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INNERTIAL FORCES WITH AN IMPACT ON THE PARTS OF AN ARTILLERY SHELL WHEN FIRED

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Abstract: *The present work studies the inertial forces arising during the movement of an artillery projectile when it is fired. It describes the effect of these forces on the details of an independent power source that is part of a defence product. In the course of the study, chemical sources of electricity of a new type have been constructed. They are used to study the effect of their mass on the performance of the final product.*

Keywords: inertial forces, chemical source of power supply,

1. Introduction

Artillery shells are composed of details which are affected by forces with different directions when fired. Power sources are details subjected to various dynamic loads, some of which are inertial forces when a shell is fired. Chemical power sources of a new type have been developed and constructed with a smaller mass than the ones used so far. It is suggested that the mass of this detail affects the magnitude of the forces acting on the entire projectile. Inertial forces are presented, which in the direction of their action can be considered as negative forces with respect to the direction of movement of the projectile.

2. Inertial forces arising during the movement of an artillery shell along the cannon bore

During the movement of the shell along the bore of the artillery cannon, usually the following inertial forces act on its details:

- **Axial inertial force *S***, caused by the acceleration of the forward motion of the shell;
- **Centrifugal inertial force C**, caused by the rotation of the shell around its axis;
- **Tangential inertial force T**, arising from the tangential acceleration of the shell upon increasing its angular velocity;
- **Coriolis inertial force K**.

2.1. Axial inertial force *S*

The acceleration of the forward motion of the fired shell J acts on a detail with mass m with an axial inertial force S, equal to:

$$\boldsymbol{S = m\,J} \qquad (1)$$

and directed opposite to the direction of movement of the projectile.

The acceleration J and the pressure P of the gunpowder gases on the bottom of the shell during its movement along the cannon bore can be expressed by the following dependence:

$$J=\left(\frac{PF}{\varphi\,G}\right)g \qquad (2)$$

where F is the cross-sectional area of the bore; G – the mass of the shell; φ – a fictitious coefficient that takes into account the secondary operation of the gunpowder gases when a shell is fired; g – the acceleration of the force of gravity.

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The cross-sectional area of the cannon bore, taking into account the area of the grooves, is determined by the formula

$$F= 0,8\,D \tag{3}$$

where D is the calibre of the shell.

The fictitious coefficient φ is approximately defined by the formula

$$\varphi = k + 1/3\ w/G \tag{4}$$

where k is a coefficient equal to1.03 for cannons;

w – the mass of the gunpowder charge.

If in equation (1) instead of J we use its value from equation (2), the result will be

$$S = (P\ F/\varphi\ G)\ p \tag{5}$$

where $p=mg$; m – the mass of the detail.

Formula (5) shows that the inertial force S is proportional to the pressure of the gunpowder gases P and the mass of the detail. The maximum value of force S will be at the moment of maximum pressure of the gunpowder gases P_{max}:

$$S_{\max}=\frac{P_{\max}F}{\varphi G}p=k_1p \tag{6}$$

The coefficient k_1, determined by the formula

$$k_1=\frac{P_{\max}F}{\varphi G}, \tag{7}$$

shows how many times the maximum value of the axial force of inertia, acting on the detail when a shell is shot, is greater than its mass. The numerical values of the coefficient k_1 for different cannons are taken from a table. For a 122 - mm shot the values are shown in Table 1.

Table 1Measured Value of the coefficient k_1 for 122-mm calibre artillery systems

Type of shot	**Mass of a fuze-equipped projectile G, kg**	**Approximate mass of the charge w, kg**	**Pressure of the gunpowder gases, MPa**	**Initial speed V_0, m/s**	k_1
122-mm shot	21.760	2.100	235	515	11774

After the projectile takes off from the cannon chase, the pressure of the gunpowder gases at the bottom of the projectile drops rapidly. In this period, the axial acceleration of the projectile and the axial force of inertia acting on the details of the projectile rapidly decrease.

2.2. Centrifugal inertial force

In the rotary motion of the projectile, a centrifugal inertial force acts on its parts and is determined by the formula

$$C=m\rho\omega^2, \tag{8}$$

where m is the mass of the part; ρ – the eccentricity of the centre of gravity of the detail relative to the axis of rotation of the projectile; ω – the angular velocity of the projectile.

The following relationship exists between the angular and linear velocity V of the projectile:

$$w=\frac{2\Pi}{\eta D}V, \tag{9}$$

where η is the curvature of the cannon grooves (length of the course of the groove, expressed in calibres D).

The projectile will have a maximum angular velocity when $V = V_0$, i.e.

$$w_{\max}=\frac{2\pi}{\eta D}V_0. \tag{10}$$

If the angular velocity ω in formula (8) is substituted with its value from (9), the result will be:

$$C=\rho\left(\frac{2\pi}{\eta D}\right)^2\frac{v^2}{g}P. \tag{11}$$

The centrifugal force is maximum when the projectile is shot from the cannon bore at $V=V_0$:

$$C_{\max}=\rho\left(\frac{2\pi}{\eta D}\right)^2\frac{V_0^2}{g}P. \tag{12}$$

A centrifugal coefficient k_2 is introduced

$$k_2=\frac{w_{\max}^2}{g}=\left(\frac{2\pi}{\eta D}\right)^2\frac{V_0^2}{g} \tag{13}$$

And then C_{max} is:

$$C_{max} = \kappa_2\rho\ P \tag{14}$$

The centrifugal coefficient k_2 is measured in 1/mm. Its numerical value shows how many times the centrifugal force, acting on the detail when the shell leaves the muzzle, is greater than its mass at an eccentricity of

ρ=1 mm. The values of the centrifugal coefficient k_2 are taken from a table, and in this case they are presented in Table 2.

Table 2 Value of the coefficient k_2 for a 122-mm calibre artillery shot

Type of the shot	Initial speed V_0, m/s	Curvature of the grooves η	Centrifugal coefficient k_2, 1/mm
122-mm shot	515	20	179

2.3. Tangential inertial force

During the movement of the shell along the cannon bore its angular velocity constantly increases. The acceleration of the rotational motion of the shell causes the emergence of a tangential inertial force T equal to

$$T = m\rho\frac{dw}{dt}. \tag{15}$$

Formula (15) may be presented in one more way as the tangential inertial force T and the axial inertial force S are proportional to the acceleration during the shell motion along the cannon bore. Force T may be valued through a comparison with force S:

$$T/S = 2\pi\rho/\eta D \tag{16}$$

The curvature of the grooves η is between $20 \leq \eta \leq 35$, and the eccentricity ρ is always significantly smaller than the radius of the shell $D/2$. If we set η_{min} and $\rho_{\max}$ in expression (18), we will receive its maximum value. During a shot, the tangential force T comprises 16 % of the axial force S. Actually, $\rho << D/2$ and the ratio T/S is significantly smaller than 0,16 [1].

The direction of the tangential force T is along the tangent of the circumference formed in the rotation of the centre of gravity in a direction that is opposite to the direction of rotation of the shell.

2.4. Coriolis inertial force

The inertial forces S, C and T described above act on the details during the shell motion along the cannon bore, regardless of whether the part is moving or is stationary to the projectile. When there is movement of a detail in relation to the projectile, another force arises – a Coriolis inertial force K. This force is induced by the Coriolis acceleration of the detail.

In this formula

$$K = 2\frac{\omega VP}{g} \cdot \sin\alpha.$$

V is the velocity of movement of the detail in regard to the shell; α – the angle between the direction of motion of the detail and the axis of rotation of the shell.

Apparently, if the detail is stationary in regard to the projectile ($V = 0$), the Coriolis force is equal to zero. When the detail moves along the shell axis or along an axis parallel to it (when $\alpha = 0$), force K is also equal to zero.

3. Effect of the mass on the inertial forces

The designed power source is a new type of electrochemical system. The measurements made show that, with the same dimensions and technical parameters, the new power source has a lower mass m, kg. The new power source (PS) is compared to the thermal battery (TB) previously supplied and used in the shell. The measured values of the masses of the two details are shown in Table 3.

For better visualisation of the graphical representation of the values obtained for the masses of the test samples, they are arranged in batches in ascending order in column 1 for TB and column 4 for PS. The power sources used in the study have been randomly selected and the ordering in ascending order in the batch practically does not affect the results obtained and sought by the study.

Table 3 Comparison of the masses of a thermal battery and the newly-developed power source

Power source №	Mass m, kg	Power source №	Mass m, kg
1	2	3	4
TB – 1	0.1554	**PS – 1**	0.0228
TB – 2	0.1559	**PS – 2**	0.0262
TB – 3	0.1562	**PS – 3**	0.0298
TB – 4	0.1572	**PS – 4**	0.0302
TB – 5	0.1587	**PS – 5**	0.0321
Average TB mass:	0.1567	**Average PS mass:**	0.0282

The data measured and presented in Table 3 (column 4) show a decrease in the average mass of the new power source by about 5 times compared to the previously used TB (column 2).

A prediction is made of the effect of this mass change on the inertial forces acting on the shot projectile details. The coefficients and dependencies outlined in point 2 are used to study this effect.

3.1. Effect of the mass of the power source on the axial inertial force

Point 2.1 of this report discusses the dependencies between the mass of the detail and the axial inertial forces which affect it. The coefficient k_1 in Table 1 refers to a 122-mm shot. A stationary detail of the projectile is the new power source. The coefficient k_1 shows how many times the maximum value of the axial inertial force (*S*max) is greater than its mass. This dependency is used to calculate *S* max and to conduct a comparison of the impact of the detail mass (TB and PS) on it.

Table 4 Maximum values of the axial inertial forces acting on TB and PS

Power source №	Mass m, kg	S max, N	Power source №	Mass m, kg	S max, N
1	2	3	4	5	6
TB – 1	0,1554	17930,860	**PS – 1**	0,0228	2631,453
TB – 2	0,1559	17988,553	**PS – 2**	0,0262	3023,092
TB – 3	0,1562	18023,168	**PS – 3**	0,0298	3438,479
TB – 4	0,1572	18138,553	**PS – 4**	0,0302	3484,633
TB – 5	0,1587	18311,631	**PS – 5**	0,0321	3703,865

The S max values obtained in column 6 compared to those in column 3 are lower; therefore, the axial inertial forces that are caused by the new power source (PS) as a projectile detail will be smaller.

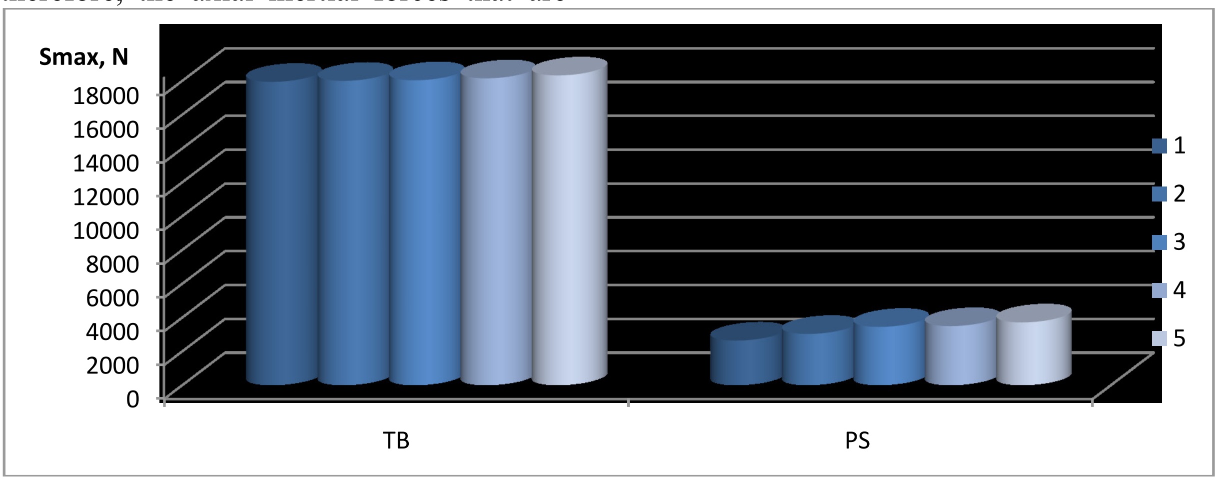

Figure 1 Axial inertial forces calculated for both batches of details TB and PS

3.2.Effect of the mass of the power source on the centrifugal inertial force

To measure the influence of the mass of the projectile detail and the centrifugal inertial forces a centrifugal coefficient k_2 is introduced in point 2.2. It determines how many times the centrifugal force (C max), acting on the detail when the shell leaves the muzzle, is greater than its mass at eccentricity ρ = 1 mm. The obtained C max values of the power sources (TB and PS) were used to compare the centrifugal inertial force generated by them.

An additional test under load was performed with the lithium batteries, and its results are presented in table 4.

Table 5 Maximum values of centrifugal inertial forces acting on TB and PS

Power source №	**Mass m, kg**	**C max, N**	**Power source №**	**Mass m, kg**	**C max, N**
1	2	3	4	5	6
TB – 1	0,1554	272,603	**PS – 1**	0,0228	39,996
TB – 2	0,1559	273,480	**PS – 2**	0,0262	45,960
TB – 3	0,1562	274,006	**PS – 3**	0,0298	52,275
TB – 4	0,1572	275,760	**PS – 4**	0,0302	52,977
TB – 5	0,1587	278,392	**PS – 5**	0,0321	56,310

Lower values of the centrifugal inertial forces, which are generated by the mass of PS, have been calculated and presented in column 6. In perspective, these forces are negative, and, therefore, the results obtained reduce the forces acting on the projectile. This assumption is also reasonably considered, given that the pressure of the gunpowder gas during the shot is preserved. The smaller mass of the parts will reduce the inertial forces and increase the muzzle exit speed of the projectile.

Figure 2 shows the centrifugal inertial forces calculated for the two batches of details TB and PS.

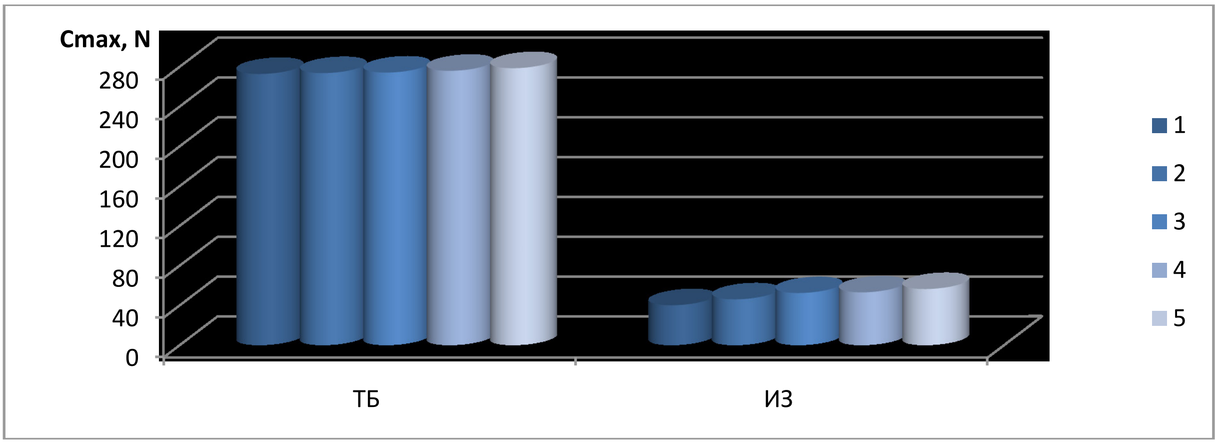

Figure 2 Centrifugal inertial forces calculated for the two batches of details TB and PS

3.3. Effect of the mass of the power source on the tangential inertial force

The assumptions made in point 2.3 lead to the conclusion that the maximum tangential inertial force (T max) is 16% of the axial inertial force. The calculated values of this force are presented in Table 6 and Figure 3.

Table 6 Maximum values of the tangential inertial forces acting on TB and PS

Power source №	Mass m, kg	*T* max, N	Power source №	Mass m, kg	*T* max, N
1	2	3	4	5	6
TB – 1	0,1554	2868,938	**PS – 1**	0,0228	421,032
TB – 2	0,1559	2878,168	**PS – 2**	0,0262	483,695
TB – 3	0,1562	2883,707	**PS – 3**	0,0298	557,517
TB – 4	0,1572	2902,168	**PS – 4**	0,0302	557,541
TB – 5	0,1587	2929,861	**PS – 5**	0,0321	592,618

The obtained values of the tangential inertial force are proportional to those in Table 4. Their direction is perpendicular to the direction of movement and they are considered negatively acting forces.

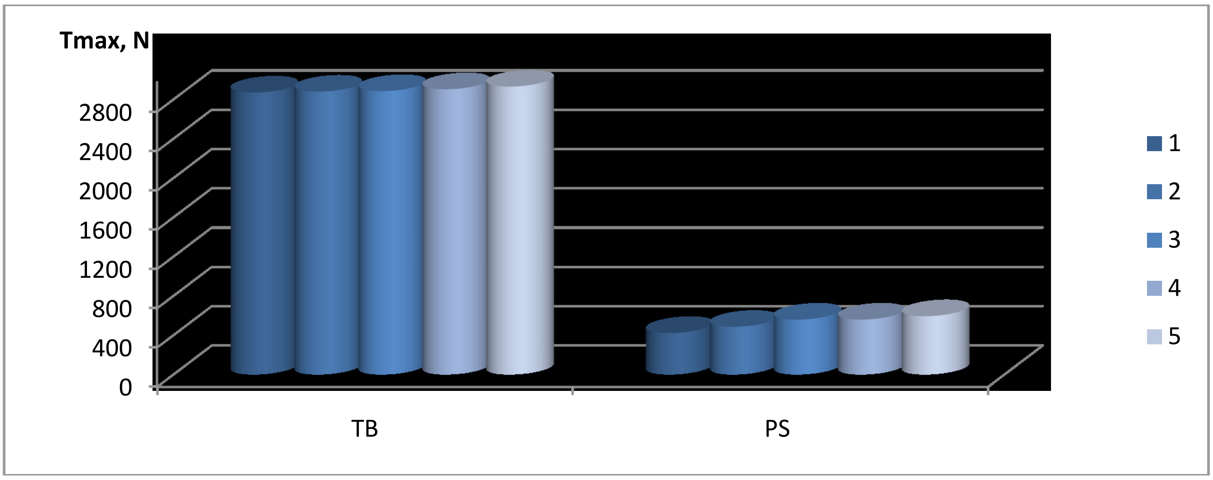

Figure 3 Tangential inertial forces calculated for the two batches of details TB and PS

4. Conclusions

The directions of the studied main inertial forces, axial (*S* max), centrifugal (*C* max) and tangential (*T* max), are mutually perpendicular and acting opposite to the direction of motion of the projectile. The maximum values of these forces depend directly on the maximum pressure of the gunpowder gases P_{max} and the initial velocity of the projectile V_0. For the newly constructed power source, the following conclusions can be made:

1. The newly constructed power source has a mass about 5 times smaller than the mass of the thermal battery used in a 122-mm artillery projectile.

2. The inertial forces – axial (*S* max), centrifugal (*C* max) and tangential (*T* max), which act when the projectile is moving straightforward in the muzzle, have about 5 times smaller values for the new power source, and change in direct ratio to the change in the detail mass.

3. The power source is a stationary part of the projectile, thus a Coriolis force does not arise.

4. The maximum pressure of the gunpowder gases P_{max} at lower values of the inertial forces and mass of the details leads to an increase in the artillery systems capabilities.

References

[1] Petkov, B. M. Artillery Fuzes. Theory, Estimate and Structures. Saint George MoD Publishing House, Sofia, 1994.