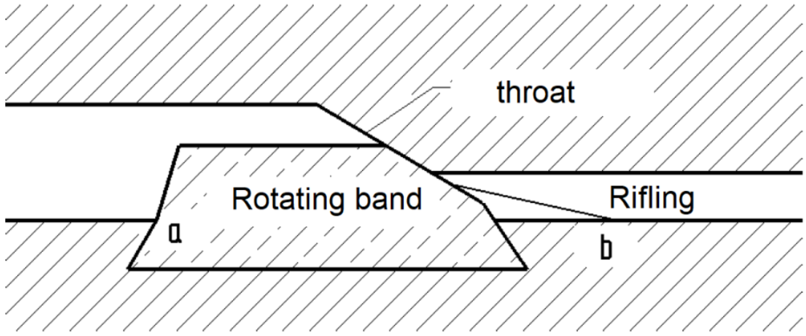


***Figure 1**. Scheme of rotating band – barrel elements configuration at the beginning of the engraving process.*

2. Model of the problem

During presented investigations, the simplified barrel launching system presented in Figure 2 was considered. The system consists of the following elements: barrel, projectile, propellant charge and ignition charge. For this system, the set of ordinary differential equations was developed, which is the mathematical representation of lumped-parameters model of the problem.

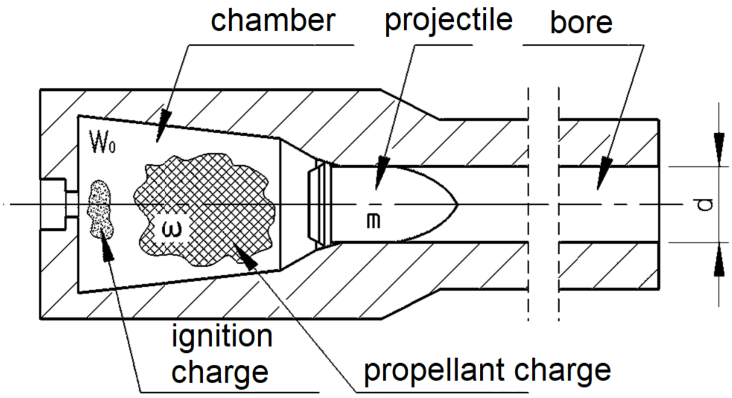


***Figure 2**. Scheme of under-consideration launching system.*

Set of considered equations includes the following relations:

- equation of projectile motion:

$$\frac{dv_p}{dt} = \frac{sp_p}{\varphi m} \tag{1}$$

in case of classical approach to model the barrel resistance; and:

$$\frac{dv_p}{dt} = \frac{s(p_p - b_R)}{m} \tag{2}$$

in case of explicit form of barrel resistance. In above equations v_p denotes projectile velocity, t is time, s means the bore cross-section area, p_p is the pressure acting on the projectile, b_R is the barrel resistance pressure, m is the projectile mass, φ is the coefficient of the 2[nd] order works (mass fictionality coefficient). This coefficient can be estimated using the following simplified relation:

$$\varphi = K + \frac{1}{3}\frac{\omega}{m} \tag{3}$$

where K is constant (for artillery systems equal to [1.05÷1.1]), ω is the propellant mass.

- fundamental pyrodynamic equation (modified equation of state) defining the propellant gases average pressure:

$$p = \frac{f\omega\psi - \theta \quad E_i}{W_0 + sl - \eta\omega\psi - \quad 1-\psi \ \frac{\omega}{\delta}} \tag{4}$$

where f denotes the propellant "force", ψ is the relative burnt mass of propellant, $\theta = \gamma - 1$, where γ means the specific heat ratio of propellant gases, W_0 is the chamber volume, l is the projectile displacement, η is the propellant gases co-volume coefficient, δ is the propellant density.

The pressure acting on the projectile base was estimated using the following formula:

$$p_p = \ p + \frac{\omega \cdot b_r}{3m} \ / \ 1 + \frac{\omega}{3m} \tag{5}$$

where b_r is the barrel resistance pressure.

- equation describing propellant gases temperature:

$$T = \frac{1}{R}\ f - \frac{\theta\ \ E_i}{\omega\psi} \quad (6)$$

where R is the propellant gases individual gas constant and ΣE_i is the total work made by propellant gases. In case of simplified (classical) approach, the total work is given by the following relation:

$$E_i = \varphi E_p \quad (7)$$

where E_p is the projectile kinetic energy.

- equation defining the gases generation rate in accordance with [9]:

$$\frac{d\psi}{dt} = G\ \ \psi\ \ p_{atm}\ \ \frac{p}{p_{atm}}^{\ n} \quad (8)$$

where ψ denotes the relative burnt mass of propellant, G is the dynamic vivacity function estimated using closed vessel tests, p_{atm} is the atmospheric pressure, n is the pressure exponent.

In case of second considered approach, the barrel resistance was included in explicit form, presented in [2], where the barrel resistance is characterized by course presented in Figure 3.

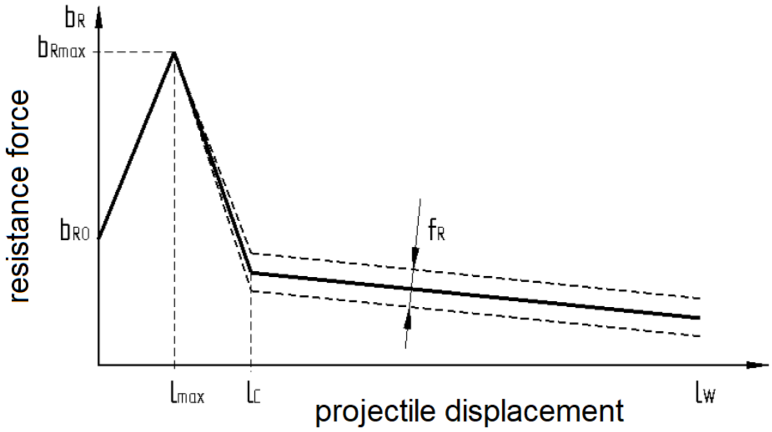


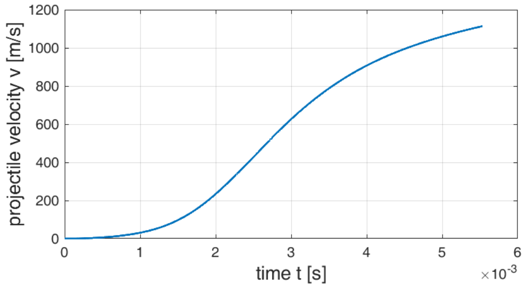
Figure 3*. Dependence of barrel resistance force as the function of projectile displacement [2].*

In both cases it was assumed, that there is no heat transfer between propellant gases and barrel.

3. Results of simulations

The comparative analysis aimed to estimate the influence of barrel resistance parameters on results of simulations of ballistic phenomena. In accordance with Eq. (3), the φ coefficient is included in the interval [0.25 0.30]. So the initial calculations were carried out using value of 1.25 and the start pressure equal to projectile disintegration pressure equal to 10 MPa. The preliminary results of simulations were presented in Figure 4. The influence of starting pressure and φ coefficient on pressure course (peak pressure) and muzzle velocity was estimated. The results were summarized in Table 1. As can be seen, the results of estimated values are in good agreement with experimental data provided by ammunition producer – i.e. peak pressure of 420 MPa and muzzle velocity of 1180 m/s measured for TP-T projectile.

As can be seen, the results for considered set of data are comparable for experimental results (for selected set the results are in very good agreement of 1 – 2 % for muzzle velocity and peak pressure). Unfortunately applied approach to model the projectile – barrel interaction force in non-physical. Moreover, as can be seen, the solution is sensitive for changes of applied parameters, which are not able to be determined without experimental data. Much better approach is the approach considered in eq. (2). The barrel resistance force can be roughly determined using modern computational approaches. In preliminary considerations presented in this paper, the set of data presented in Table 2 were applied in numerical simulations. Obtained results (which were also summarized in Table 2) show very good agreement with experimental data. In presented preliminary approach, is was assumed, that maximum resistance pressure is obtained for maximum engraving depth of rotating band. In all considered cases, the start pressure was estimated on 10 MPa. STANAG approach shows much more higher level of flexibility due to greater number of fitting coefficient. Moreover, it was also noticed, that the barrel resistance formulation softly impacts on the time of reaching the maximum pressure, which should be also taken into account in assessment of barrel resistance as the function of displacement.



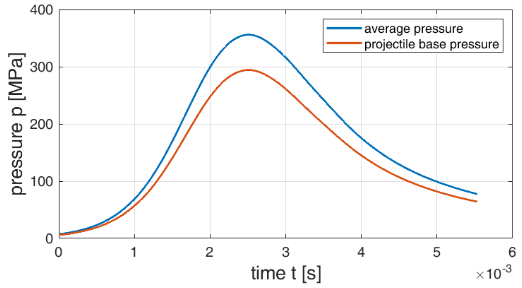


Figure 4. *Results of simulations (ballistic curves) for preliminarily applied model parameters.*

Table 1. *Set of data applied in numerical simulations for simplified approach.*

Set of data	φ coefficient	Start pressure [MPa]	Peak pressure [MPa]	Pressure relative error [%]	Muzzle velocity [m/s]	Muzzle velocity relative error [%]
1	1.25	10	356	-15.3	1141	-5.6
2	1.25	20	386	-8.2	1135	-3.8
3	1.25	30	415	-1.3	1153	-2.3
4	1.25	40	443	5.5	1169	-0.9
5	1.3	10	379	-9.8	1111	-5.9
6	1.3	20	410	-2.3	1130	-4.2
7	1.3	30	441	4.9	1147	-2.8
8	1.3	40	471	12.1	1163	-1.4

Table 2. *Set of data applied in numerical simulations for explicit resistance force approach.*

<table>
<tr><th>Set of data</th><th>Projectile displacement [mm]</th><th>Resistance pressure [MPa]</th><th>Peak pressure [MPa]</th><th>Pressure relative error [%]</th><th>Muzzle velocity [m/s]</th><th>Muzzle velocity relative error [%]</th></tr>
<tr><td rowspan="4">1</td><td>0</td><td>10</td><td rowspan="4">331</td><td rowspan="4">-21.2</td><td rowspan="4">1151</td><td rowspan="4">-2.4</td></tr>
<tr><td>12</td><td>20</td></tr>
<tr><td>140</td><td>9</td></tr>
<tr><td>3000</td><td>6</td></tr>
<tr><td rowspan="4">2</td><td>0</td><td>10</td><td rowspan="4">386</td><td rowspan="4">-8.3</td><td rowspan="4">1173</td><td rowspan="4">-0.5</td></tr>
<tr><td>12</td><td>40</td></tr>
<tr><td>140</td><td>18</td></tr>
<tr><td>3000</td><td>12</td></tr>
<tr><td rowspan="4">3</td><td>0</td><td>10</td><td rowspan="4">416</td><td rowspan="4">-0.8</td><td rowspan="4">1184</td><td rowspan="4">0.3</td></tr>
<tr><td>12</td><td>50</td></tr>
<tr><td>140</td><td>22</td></tr>
<tr><td>3000</td><td>15</td></tr>
<tr><td rowspan="4">4</td><td>0</td><td>10</td><td rowspan="4">450</td><td rowspan="4">7.23</td><td rowspan="4">1193</td><td rowspan="4">1.1</td></tr>
<tr><td>12</td><td>60</td></tr>
<tr><td>140</td><td>27</td></tr>
<tr><td>3000</td><td>18</td></tr>
</table>

4. Conclusions

As can be concluded from the results of calculations, both applied approaches (classical and according to Standardization Agreement) are close to the experimental results. It should be noted, that explicit formulation of barrel resistance in mathematical model seems to be much more physical due to including of extended character of rotating band engraving process. The STANAG model also includes greater number of fitting coefficient, which allows for better accuracy of computational results.

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