

ВІЙСЬКОВА ТЕХНІКА І ТЕХНОЛОГІЇ ПОДВІЙНОГО ПРИЗНАЧЕННЯ

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IMPROVEMENT IN QUALITY OF MANUFACTURING THE LARGE-CALIBER ARTILLERY PROJECTILES (122, 152, 155) FOR GUNS WITH A RIFLED TUBE

An analysis of the technique of manufacturing the large-caliber artillery projectiles (122, 152, 155 mm) on modern screw-cutting lathes was carried out taking into account normalized tolerances for metalworking of the projectile components in accordance with international standards in force. It has been established that regardless of the qualifications of the personnel and the use of modern machines in compliance with the requirements of international standards for metalworking, the quality of projectiles from one batch can differ significantly in the value of drift. The reason for the drift of the projectile in the air is the torque of forces arising from the discrepancy in the location of the center of gravity and aerodynamic pressure in reference to the dynamic axis. Since the projectile rotates rapidly in the air, it has been suggested that because of the presence of manufacturing tolerances in metalworking, the center of gravity of the projectile can shift in the transverse plane in reference to the dynamic axis of rotation, and this is the second probable reason which, together with the first one, can affect the kinematics of the flying projectile and drift value. Thus, shocks which deviate the projectile away from the trajectory in space and have a direct impact on the value of drift are exactly caused by the presence and ratio of the forces of two torques caused by a shift in the location of the center of gravity and the center of aerodynamic pressure in reference to the dynamic axis of rotation. To reduce the range of variation (scatter) of drift values, it is proposed to improve the quality control of artillery projectiles by introducing an additional manufacturing operation into the engineering process for calibrating projectiles, and, if necessary, balancing them, by means of the determining parameter in the value of residual disbalance. Both procedures can be carried out on a balancing machine using special manufacturing equipment. Theoretically, projectiles calibrated by the residual disbalance parameter in the same weather conditions of firing will have a reduced range of variation (scatter) of drift values, but it is desirable to check this in practice.

Key words: quality of artillery projectiles, calibrating the projectiles, balancing the projectiles, projectile lateral deflection, projectile flight range, rifled-tubed guns firing accuracy.

Introduction. The first attempt to adjust the serial production of projectiles at Ukroboronprom failed in 2018 [1], and the equipment purchased in South Korea was stopped. In the period from 2019 to 2021, the Ukrainian Ministry of Defense purchased projectiles from various private companies, but many questions arose about the quality of projectiles that did not meet requirements of the modern standards [2]. And finally, in November 2022, Ukroboronprom launched the production of scarce ammunition of Soviet calibers 152 and 122 mm [3]. This news came as a surprise to everyone, since the need for artillery projectiles for the war with the Russians was very high.

Problem statement in general. Ukraine does not have its own long-term experience in the production of artillery projectiles for guns and is taking the first steps in this direction. According to the head of the state joint-stock holding company "Artem", the purchased Korean equipment [4] is

capable of producing up to 18 thousand projectiles per year, which cannot meet the existing needs of the Armed Forces of Ukraine. Therefore, Ukraine cannot manage without the supply of projectiles from foreign partners in the war with Russia. The firing range and accuracy depend on various factors [5]: firstly, on the technical condition of the gun (the quality of the metal from which the gun tube was made, the tube's operating time by the number of shots fired); secondly, on the natural conditions of use (pressure, humidity, air temperature, wind speed and direction, etc.); thirdly, on the qualifications of the servicemembers and the reliability of the coordinates obtained from reconnaissance on the target; and fourthly, on the quality of manufacture of the projectiles themselves. Improving the quality control of artillery projectiles of calibers: 122 mm, 152 mm, 155 mm for guns with a rifled tube is an urgent problem, since the higher the quality of the projectiles, the fewer projectiles need to be spent on hitting one target on the battlefield, and the better the result of artillery shooting, the more military losses the enemy has and the fewer losses in the Armed Forces of Ukraine [6].

Analyzing the recent achievements and publications. The motion trajectory of the projectile in the air is very complex [7] (Fig. 1).

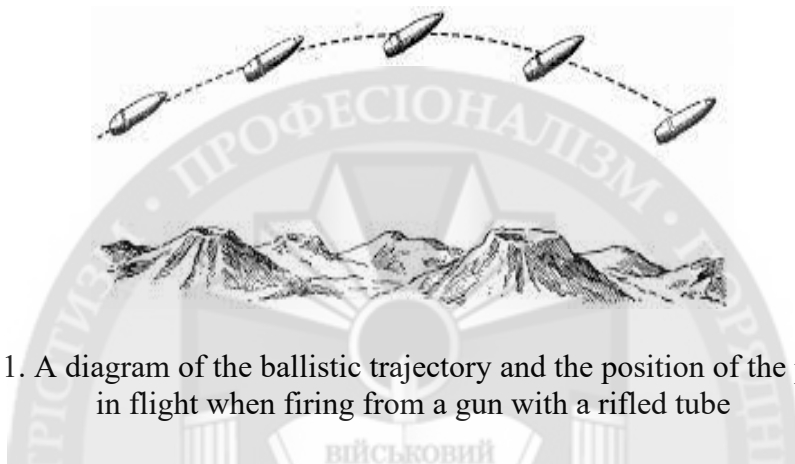


Figure 1. A diagram of the ballistic trajectory and the position of the projectile in flight when firing from a gun with a rifled tube

Thanks to the rifling in the gun tube and a special belt on the outer surface, the projectile, after leaving the tube, assumes a position in space along the axis of rotation at the expense of the gyroscopic effect, but with the loss of kinetic energy under the influence of external forces, the geometric axis of the projectile deviates from the axis of rotation (dynamic axis) [8] in the transversal direction by a small angle α . Lateral deviation of the projectile in the air is called drift. The gyroscopic effect is able to resist the action of torque from external forces and keep the projectile in the direction of the axis of rotation until the rotation speed gradually decreases to a value at which the interaction forces become equal to each other. Since the projectile in the air does not have rigid supports that hold it on a given trajectory, then gradually, with the loss of kinetic energy, the gyroscopic effect that keeps the projectile on the trajectory loses its influence, and the torque of external forces becomes more significant, the phenomenon of precession occurs, in which the axis of rotation the projectile can change its position in space (Fig. 2).

The steeper the trajectory and duration of the flight (shooting distance to the target), the greater the drift will be. When firing at short distances, where the trajectory can be taken as a straight line, there is no drift, since the projectile on the trajectory line keeps the gyroscopic effect at the expense of the high angular velocity of the projectile, while there will be no lateral deflection either. Thus, the main causes of drift are: the presence of a rotational motion of a decelerating projectile; change in air resistance at the expense of the precession of the projectile in space; constant decrease of the tangent to the trajectory.

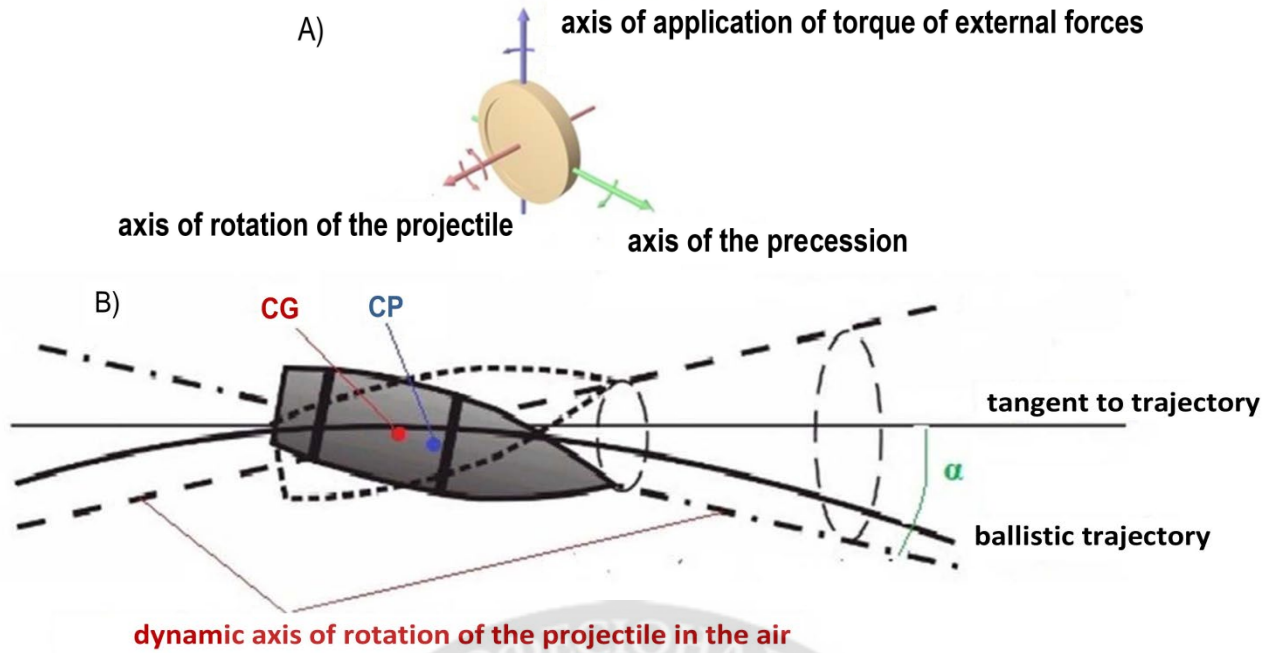


Figure 2. The phenomenon of projectile precession in flight at a long distance with a decrease in the speed of rotation in flight: A) is a diagram of the location of forces; B) is a precessional movement of the projectile in the air. CG is the center of gravity; CP is the center of aerodynamic air pressure

The magnitude of the impact of external forces on the position of the projectile in space is directly proportional to the magnitude of the kinetic energy of the projectile. Under the influence of aerodynamic resistance forces F_{res} , the kinetic energy of the projectile decreases in proportion to the square of the linear velocity according to the formula:

$$E_k = \frac{m \cdot v^2}{2 \cdot g}, \quad (1)$$

where

E_k = kinetic energy of a moving body (kg·m),

m = projectile mass (kg),

V = projectile linear velocity (m/s).

Let us find the corresponding values for E_k using formula (1) for a 122 mm artillery projectile weighing 21.76 kg, taking into account the difference between the initial velocity of 565 m/s and the final velocity of 276 m/s of a high-explosive fragmentation (HE) projectile [9]:

$$E_k^{in} = \frac{21.76 \cdot (565)^2}{2 \cdot 9.81} = 354,044 \text{ kg} \cdot \text{m}. \quad (2.a)$$

$$E_k^{fin} = \frac{21.76 \cdot (276)^2}{2 \cdot 9.81} = 84,485 \text{ kg} \cdot \text{m}. \quad (2.b)$$

The difference in the loss of kinetic energy of the projectile at a long distance to hit the target is

$$E_k = \frac{E_k^{in} - E_k^{fin}}{E_k^{in}} \cdot 100\% = \frac{354,044 - 84,485}{354,044} \cdot 100\% = 76\%. \quad (3)$$

Accordingly, the lower the aerodynamic drag force F_{res} and the magnitude of the drift, the lower the loss of the kinetic energy of the projectile in the air E_k , and, accordingly, the greater the range of artillery fire and the power of hitting the target (for armor-piercing projectiles).

Usually, the center of gravity of the projectile (CG) does not coincide with the center of aerodynamic pressure (CP), which causes a torque, which just turns the projectile in the air (Fig. 3).

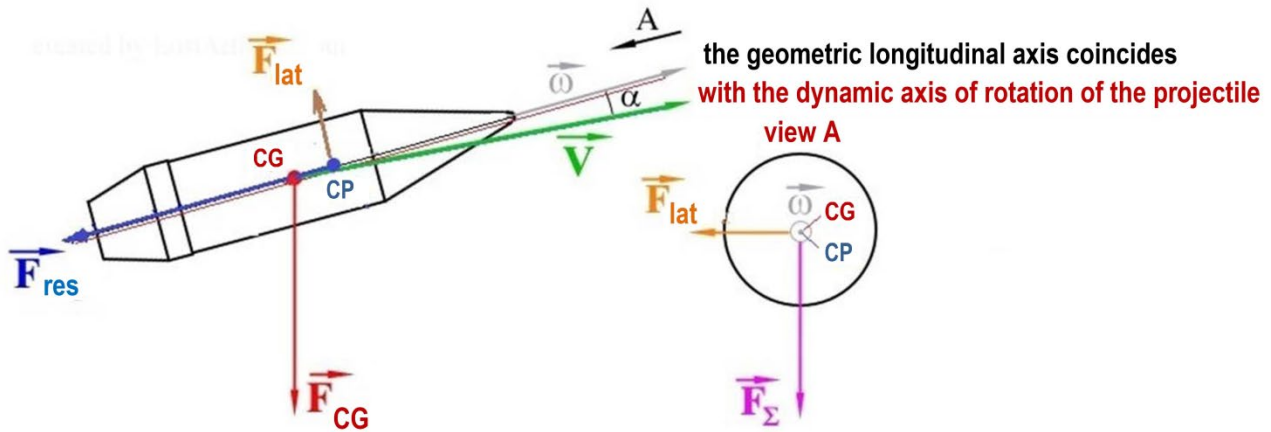


Figure 3. Location of forces when CG and CP do not coincide and are together on a geometric longitudinal axis coinciding with the dynamic axis of rotation of the projectile

This is the first possible reason of projectile drift, which is not the only one. The second reason that can affect the kinematics of the fired projectile and the value of drift is discovered in the possible displacement of the CG not only relative to the CP, but also relative to the dynamic axis of rotation of the projectile in the transversal plane (Fig. 4)

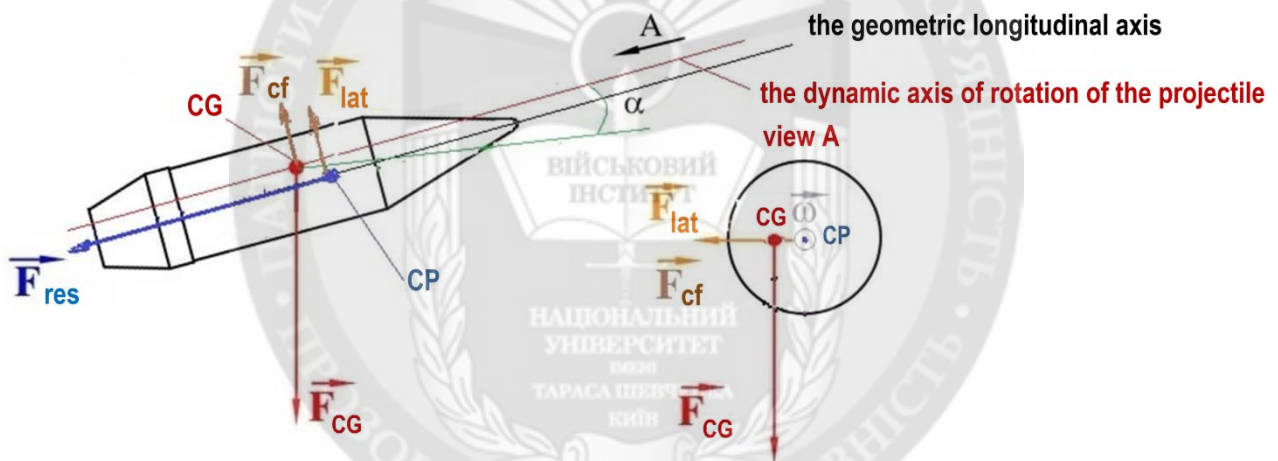


Figure 4. Location of forces when the CG and CP do not coincide and the CG is on the dynamic axis of rotation of the projectile, and the CP is on the geometric longitudinal axis, which do not coincide

It is quite obvious that in the presence of eccentricity between the dynamic axis of rotation and the geometric axis of the projectile, in addition to the lateral displacement force $\overline{F_{lat}}$, there is also a centrifugal force $\overline{F_{cf}}$, coinciding in direction with the force $\overline{F_{lat}}$. Based on this, it can be concluded that the nonequilibrium of the projectile associated with the displacement of the CG from the axis of rotation of the projectile (the presence of eccentricity and the action of the centrifugal force of inertia $\overline{F_{cf}}$) can additionally affect the drift value (lateral deviation $\overline{F_{lat}}$) and, accordingly, on the motion trajectory of the projectile. It can be assumed that the shocks that deviate the projectile towards the trajectory in space and directly affect the drift value are exactly caused by the presence and ratio of the forces of two torques caused by the displacement of the location of the CG and CP relative to the dynamic axis of rotation. The location of the center of gravity depends on the density of the material distribution along the geometric shape of the projectile, and the location of the center of aerodynamic pressure depends solely on the geometric shape of the projectile (Fig. 5).

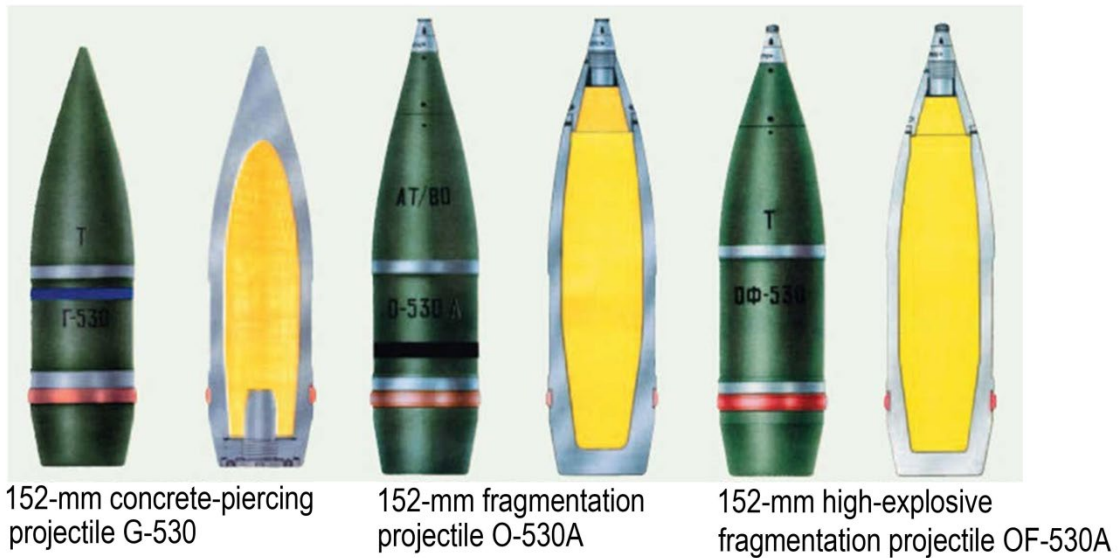
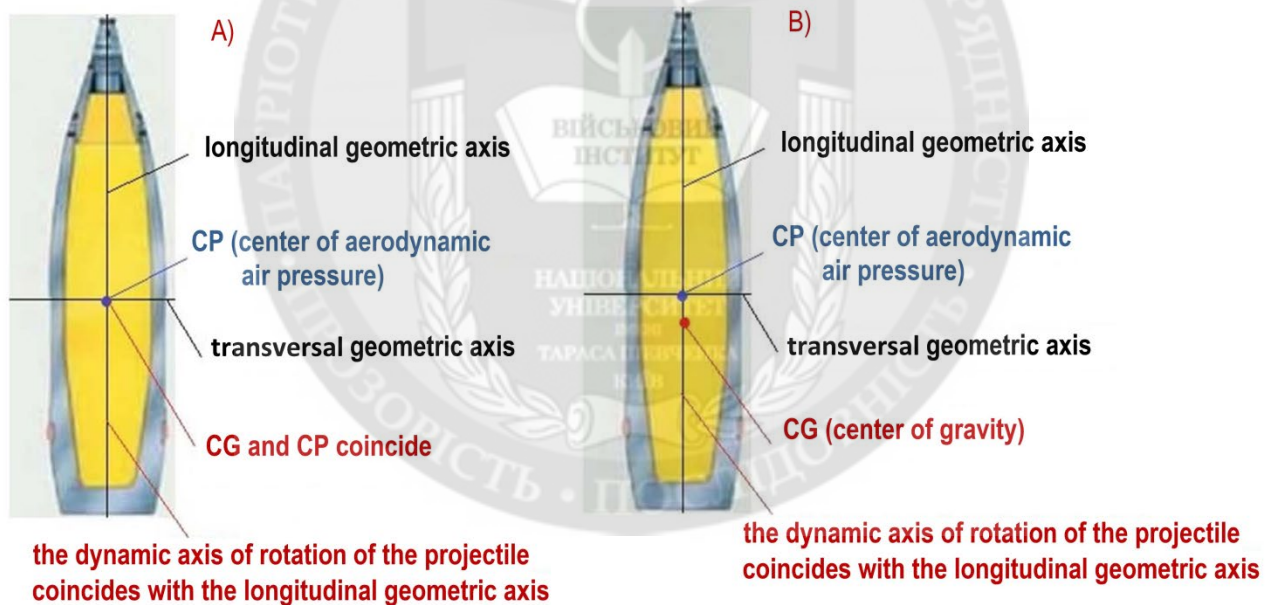


Figure 5. The most common types of artillery projectiles

Consequently, with almost the same geometric shape of projectiles of the same caliber [10], the aerodynamics of a fired projectile in the air depends entirely on its position in space, which it occupies depending on the location of the CG and CP (Fig. 6).



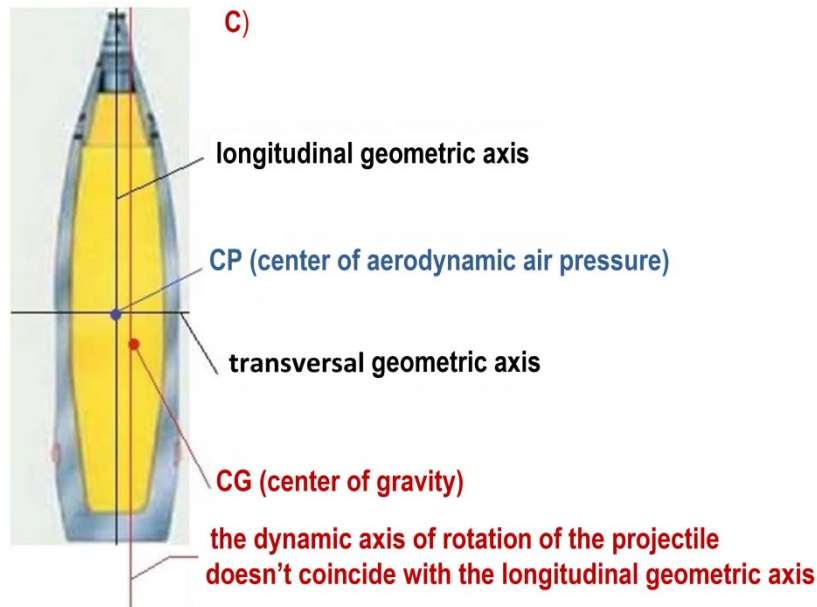


Figure 6. Possible options for the location of the centers of the CG and CP, affecting the ballistic trajectory of the projectile in the air, which can be conditionally divided into three types: A) is high quality workmanship; B) is average workmanship; B) is low quality workmanship

The type A projectile has only one drift value (lateral deflection), which is controllable and depends solely on natural weather conditions and the skill level of artillerymen when firing at a long distance. The use of type A projectiles implies minimal costs in quantity to hit one target. High ballistic characteristics of such projectiles are achieved at the expense of reducing the nonequilibrium of the projectile in the longitudinal and transversal axes of rotation (coincidence of the centers of the CG and CP) by applying a balancing procedure in two perpendicular directions of movement (in this case, the centrifugal force \vec{F}_{cf} and the lateral displacement force \vec{F}_{lat} will have too small values to deflect the projectile away from the trajectory). In so doing it does not matter which method is applied when manufacturing the projectile body: “centered casting” or “hot pressing” with subsequent metalworking. This is quite possible, provided that the body of the projectile is made in one piece or prefabricated, and the main thing here is that the body does not have threaded connections (individual parts of the body are connected to each other by “hot pressing” or “cold pressing with tension”).

The type B projectile has not one value, but a range of drift (lateral deflection) values, which should be taken into account together with natural weather conditions when firing at a target at a long distance and requires an increase in the number of projectiles to hit a single target. The difference is that when manufacturing, the balancing procedure for the type B projectile is applied only for one longitudinal axis of rotation, which minimizes the value of the centrifugal force \vec{F}_{cf} to affect the ballistic trajectory of the projectile, but does not exclude the effect of the lateral displacement force \vec{F}_{lat} , since the centers CG and CP do not coincide, although they are located on the same geometric axis coinciding with the dynamic axis of rotation of the projectile (Fig. 3). It is for this reason that the quality of the type B projectile is classified as medium.

The type C projectile has an uncontrolled range of drift values (lateral deflection), therefore, it requires artillerymen of a high level of skill to empirically determine corrections to the ballistic trajectory when firing at a long distance to hit a single target taking into account natural weather conditions. The type C projectiles are the most inexpensive projectile manufacturing option because of the fact that the projectile body is assembled from separate parts that are connected to each other using metric threads without further balancing of the projectile. Since the balancing procedure is not applied when manufacturing the projectiles of type C, the CG and CP do not coincide and, in addition, they can be located on different axes: the CG is on the dynamic axis of rotation, and the CP is on the geometric longitudinal axis of the projectile (Fig. 4). Therefore, when using such projectiles to hit one target, a much larger number is required than projectiles of types A or B. This assumption is based on the following.

Nonequilibrium is inherent in any physical body rotating in the longitudinal direction around its geometric axis. For example, the angular velocity of rotation of a car wheel at full speed is about 16 rpm, for an aircraft propeller it is within 35–75 rpm, and therefore, in mechanical engineering, before putting into operation, the procedure for preliminarily balancing such rotors on special stands is applied. An artillery projectile fired from a rifled gun tube rotates between 200–500 rpm [11], which is 30 times faster than a car wheel and 5–7 times faster than an aircraft propeller, however there is no any reference about applying a calibration procedure according to the parameter of nonequilibrium (residual disbalance) or balancing the artillery projectiles during their production in open sources of information, and this is understandable [12].

The majority of manufacturers encounter the problem of adjusting the production technique of artillery projectiles for their compliance with international quality standards [13]. According to the world's manufacturing technique of artillery projectiles by "hot pressing", the projectile body is made up of several separate parts (two or three), which, after metalworking on CNC machines, are then connected to each other using threaded connections. Despite the accuracy of measuring the geometric dimensions of the components in the engineering process of manufacturing the projectile (1.5 μm) declared by the Ukrainian manufacturer, let's pay attention to the words of the head of the state joint-stock holding company "Artem" that the Korean equipment purchased for metalworking is an inexpensive option. This means that the Korean metalworking machines most likely comply with the current interstate standard [14], have the usual accuracy class "H", and have an instrumental error of 40 μm when manufacturing a part of length up to 300 mm (i.5.5 Constancy of diameters in longitudinal section, table 13). In addition, the projectile consists of several separate parts which are interconnected by a metric thread. According to GOST 16093-81 (ST SEV 640-77, which was replaced in Ukraine with three new parts of DSTU ISO 965 [15-17], the threaded connection of projectile parts additionally has its own tolerance, for example, according to the nominal diameter of the part 90–180 mm with thread pitch 1.5 mm tolerance (tables 4 and 5) within $\frac{1}{2}$ of 150–475 μm is taken. Thus, on the fact of permissible errors in metalworking on class "H" machines, a finished projectile, for example, with a caliber of 122 mm with a weight of 21.76 kg [18] or 152 (155) mm with a weight of 43.5 (44.5) kg [19, 20] when flying along a ballistic trajectory, it can have an eccentricity of displacement of the center of gravity in the transversal direction relative to the longitudinal geometric axis of rotation in the air at the expense of the aforementioned manufacturing tolerances within 40–75 μm . And this is provided that the metalworking of the outer surface of the projectile body is carried out after assembling all its components into a single whole with one cutter in one pass. If a different metalworking technique is applied in production, for example, when each part of the projectile body is processed separately before connecting to each other, then the total metalworking error in diameter will be even higher (2–3 times) at the expense of the presence of a manufacturing tolerance in the threaded connection. Owing to this, the longitudinal axes of individual parts of the projectile body can be displaced in the transversal direction and not coincide with the axis of rotation of the projectile.

Thus, the technical prerequisites for the occurrence of a residual disbalance in an artillery projectile at the expense of the available tolerances in metalworking when manufacturing the projectiles are sufficient, which means that the assumption put forward about the presence and influence of torque from a residual disbalance on the drift value of an artillery projectile has a weighty basis, and with this it is necessary that to do something.

The aim of the article is: to increase the accuracy and firing range of projectiles, which will lead to:

- the decrease in the total number of projectiles to hit one target and the corresponding decrease in the cost of logistic support with projectiles (at the expense of reducing of the need for the number of projectiles to hit one target),

- the reducing of the cost of maintenance service of guns (at the expense of the increase in the overhaul period before replacing the tube in the gun because of the less of shots from one tube to hit one target),

- the obtaining of a tactical advantage in military operations and successful artillery fire on hitting enemy's targets (owing to a reduction in the shortage in the number of projectiles of the required caliber).

Main part. A flying artillery projectile can be roughly compared with the first samples of automobile turbines installed on diesel engines. Now their angular velocity of rotation has increased significantly and can reach up to 200,000 rpm, which is why so much attention is paid to the balancing procedure of turbines, as this is the key to its further long-term operation. The difference between these two rotating physical bodies (rigid rotors) is seen in the presence of two supports for the turbine, on which it is fixed in rolling bearings. The supports firmly hold the turbine in place during rotation, which cannot be said about a flying projectile fired from an artillery gun with a rifled tube and rotating around a longitudinal axis in space without supports. The nonequilibrium of the projectile CG, which is determined by the eccentricity and angular velocity of the projectile, can greatly affect the value of the lateral deflection of the projectile. Such a conclusion can be drawn if we look at formula (4) for calculating the centrifugal force of inertia of projectile rotation relative to the geometric axis:

$$F_{cf} = m \cdot r_{ecc} \cdot \omega^2 = D \cdot \omega^2, \quad (4)$$

where

F_{cf} = centrifugal force (kN),

m = projectile mass (kg),

r_{ecc} = eccentricity (distance) of the location of the CG from the geometric axis of rotation of the projectile (mm), which is directly determined by the manufacturing errors in the metalworking of the projectile body on machine tools,

$D = m \cdot r_{ecc}$ = nonequilibrium (disbalance) of the projectile mass relative to the geometric axis of rotation (g·mm),

ω = the angular velocity of the projectile in space (rad/s).

To avoid an unpredictable scatter of the values of projectile lateral deflection over a long firing range, it is proposed to improve the quality control of artillery projectiles at the expense of introducing an additional manufacturing operation for calibrating, and, if necessary, for balancing them by several quality classes, for example, 1, 2, 3. As a determining calibration parameter, it is proposed to take the value of the residual disbalance (g·mm) of the projectiles. Both procedures can be carried out on a balancing machine using special manufacturing equipment. To normalize the residual disbalance of artillery projectiles, the current international standard [21] can be used. For example, for rigid rotors of accuracy class G 6.3 (table 1) with an operating angular velocity of rotation in the range of 12,000–30,000 rpm, the permissible value of the specific residual disbalance is 2–5 g·mm/kg (Fig. 7).

Accordingly, for 122 mm caliber projectiles with a weight of ≈ 22 kg, the permissible rate of residual disbalance for class 1 projectiles will be within 44–110 g·mm, and for a 152 (155) mm caliber projectile with a weight of ≈ 44 kg, within 88–220 g·mm. Now, in the production of artillery projectiles, this indicator is not available, and therefore it is not measured in any way, but in vain. It is easy to calculate that a projectile of 122 mm caliber with a weight of 22 kg, which has manufacturing tolerances for metalworking on class H machines with an outer diameter of 40–75 microns (in cross section) can have a residual disbalance value of 880–1,650 g·mm, respectively, and for a projectile larger caliber 152 (155) mm with a weight of 44 kg, respectively, within 1,760–3,300 g·mm, which is 15–20 times higher than the rate allowed by the international standard.

The manufacturing procedure for calibrating projectiles in production should be automated, but first it is better to test the theoretical assumptions experimentally. Therefore, it would be advisable to take samples from one batch of artillery projectiles of any large caliber (122, 152, 155 mm) in the amount of 40 units, to calibrate 30 samples on a balancing stand in accordance with different residual disbalance values for three quality classes of projectiles at the range from one gun on the basis of the same climatic conditions of the experiment, and on the basis of the results obtained to draw a conclusion on the economic feasibility of introducing an additional manufacturing calibration procedure into the production of artillery projectiles.

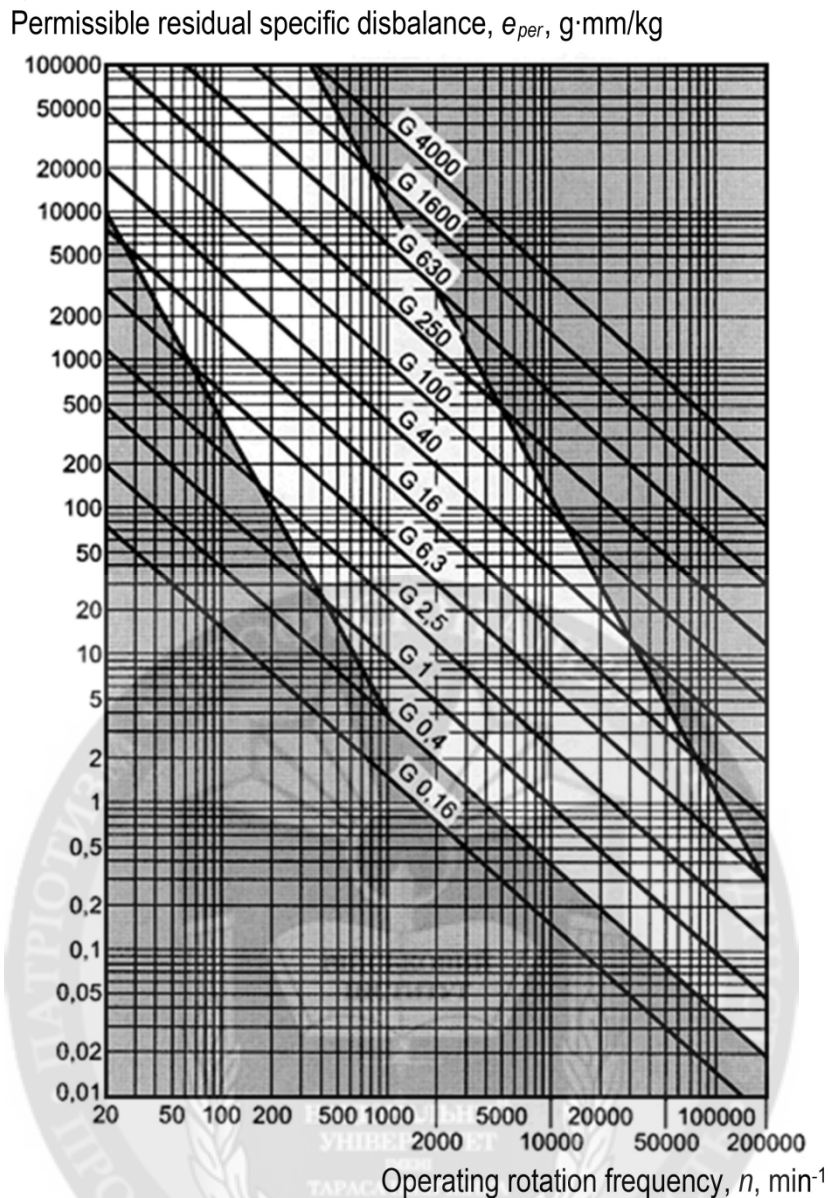


Figure 7. Permissible specific value of residual disbalance for rigid rotors

It may happen that, according to the results of measuring the residual disbalance (calibration procedure), most of the projectiles in one batch will fall into one class in quality and this will most likely not be class 1, but class 2 or 3. Therefore, it is desirable, based on the technique existing in production, assign a balancing method (adding or removing excess mass from the surface of the physical body) and the place of correction on the physical body of the projectile, select tools for this manufacturing operation and try to balance a separate part of the projectiles to class 1 quality.

Let us calculate by formula (4) the value of the centrifugal force of inertia \overline{F}_{cf} , which will act on a 122 mm caliber artillery projectile with an angular velocity of 500 rpm, equal to 3,142 rad/s, if it is pre-balanced on a balancing machine up to the rate of $110 \text{ g}\cdot\text{mm} = 110 \cdot 10^{-6} \text{ kg}\cdot\text{m}$ according to quality class 1:

$$F_{cf} = D \cdot \omega^2 = 110 \cdot 10^{-6} \cdot 3,142^2 = 1,086 \text{ N} \approx 1.1 \text{ kN}. \quad (5)$$

For the convenience of perceiving the result obtained, we calculate the value of the gravity force F_{CG} , which also acts perpendicular to the geometric axis of rotation of the projectile weighing 22 kg during the flight:

$$F_{CG} = m \cdot g^2 = 22 \cdot 9.81^2 = 2,117 \text{ N} \approx 2.1 \text{ kN.} \quad (6)$$

Since the value of the centrifugal force of inertia F_{cf} for the balanced projectile is 2 times less than the value of gravity F_{CG} , it can be assumed that the influence of F_{cf} on the projectile trajectory (lateral deflection) will also be minimal.

However, for a projectile manufacturer, this is an unnecessary trouble and additional costs associated with the acquisition of new balancing equipment, changes in technique, and an increase in the payroll fund by hiring new workers to work on new equipment. Therefore, a compromise is seen in a proportional increase by the manufacturer in the price of better (balanced) artillery projectiles. Today, the cost of a conventional 155 mm projectile costs about 1,500–2,000 US Dollars [22], and a high-precision projectile, for example, Excalibur Increment Ia-2 (M982) costs 112,800 US Dollars for the US Army [23], but Excalibur hits the target by almost 100 % (lateral deviation is only $\pm 4\text{m}$), for which one need to spend more than 50 ordinary projectiles.

Conclusions. Based on the foregoing, it can be concluded that despite the manufacturer's compliance with all the requirements of international metalworking standards and the use of modern CNC machines in the production of projectiles, the residual disbalance of the projectile will still be 15–20 times higher than the permissible rates regardless of the qualifications of the personnel. Theoretically, at the expense of the procedure of calibrating (and even better, of balancing) projectiles using a balancing stand, it is quite possible to increase the accuracy and range of fire by reducing the range of variation (scatter) of the drift values, respectively, within the same class (1, 2, 3) of calibrated projectiles in the same weather conditions of firing, which in turn will lead to:

- the decrease in the total number of projectiles to hit one target and the corresponding decrease in the cost of logistic support with projectiles (at the expense of reducing of the need for the number of projectiles to hit one target),
- the reducing of the cost of maintenance service of guns (at the expense of the increase in the overhaul period before replacing the tube in the gun because of the less of shots from one tube to hit one target),
- the obtaining of a tactical advantage in military operations and successful artillery fire on hitting enemy's targets (owing to a reduction in the shortage in the number of projectiles of the required caliber).

The introduction of balancing (calibration) of large-caliber projectiles into production is an economically justified procedure not only for the manufacturer, but also for the Ukrainian Ministry of Defense in the form of real financial savings when purchasing a smaller number of projectiles by improving their quality, and hence reducing the cost of periodic maintenance service for the replacement of gun tubes, which implies a tactical advantage in military operations when using artillery.

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