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Numerical Parametric Analysis of PW INKA Pistol

Przemysław BADUROWICZ[1*] (badurowiczp@witu.mil.pl)
Przemysław KUPIDURA[2] (przemyslaw.kupidura@wat.edu.pl)
Bartosz FIKUS[2] (bartosz.fikus@wat.edu.pl)

[*]Corresponding author
ORCID: https://orcid.org/0000-0002-6110-0035

[1]*Military Institute of Armament Technology,*
7 Prymasa Stefana Wyszyńskiego Str., Zielonka, Poland
[2]*Military University of Technology,*
2 Sylwestra Kaliskiego Str., 00-908 Warsaw, Poland

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Abstract. The paper describes the results of the parametric analysis obtained using the multibody systems. Numerical analysis allows checking different variants of the weapon without the need of building a lot of experimental models. As a part of the analysis, the impact of the slide mass, the recoil spring stiffness, the friction coefficients, the propellant gas pressure, and the force of bullet engraving the barrel on the kinematic characteristics of the weapon were checked. The extreme values of the slide mass and the recoil spring stiffness were selected, after crossing them, the correct operation of the weapon would not be possible. The operation of the pistol was checked for its multiple variants, taking into account its lubrication, lack of lubrication, and lack of friction by appropriate selection of the friction coefficients. The propellant gas pressure variants were selected to reflect the pressure in the barrel during shoot using ammunition manufactured according to different standards and of different quality. The models, taking into account the force of bullet engraving the barrel and those ignoring such force, were developed to check their impact on the kinematic characteristics of a short recoil operated weapon.
Keywords: mechanics, weapon design, parametric analysis, multibody systems, short recoil operation

1. INTRODUCTION

Parametric analysis allows us to prove the correctness of the weapon operation cycle and it is a basis for optimising the weapon operational characteristics, so it is one of the crucial elements of design process.

The optimising kinematic characteristics process of the gas-operated weapon is presented in the papers [1-4]. Authors describe theoretical and experimental investigations of gas hole diameter, gas control hole diameter, initial volume of gas chamber, and gas piston diameter influence on ballistic and kinematic parameters. The paper [5] contains some results of theoretical tests on the influence on ballistic and kinematic characteristics of selected action parameters of the gas-operated weapon, such as: slide weight, recoil springs stiffness, distance from the gas piston front surface in the initial position to the axis of the gas slots. In the paper [6], the authors tested numerically the influence of slide inertial properties on kinetic characteristics of the gas-operated assault rifle. Influence of recoil springs stiffness on slide velocity of gas-operated weapon was shown in the works [7-8]. The paper [9] presents the results of simulation research at 5.56 mm gas-operated weapon jump and recoil. Impact of propellant gas pressure on stress distribution on the parts of the weapon was described in article [10].

Parametric investigation of kinematic characteristics, contained in this paper, was carried out using MBS (multibody systems). The MBS numerical model was developed as it was described in the papers [11, 12]. A similar sensitivity analysis was carried out in papers [6, 7], where the author performed investigations using the MBS and also the MSC Adams software. So, the same mathematical model as presented in this paper was used.

2. MBS MATHEMATICAL MODEL

In the MBS, the equations of motion can be formulated in general coordinates, most often using the Lagrange equations [13]:

$$\frac{d}{dt}\left(L_{\dot{q}}^{T}\right) - L_{q}^{T} + \Phi_{q}^{T}\lambda = Q \tag{1}$$

where:

L – Lagrangian function (L=T-V, T – kinetic energy, V – potential energy),

ϕ – represents the constraint conditions,

λ – Lagrange multiplier,

$Q = Q(q, \dot{q}, t)$ – generalised forces.

Another possible formulation of the problem is to use the Newton–Euler equations [13]:

$$\begin{bmatrix} mI & 0 \\ 0 & J_c \end{bmatrix} \begin{bmatrix} \dot{V}_c \\ \dot{\omega} \end{bmatrix} + \begin{bmatrix} 0 \\ \tilde{\omega} J_c \omega \end{bmatrix} = \begin{bmatrix} F \\ N_c \end{bmatrix} \tag{2}$$

where:

m – mass of the body,

I – identity matrix;

J_c – moment of inertia about the centre of mass,

$\dot{V}_c$ – acceleration of the centre of mass,

ω – angular velocity of the body,

$\dot{\omega}$ – angular acceleration of the body,

F – total force acting on the centre of mass,

N_c – total torque acting about the centre of mass,

~ – skew-symmetric cross-product matrices.

Contact forces in the numerical model are based on the following formula [14]:

$$F_{cont} = \begin{cases} 0 & \text{for } x > x_0 \\ k(x_0 - x)^e - c_{max}\dot{x} * STEP(x, x_0 - d, 1, x_0, 0) & \text{for } x \le x_0 \end{cases} \tag{3}$$

where:

F_{cont} – normal contact force,

k – contact stiffness,

x_0 – displacement followed by contact of the members,

x – relative displacement of contact surfaces,

e – exponent of the force deformation characteristic,

c_{max} – maximum damping coefficient,

$\dot{x}$ – relative velocity of contact surfaces,

d – boundary penetration with full damping.

3. PARAMETRIC ANALYSIS

3.1. Impact of the slide mass on the kinematic characteristics

Results of investigation for different slide masses are shown in Table 1 and in Fig. 1. The limit values of the slide mass were assumed to reach maximum slide recoil velocity aprox. 10 m/s (55% lighter than nominal) and velocity of slide impact to buffer (v_{sb}) equals 0.00 m/s (137% heavier than nominal). After crossing the last mass value, the slide does not reach the rearmost position what causes malfunction in weapon operation.

The lower mass of the slide results in a higher velocity in the rearward (v_{rmax}) and lower velocity during forward (v_{fmax}) movements. The reverse relationship applies to the time of rear (t_r) and forward (t_f) movements, however, differences (comparing to nominal variant) are aprox. twice smaller during the forward motion.

The velocity of nominal mass slide impact to buffer (v_{sb}), amounting to 2.99 m/s proves that the slide has an excess of energy, which is necessary to ensure the weapon operation reliability in difficult environmental conditions. On the other side, such a value is acceptable regarding the weapon jump.

Table 1. Results of numerical investigation for different slide mass variants

Slide mass changing [%]	Slide mass [g]	v_{rmax} [m/s]	Δv_{rmax} [%]	t_r [ms]	Δt_r [%]	v_{sb} [m/s]	Δv_{sb} [%]	v_{fmax} [m/s]	Δv_{fmax} [%]	t_f [ms]	Δt_f [%]
-55	153.05	10.18	+57.83	5.9	-50.42	7.46	+149.50	3.43	+26.57	22.9	-19.37
-30	238.07	8.14	+26.20	9.3	-21.85	3.96	+32.44	2.96	+9.23	25.2	-11.27
-15	289.09	7.21	+11.78	10.5	-11.76	3.49	+16.72	2.78	+2.58	27.2	-4.23
0 (nominal)	340.10	6.45	0.00	11.9	0.00	2.99	0.00	2.71	0.00	28.4	0.00
+15	391.12	5.83	-9.61	13.0	+9.24	2.63	-12.04	2.69	-0.74	29.5	+3.87
+70	578.17	4.33	-32.87	19.2	+61.34	1.39	-53.51	2.38	-12.18	34.1	+20.07
+137	806.04	3.30	-48.84	32.6	+173.95	0.00	-100.00	2.03	-25.09	39.1	+37.68

where:
v_{rmax} – maximum velocity of slide recoil, Δv_{rmax} – change in maximum velocity of slide recoil relative to nominal, t_r – time of slide recoil, Δt_r – change in time of slide recoil relative to nominal, v_{sb} – velocity of slide impact to buffer, Δv_{sb} – change in velocity of slide impact to buffer relative to nominal, v_{fmax} – maximum velocity of slide forward motion, Δv_{fmax} – change in maximum velocity of slide forward motion relative to nominal, t_f – time of slide forward motion, Δt_f – change in time of slide forward motion relative to nominal.

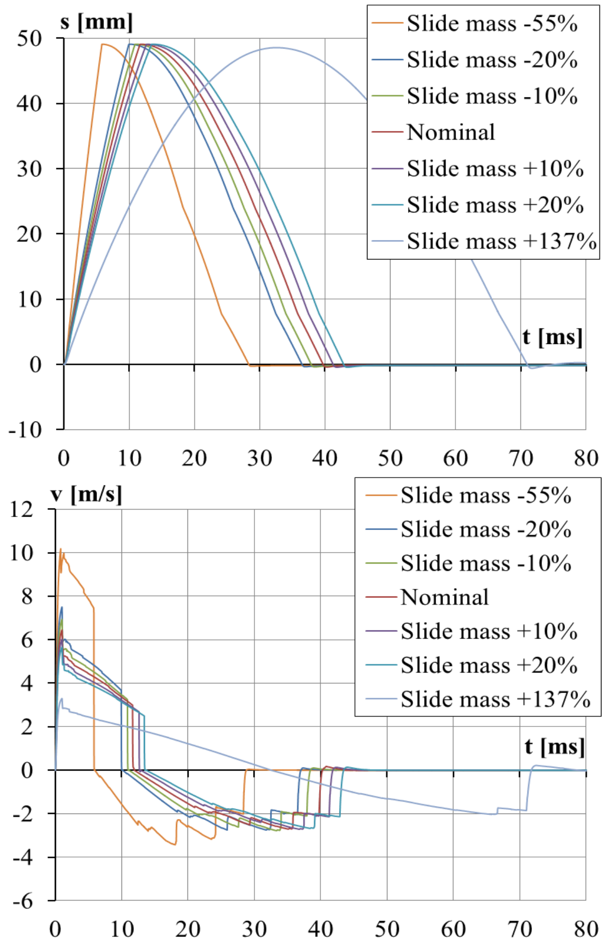

Fig. 1. Kinematic characteristics of the slide for different slide mass variants: on the left – displacement versus time, on the right - velocity versus time

3.2. Impact of the recoil spring stiffness on the kinematic characteristics

Results of investigation for different recoil spring stiffness are shown in Fig. 2 and in Table 2. Reducing spring stiffness more than 60% causes that the slide would not have enough energy to feed the next cartridge. The velocity of slide impact to buffer (v_{sb}) is 0.00 m/s for the highest assumed recoil spring stiffness (62% higher than nominal), but the slide reaches the rearmost position. After crossing this value of recoil spring stiffness, the slide does not reach the rearmost position.

The recoil spring stiffness has a small effect on the maximum velocity of slide recoil (v_{rmax}), however, noticeable differences of the velocity of slide impact to buffer (v_{sb}) and maximum velocity of the slide forward motion (v_{fmax}) can be observed. The time of slide recoil (t_r) is longer and the time of slide forward motion (t_f) is shorter for higher spring stiffness. The differences in the time of slide forward motion (t_f) are greater than in the time of slide recoil (t_r).

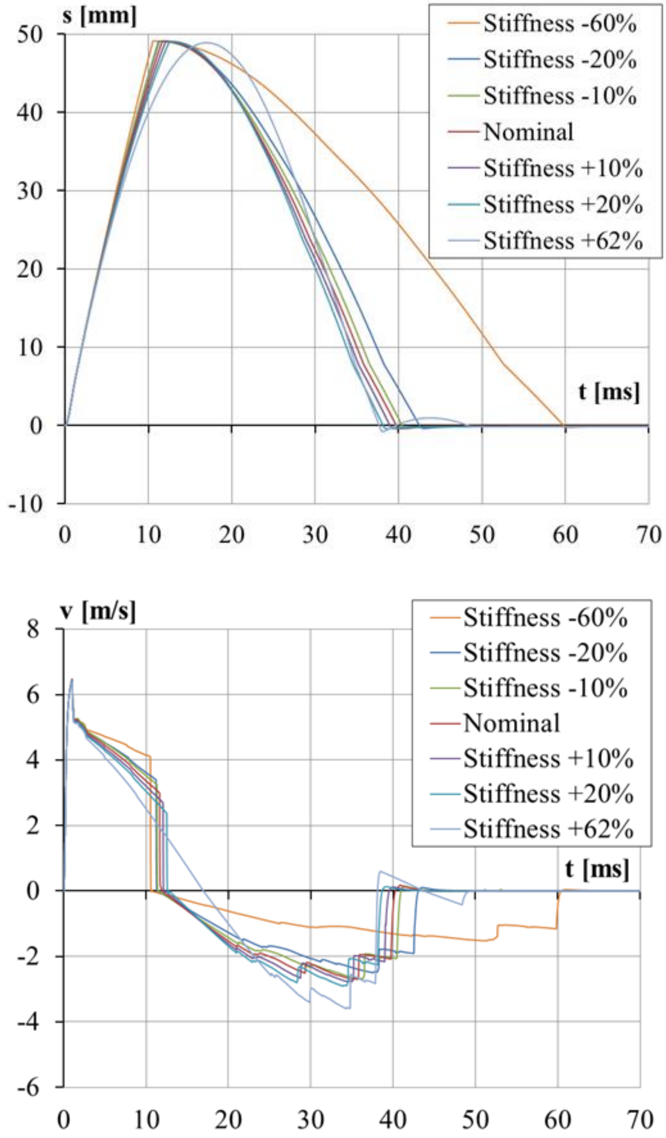

Fig. 2. Kinematic characteristics of the slide for different spring stiffness variants: on the left – displacement versus time, on the right - velocity versus time

Table 2. Results of numerical investigation for different recoil spring stiffness

Recoil spring stiffness changing [%]	Recoil spring stiffness [N/mm]	v_{rmax} [m/s]	Δv_{rmax} [%]	t_r [ms]	Δt_r [%]	v_{sb} [m/s]	Δv_{sb} [%]	v_{fmax} [m/s]	Δv_{fmax} [%]	t_f [ms]	Δt_f [%]
-60	0,410	6.48	+0.47	10.6	-10.92	4.11	+37.46	1.52	-43.91	49.8	+75.35
-40	0,614	6.47	+0.31	11.1	-6.72	3.72	+24.41	2.15	-20.66	36.6	+28.87
-20	0,819	6.46	+0.16	11.3	-5.04	3.4	+13.71	2.5	-7.75	31.8	+11.97
0 (nominal)	1,024	6.45	0.00	11.9	0.00	2.99	0.00	2.71	0.00	28.4	0.00
+20	1,229	6.44	-0.16	12.5	+5.04	2.37	-20.74	2.91	+7.38	26.2	-7.75
+40	1,434	6.43	-0.31	12.6	+5.88	2.23	-25.42	3.15	+16.24	23.7	-16.55
+62	1,659	6.41	-0.62	16.9	+42.02	0.00	-100.00	3.60	+32.84	21.2	-25.35

3.3. Impact of friction coefficients on the kinematic characteristics

Numerical investigation was performed for three variants of friction coefficients (Table 3). The nominal variant assumes that the weapon is lubricated such as during the experimental tests used to validate the numerical model, which was described in the paper [12]. Other variants are: dry weapon (not lubricated) and the frictionless model.

Table 3. Friction coefficient variants used in analysis [15-17]

Type of friction materials	0 (nominal, lubricated weapon)		1 (non-lubricated weapon)		2 (no friction)	
	μ_s	μ_d	μ_s	μ_d	μ_s	μ_d
Steel – steel	0.15	0.08	0.20	0.15	0	0
Steel - brass	0.11	0.06	0.19	0.15	0	0
Brass – brass	0.10	0.05	0.30	0.12	0	0
Steel – Itamid	0.15	0.10	0.35	0.20	0	0
Brass – Itamid	0.12	0.08	0.25	0.15	0	0

where: μ_s – static friction coefficient, μ_d – dynamic friction coefficient.

Results of investigation were shown in Fig. 3 and in Table 4. Higher friction coefficients result in lower slide velocity and higher movement times.

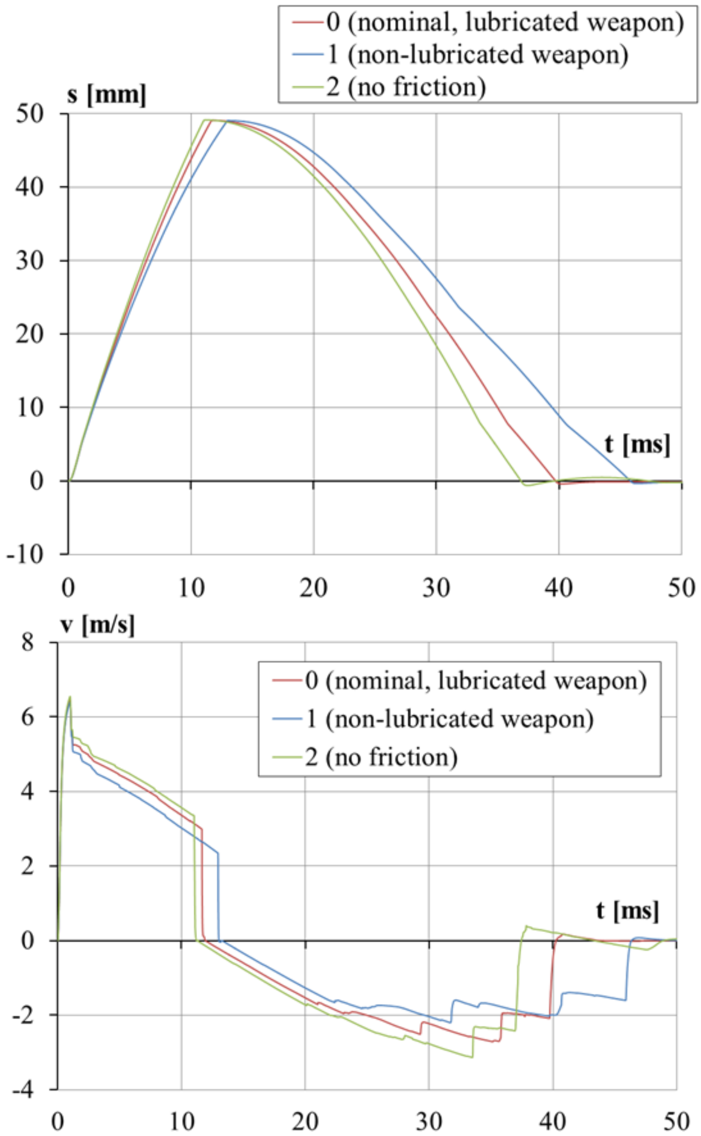

Fig. 3. Kinematic characteristics of the slide for different friction coefficients: on the left – displacement versus time, on the right - velocity versus time

Table 4. Results of numerical investigation for different friction coefficients

Friction coefficients variant	v_{rmax} [m/s]	Δv_{rmax} [%]	t_r [ms]	Δt_r [%]	v_{sb} [m/s]	Δv_{sb} [%]	v_{fmax} [m/s]	Δv_{fmax} [%]	t_f [ms]	Δt_f [%]
0 (nominal. lubricated weapon)	6.45	0.00	11.9	0.00	2.99	0.00	2.71	0.00	28.4	0.00
1 (non-lubricated weapon)	6.40	-0.78	13.0	+9.24	2.33	-22.07	2.20	-18.82	33.3	+17.25
2 (no friction)	6.55	+1.55	11.2	-5.88	3.35	+12.04	3.13	+15.50	26.3	-7.39

3.4. Impact of the propellant gas pressure on kinematic characteristics

Numerical investigation was carried out for six variants of propellant gas pressure (Fig. 4). The adopted values higher than the nominal one correspond to the maximum gas pressure (p_{max}) according to the following standards:

- C.I.P. – 235 MPa (+5%),
- SAAMI – 241 MPa (+10%) for standard ammunition and 265 MPa (+20%) for higher pressure ammunition +P,
- NATO – 252 MPa (+15%).

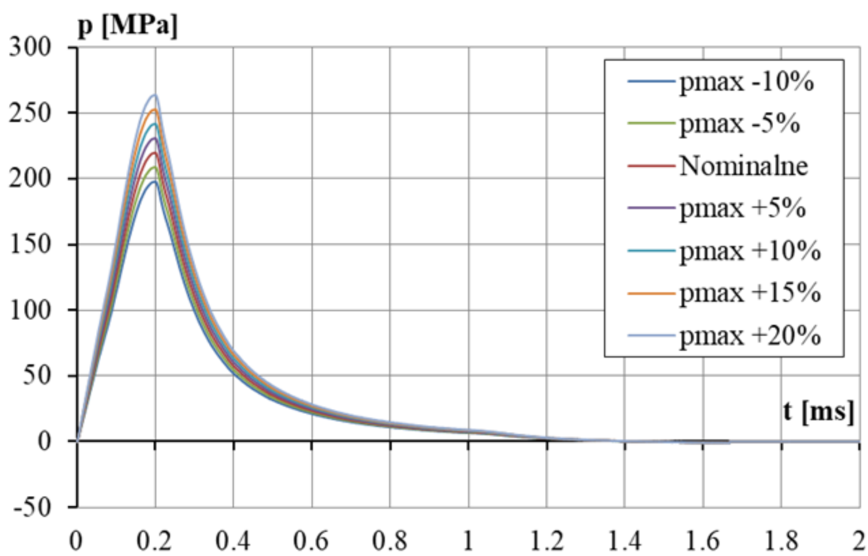

Fig. 4. Propellant gas pressure variants adapted to numerical investigation

Results of investigation for different propellant gas pressures were shown in Fig. 5 and in Table 5. The change of the gas pressure significantly influences on the kinematic characteristics of the weapon during the slide rearward movement.

On the other hand, during the forward movement, impact of gas pressure is negligible. This is because the pressure occurs only during the rearward movement of the slide, and the bumper has a high damping and no rebound occurs.

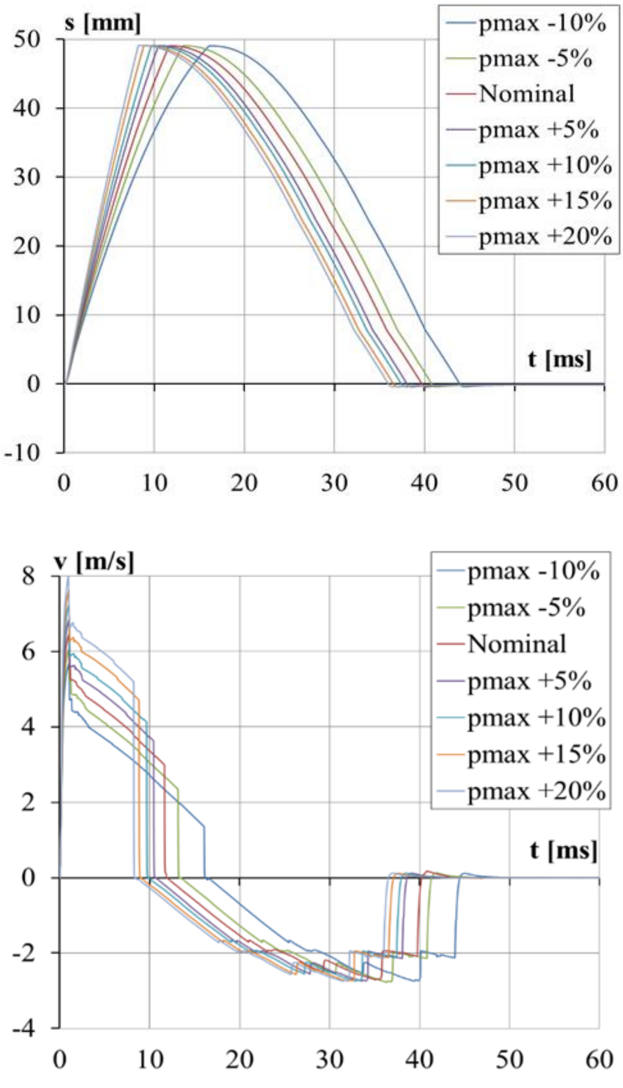

Fig. 5. Kinematic characteristics of the slide for different propellant gas pressure: on the left – displacement versus time, on the right - velocity versus time

Table 5. Results of numerical investigation for different propellant gas pressure

Propellant gas pressure changing [%]	Propellant gas pressure [MPa]	v_{rmax} [m/s]	Δv_{rmax} [%]	t_r [ms]	Δt_r [%]	v_{sb} [m/s]	Δv_{sb} [%]	v_{fmax} [m/s]	Δv_{fmax} [%]	t_f [ms]	Δt_f [%]
-10	198	5.66	-12.25	16.2	+36.13	1.36	-54.52	2.74	+1.11	28.3	-0.35
-5	209	6.04	-6.36	13.3	+11.76	2.34	-21.74	2.77	+2.21	28.0	-1.41
0 (nominal)	220	6.45	0.00	11.9	0.00	2.99	0.00	2.71	0.00	28.4	0.00
+5	231	6.84	+6.05	10.6	-10.92	3.63	+21.40	2.74	+1.11	28.0	-1.41
+10	242	7.24	+12.25	9.8	-17.65	4.13	+38.13	2.74	+1.11	28.2	-0.70
+15	253	7.63	+18.29	8.9	-25.21	4.72	+57.86	2.75	+1.48	28.2	-0.70
+20	264	8.01	+24.19	8.4	-29.41	5.20	+73.91	2.75	+1.48	28.2	-0.70

3.5. Impact of force of bullet engraving the barrel on the kinematic characteristics

The force of the bullet engraving the barrel bore rifling bore (F_{bb}) was adopted from the works [18, 19] (Fig. 6). The authors of paper [18] have obtained this force using FEM (Finite Element Method) and the authors of [19] using experimental and analytical methods.

Results of investigation for force of the bullet engraving the barrel bore (F_{bb}) were shown in Fig. 7 and in Table 6. The difference of investigation results between estimation No. 1 and 2 is small. Large differences are observed for the calculations where the force of bullet engraving the barrel bore is not taken into account, which show how important is this force in that case.

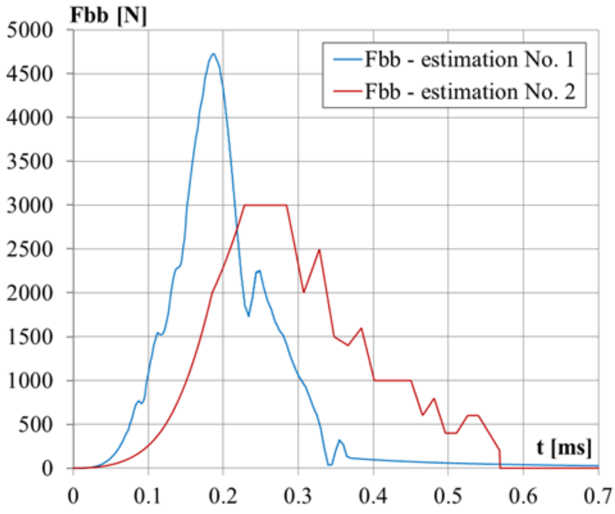

Fig. 6. Force of bullet engraving the barrel rifling bore (F_{bb}) versus time for 9x19 mm Parabellum projectile: estimation No. 1 – in accordance with [18]; estimation No. 2 – [19]

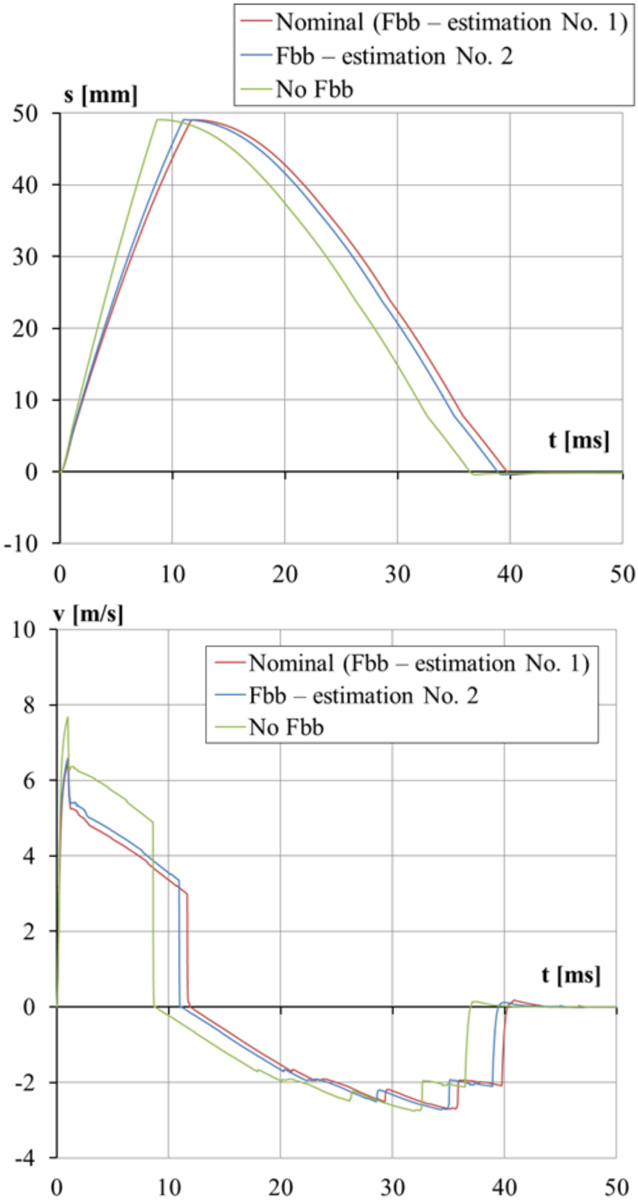

Fig. 7. Kinematic characteristics of the slide for different forces of bullet engraving the barrel: on the left – displacement versus time, on the right - velocity versus time

Table 6. Results of numerical investigation for different forces of bullet engraving the barrel

No. of estimation	v_{rmax} [m/s]	Δv_{rmax} [%]	t_r [ms]	Δt_r [%]	v_{sb} [m/s]	Δv_{sb} [%]	v_{fmax} [m/s]	Δv_{fmax} [%]	t_f [ms]	Δt_f [%]
Nominal (No. 1)	6.45	0.00	11.9	0.00	2.99	0.00	2.71	0.00	28.4	0.00
No. 2	6.59	+2.17	11.0	-7.56	3.35	+12.04	2.72	+0.37	28.4	0.00
No F_{bb}	7.68	+19.07	8.7	-26.89	4.88	+63.21	2.76	+1.85	28.3	-0.35

4. CONCLUSIONS

After carrying out the parametric analysis, the following conclusions can be drawn:

1) This kind of analysis allows us to check the correctness of weapon operation without necessity to build multiple experimental models and it is a basis for optimisation. It proves that the mass of the slide and the recoil spring stiffness have been selected correctly.
2) Analysis of impact of friction coefficients on the kinematic characteristics shows correctness of working weapon when it is lubricated or dry.
3) Investigation of impact of the propellant gas pressure on kinematic characteristics proves propriety of design assumption. The weapon works well for the lowest and the highest pressure ammunition.
4) Analysis of impact of the force of bullet engraving the barrel rifling bore shows that taking this force into account is necessary to obtain correct results of calculations for short recoil operated weapon.
5) There is a qualitative similarity of the results obtained in the works with sensitivity analysis [6-8] comparing to the above results which authenticate the presented analyses.

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Numeryczna analiza parametryczna pistoletu PW INKA

Przemysław BADUROWICZ[1], Przemysław KUPIDURA[2],
Bartosz FIKUS[2]

[1] *Wojskowy Instytut Techniczny Uzbrojenia*
ul. Prymasa Stefana Wyszyńskiego 7, Zielonka,
[2] *Wojskowa Akademia Techniczna*
ul. gen. Sylwestra Kaliskiego 2,, 00-908 Warszawa

Streszczenie. W artykule opisano wyniki analizy parametrycznej wykonanej z użyciem metody układów wieloczłonowych. Analiza numeryczna pozwala na sprawdzenie różnych wariantów broni bez potrzeby budowania wielu modeli doświadczalnych. W ramach analizy sprawdzono wpływ masy zamka, sztywności sprężyny powrotnej, współczynników tarcia, ciśnienia gazów prochowych oraz oporów przetłaczania pocisku w lufie na charakterystyki kinematyczne broni. Dobrano skrajne wartości masy zamka oraz sztywności sprężyny powrotnej, po przekroczeniu, których poprawna praca automatyki broni nie była by możliwa. Sprawdzono pracę pistoletu dla różnych jego wariantów, uwzględniając jego nasmarowanie, brak smarowania oraz brak tarcia poprzez odpowiedni dobór współczynników tarcia. Warianty ciśnienia gazów prochowych dobrano tak, aby odwzorować ciśnienia w lufie panujące podczas strzelań z użyciem amunicji wyprodukowanej według różnych standardów oraz różnej jakości. Opracowano modele uwzględniające opory przetłaczania pocisku przez przewód lufy oraz pomijający te siły, aby sprawdzić jaki wpływ mają one na charakterystyki kinematyczne broni działającej na zasadzie krótkiego odrzutu lufy.
Słowa kluczowe: mechanika, konstrukcja broni, analiza parametryczna, metoda układów wieloczłonowych, krótki odrzut lufy.