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The Improvements of Ballistic Characteristics of Artillery Projectiles of 152 and 155 mm Calibers

KOSTIANTYN BORIAK

Scientific Research Department for the Weapons Development and Military Equipment of the Institute of Naval Forces of the National University "Odessa Maritime Academy", 8 Didrihsona St., Odessa, 65029, Ukraine, kostya.boryak@gmail.com

Abstract: The existing methods of manufacturing artillery projectiles with calibration and marking only in one parameter for measuring the total mass by statically weighing do not take into account the dynamics when a projectile moves in the air, namely, the dynamic unbalance of the mass owing to unevenly distributing the mass throughout the geometric shape of the projectile. When flying along a ballistic trajectory, projectiles rotate in the air with a high angular velocity in the range of 200–500 rev/min and, therefore, they are similar in the dynamics of the rotating motion to the rotation of rigid rotors. Based on the presence of manufacturing tolerances in the metalworking of the body, artillery projectiles can have dynamic unbalance and a large amount of unbalance, which can exceed the allowable norm for rigid rotors by 15–20 times and unpredictably affect the dynamics of a projectile when moving along a ballistic trajectory. The solution to this problem is seen in the improvement of the methods being used for manufacturing artillery projectiles by performing an additional manufacturing operation for correcting (diminishing) the unbalance vector, which will reduce the lateral deviation and drift of the projectiles in flight as well as stabilize their dynamic parameters when moving along a ballistic trajectory in the air, and that will certainly lead to an increase in the range of the projectiles and enhancement of the accuracy of hitting the target. The article proposes several options for the practical implementation of the manufacturing operation for correcting the unbalance vector of projectiles in one plane. When applying the method of balancing the projectiles by adding missing metal (mass), it is proposed to place the corrective weight in a special "corrective groove" on the outer surface of the projectile body, which can be preliminarily made on a metalworking machine during the general processing of the projectile body. To ensure the strength of fixing in the grooves of the corrective weights from the influence of the pressure of powder gases on them when firing from a gun, it is proposed to make the geometrical profile of the groove in the cross section of a trapezoidal shape of the dovetail type. When applying the method of removing excess metal (mass), it is proposed to make holes on the outer surface of the projectile body by milling (or drilling). The mass and place

(angle) of the correction, the geometric dimensions, and the number of corrective weights or corrective holes shall be preliminarily determined in the course of balancing the projectiles on a balancing stand. It is proposed to introduce the marking of projectiles in five classes through two parameters of mass and their deviations from the norm: the first of which is the measurement of the total mass of the projectile in statics, and the second one is the measurement of unbalance of the mass of the projectile in the form of the amount of unbalance in dynamics.
Keywords: projectiles, ballistic characteristics, balancing, calibrating, unbalance vector
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1. Introduction

Ukraine does not have its own long-standing experience in the production of artillery projectiles for guns, and it is now taking the first steps in this direction. The first attempt to arrange serial production of projectiles at the Ukroboronprom State Concern 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 regarding their quality, which did not meet modern standards [2]. In 2022, the outbreak of war with Russia accelerated the rearmament of Ukraine and its transition to NATO standards.

2. Analysis of Literature Data and Statement of the Problem

The use of large-caliber cannon artillery of 152 and 155 mm plays a key role in modern warfare and it has a direct impact on the strategy and tactics of the combat operations on both sides. The range and accuracy of firing depends on various factors [3]: firstly, on the technical state of the gun (the quality of the metal from which the gun tube was made; the operating time of the tube by the number of shots fired); secondly, on the natural conditions during the use (pressure, humidity, air temperature, wind speed and direction, etc.); thirdly, on the qualifications of the service members and reliability of the coordinates of the target that is hit obtained from reconnaissance; fourthly, on the quality of manufacturing the projectiles themselves. The better the ballistic characteristics in the manufactured batch of projectiles (stable and predictable drift when firing at a long distance), the better their quality is considered, the less number of projectiles should be spent on hitting each single target on the battlefield, and the better the result of artillery firing—more military losses the enemy has and fewer losses in the Ukrainian Armed Forces [4]. Therefore, the improvement in the ballistic characteristics of large-caliber artillery projectiles of 152 and 155 mm for guns with a rifled bore is a topical scientific problem at the present time.

The high-explosive artillery projectile M107 of 155 mm caliber, developed in the USA in the 1940s, was adopted by many armies of the world and produced in different countries [5]. Subsequently, the M107 became the standard projectile of NATO for 155 mm artillery. It is also the primary projectile under the NATO Joint Memorandum of Understanding on Ballistics. Until 1996, the M107 was the standard 155 mm high-explosive artillery projectile for U.S. Army howitzers (Fig. 1).

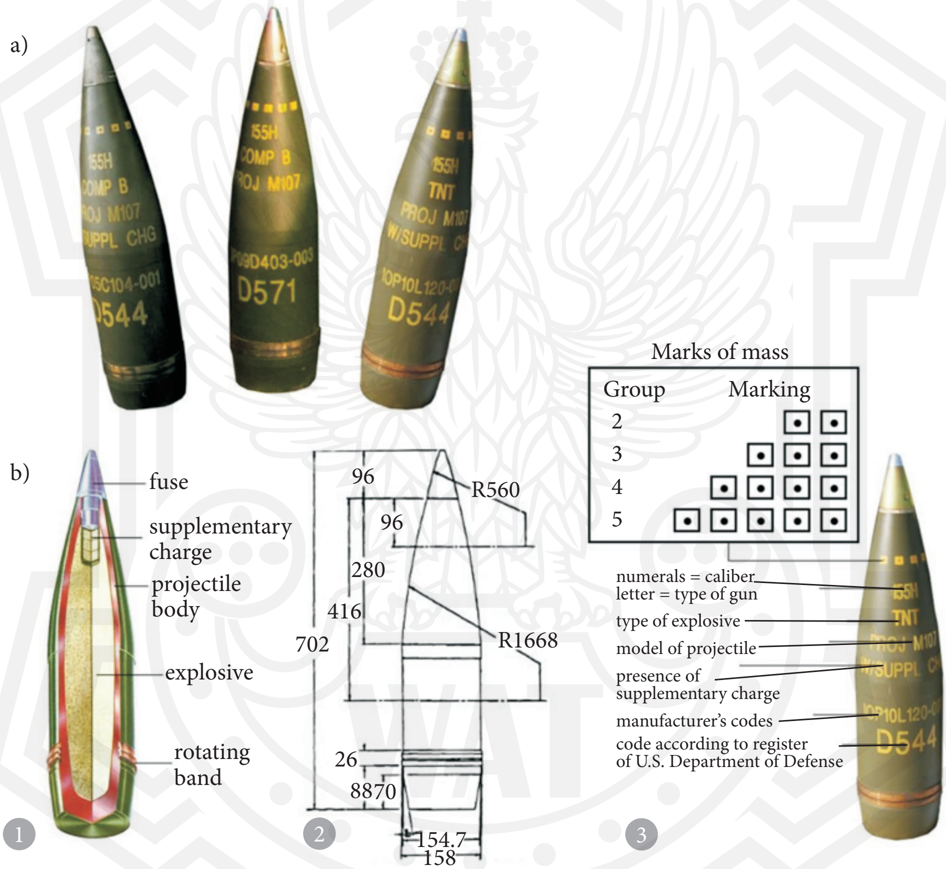

Fig. 1. M107 projectile of 155 mm caliber: (a) = appearance; (b) = designations: 1 = constructive composition; 2 = geometric dimensions, mm; 3 = marking of the projectile on the body

Almost all 155 mm howitzers can fire the M107 projectile. The projectile has a length of 605.3 mm (without a fuse) and a diameter of 154.71 mm, and with the rotating band the diameter of the projectile is 157.98 mm [6]. The ballistic coefficient of the projectile is 0.51. The body is hollow, made of forged steel AHSS (AISI 1045).

An explosive is laid inside the body: 6.62 kg of TNT (such projectiles are marked as "TNT" on the body) or 6.985 kg of "composition B" (marked as "COMP B"). A threaded hole is provided in the upper part of the projectile for screwing a fuse. When delivered from the factory, an eyebolt is screwed into it, which is unscrewed before firing and replaced by a fuse. The loaded projectile weighs between 40.82 and 43.88 kg depending on the explosive and detonator used. The unfused projectiles are divided into five groups (zones) by mass. Calibrating the manufactured projectile is carried out only according to one parameter of measuring the total mass, by statically weighing and marking the corresponding number of yellow squares in the upper part of the projectile [7], where the number of squares corresponds to a sequential increase in the total mass of the projectile by 0.4–0.6 kg, which is taken into account in ballistic calculations when firing.

The main disadvantages of the M107 projectile are a short firing range. Range limitations are related to the design (width of the rotating bands) and the material of the projectile body, which does not allow firing from guns with a tube longer than 45 calibers (Fig. 2).

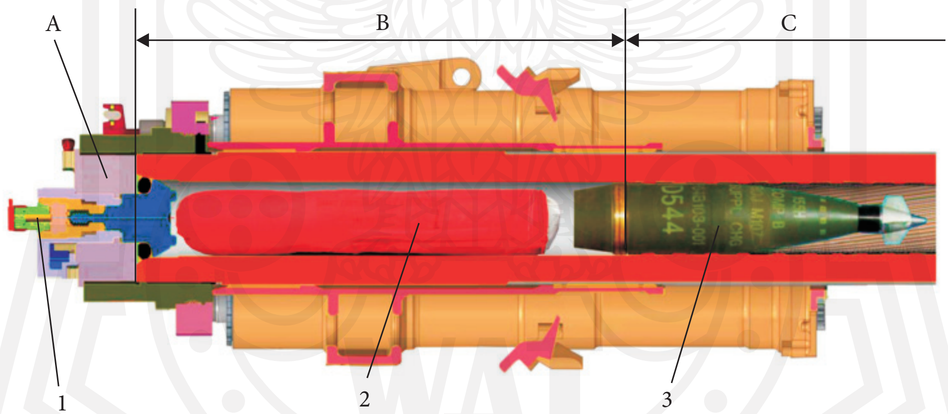

Fig. 2. Loaded gun M284 of self-propelled howitzer M109A7 Paladin, where: A = breech; B = chamber; C = the rifled part of bore; 1 = percussion primer M82; 2 = propellent charge M119A2, charge 7; 3 = M107 projectile with M1156 PGK fuse for correcting the ballistic trajectory

Unfortunately, the existing methods of manufacturing artillery projectiles with calibration and marking only in one parameter for measuring the total mass by statically weighing do not take into account the dynamics of a flying projectile in the air, namely, the dynamic unbalance of the mass owing to unevenly distributing the mass throughout the geometric shape of the projectile. An artillery projectile fired from a rifled bore of gun rotates at a speed of 200–500 rpm [8], which is 30 times faster than a rotating car wheel, and when compared with an aircraft propeller, the difference in speed is 5–7 times. Based on the technique being applied in the production of large-caliber artillery projectiles (152–155 mm) and the manufacturing tolerances being used in the range of 40–75 μm (in cross section) for processing the outer surface of the projectile body during metalworking on "H" class machines [9], the projectiles rotating in the air with a high angular velocity along a ballistic trajectory during the flight, have similarities in the kinematics of rotational motion with the rotation of rigid rotors which are widely used in mechanical engineering and military equipment.

Unbalance is inherent in any physical body rotating in the longitudinal direction around its geometric axis, and therefore, in mechanical engineering, before commissioning, the manufacturing operation of preliminarily balancing the rotors on special balancing stands is used. Artillery projectiles can also have dynamic unbalance, but there is no any mention of the application of the manufacturing operation of calibrating according to an unbalance parameter (e.g., amount of residual unbalance) or balancing of artillery projectiles during their production, in particular in publicly available sources of information. In addition, there are no special marks associated with calibrating or balancing in the marking of the projectiles, and this is quite obvious [10].

The presence of a large amount of unbalance in artillery projectiles, which can exceed by 15–20 times [11] the norm for rigid rotors allowed by the international standard [12], in combination with natural conditions (wind, pressure, ambient temperature) and the technical state of the gun itself, can unpredictably affect the dynamic parameters of a projectile flying along a ballistic trajectory in the air, which will negatively affect the quality of artillery fire and the accuracy of hitting the target.

The solution to this problem is seen in the improvement in the methods being used for manufacturing artillery projectiles by performing an additional manufacturing operation for correcting (diminishing) the unbalance vector, which will reduce the lateral deviation and drift of the projectiles in flight as well as will stabilize their dynamic parameters when moving along a ballistic trajectory in the air, and that will certainly lead to an increase in the range of the projectiles and enhancement of the accuracy of hitting the target. Before the introduction of this manufacturing operation into production, it is necessary to fulfill several concomitant sequential tasks:

Task 1: choosing one of two balancing methods (through adding or removing excess mass from the surface of the physical body of the rotor).

Task 2: selecting a place for correcting on the outer surface of the body along the length of the projectile and elaborating manufacturing options for implementation of the manufacturing operation for correcting the unbalance vector of artillery projectiles in practice.

Task 3: selecting the appropriate materials and tools for performing this manufacturing operation.

3. The Purpose and Objectives of the Research

The improvement in the ballistic characteristics of large-caliber artillery projectiles (152–155 mm) at the expense of stabilization of the lateral deflection and drift in flight when firing at a long distance from guns with a rifled bore through introduction of an additional manufacturing operation of balancing into production taking into account calibrating and appropriately marking in five classes through two parameters, namely, depending on the amount of residual unbalance and the deviation from the total mass of a projectile.

4. Materials and Methods of the Research

The aforecited first and third tasks are closely related to each other, so they need to be fulfilled directly in production in accordance with the technique used taking into account the properties of a manufacturing plant and the metalworking equipment applied there, so choosing a method for balancing projectiles and also selecting the materials and tools for the implementation of the manufacturing operation for balancing should be done by the manufacturer. Let us analyse possible decisions for fulfilling the above-mentioned second task.

Since the geometric parameters of a 155 mm caliber projectile (Fig. 1) with a length without a fuse of 605.3 mm (702 mm with a fuse) and a diameter of 154.71 mm do not exceed the limiting criterion of the $L/H \leq 5$ ratio for balancing rigid rotors [13, 14], then one can expect a positive result from the operation of dynamically balancing the projectiles in only one correction plane of the unbalance vector. Figure 3 below shows the first possible option for selection of the place and plane for correcting the unbalance vector in the end part of the projectile body (in the bottom).

To correct the unbalance vector, both known balancing methods can be applied:

- through adding the mass of missing metal in the form of a corrective weight, the mass value of which and the corresponding setting angle in the correction plane are determined in the course of balancing the projectile on a balancing stand taking into account the placement of the weight in a special hole in the form of a “corrective groove” [15] which is located along the circumference of the end rear part of the projectile body and which can be preliminarily made on a metalworking machine during the general processing of the projectile body;
- through removing the mass of excess metal from the end part of the projectile body by milling (or drilling) holes in the corresponding corner in the correction plane, where the number and geometric dimensions of the holes are preliminarily determined in the course of balancing on a balancing stand.

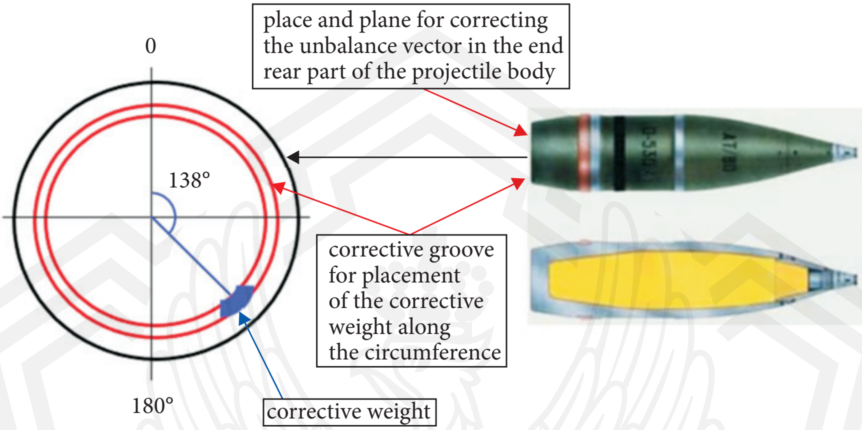

Fig. 3. Option 1 for selection of the place and plane for correcting the unbalance vector in the end rear part of the projectile body

The second possible option for selection of the place and plane for correcting the unbalance vector by adding missing metal, as an alternative to the first one, is to move the place and plane for correcting the unbalance vector from the rear part to the lateral surface of the projectile body. In so doing, the "corrective groove" along the circumference of the projectile body can be made along a double rotating band, where the projectile body has a slightly thinner thickness than in the end part, and it is not subjected to such great pressure from the powder gases as in the end (Fig. 4).

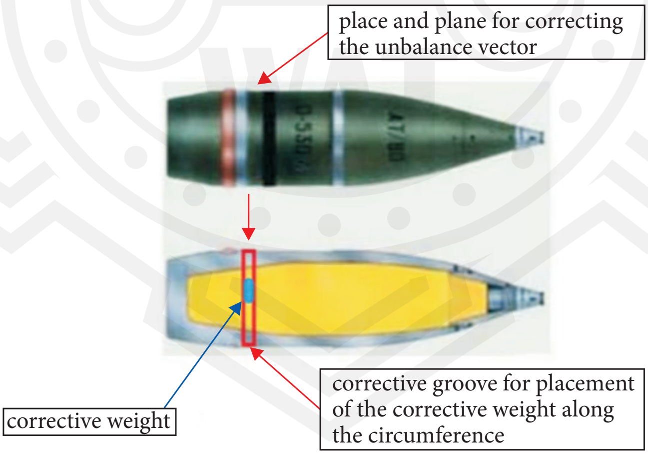

Fig. 4. Option 2 for selection of the place and plane for correcting the unbalance vector on the lateral surface of the projectile body

Taking into account that in this place the thickness of the projectile body has a much smaller metal thickness, and at the same time, the geometric dimensions of the "correcting groove" have depth limitations for correcting the unbalance vector with one weight of the balancing mass, it is advisable to make several "corrective grooves" for correcting the unbalance vector with two weights of the balancing mass, which will be placed in these grooves next to each other. "Corrective grooves" can also be made in advance on a metalworking machine during the general processing of the projectile body.

Figure 5 shows two possible options for selection of the place and plane for correcting the unbalance vector by removing excess metal from the end rear part or from the lateral surface of the projectile body by milling or drilling corrective holes in the corresponding angle in the correction plane, where the number and geometric dimensions of the holes shall be preliminarily determined in the course of balancing on a balancing stand.

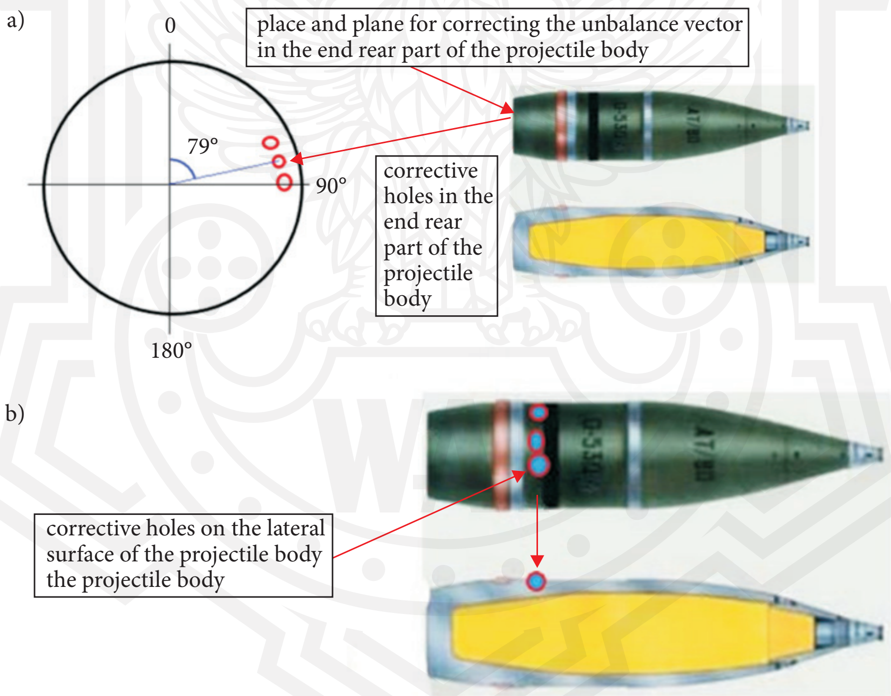

Fig. 5. Options for selection of the place and plane for correcting the unbalance vector through removing the mass of excess metal by milling or drilling: (a) = from the end rear part; (b) = from the lateral surface of the projectile body

It should be especially noted that corrective weights or corrective holes at the correction points shall be placed symmetrically relative to a well-determined angular coordinate of the points of unbalance vector.

It is quite obvious that when choosing the method of correcting the unbalance vector and also of performing the manufacturing operation, one should take into account the requirements for maintaining the overall strength of the rear part of the projectile body, which must withstand the maximum allowable gas pressure to the double rotating band of 3,000 bar = 300,000 kN/m^2 = 300 MPa when firing from the gun with a rifled bore. To ensure the strength of fixing in the grooves of the corrective weights from the influence of the pressure of powder gases on them when firing from a gun, it is proposed to make the geometric profile of the groove in the cross section of a trapezoidal shape of the dovetail type. Besides, it is advisable to make the design of the projectile body in accordance with the strength calculation and obtain the minimum allowable decrease in the thickness of the rear part (as well as the middle one) of the body when correcting the unbalance vector, or to preliminarily increase this thickness at the beginning of the manufacturing process of the body in order to then be able to apply this manufacturing operation. At the same time, a constructive increase in the thickness of the rear part (or the middle one) of the projectile body will automatically entail an increase in the total mass of the projectile, which can affect the ballistics of firing, which we want to improve through diminishing unbalance by correcting the unbalance vector.

5. Research Results

To improve ballistic characteristics, it is proposed to calibrate and appropriately mark projectiles in five classes through two parameters of mass and their deviations from the norm: the first of which is the measurement of the total mass of the projectile in statics, and the second one is the measurement of unbalance of the mass of the projectile in the form of the amount of unbalance in dynamics [16]. When performing manufacturing operations for balancing and calibrating artillery projectiles through these two parameters, the following sequence of actions is proposed.

When metalworking the body of an artillery projectile of a given caliber, for example, 155 mm, trapezoid-shaped grooves of the dovetail type of the corresponding geometric dimensions are cut along the circumference on the lateral surface or in the end rear part of the body, which do not change the structural strength of the projectile from the pressure of powder gases during firing. After that, the projectile is placed on a balancing stand, on which the amount and angular coordinates of the existing unbalance are determined through balancing.

The unbalance vector of the projectile is corrected by a metalworker either directly on the balancing stand or at another workplace adapted for this operation, but after the correction, the balanced projectile is re-checked for the quality of the correction on a balancing stand. If necessary, the operation of correcting the unbalance vector is repeated until the normalized unbalance amount is reached. Correcting the unbalance vector is performed either on the end surface of the projectile (Fig. 3); or on the lateral surface of the body along the double rotating band (Fig. 4) through the use of one of two methods: either by placing corrective weights in pre-cut grooves (Figs. 3; 4), or by drilling or milling corrective holes (Fig. 5) of the appropriate number and dimensions. In so doing, the corrective weights or corrective holes at the correction points are placed symmetrically relative to a well-determined angular coordinate of the points of the unbalance vector.

After the operation of correcting the unbalance vector is completed, artillery projectiles are calibrated in the mass parameter (by statics) through weighing and applying appropriate markings to the body of each projectile taking into account the principle of distributing projectiles into five groups based on the amounts of residual unbalance obtained after the correction operation, which have amounts close to each other. In the event that amounts of residual unbalance of the projectiles after the correction operation differ significantly, although, in general, they do not exceed the normalized amount, then it is necessary to recalibrate these projectiles (an additional calibration) according to the second mass parameter (by dynamics), namely, according to the amount of residual unbalance, taking into account the same principle of distribution into groups: from two to five groups.

6. Discussion of the Results

Calibration of artillery projectiles through two mass parameters (in statics and in dynamics) will improve the accuracy of firing at a long distance at the expense of the possibility of using projectiles with the same ballistic characteristics (lateral deflection and drift) for more accurate determination of coordinates in ballistic calculations of firing to hit each single target. Consequently, stabilization of the ballistic characteristics of artillery projectiles at the expense of their calibration through two mass parameters contributes to an increase in firing accuracy and a decrease in the normalized consumption of projectiles (in quantity) to hit each single target.

In spite of the fact that the geometric parameters of the 155 mm caliber projectile do not exceed the limiting criterion of the $L/H \leq 5$ ratio for balancing rigid rotors in one correction plane, they are very close to critical values: without a fuse $L/H = 3.9$, and with a fuse $L/H = 4.5$. It is quite possible that in only one plane it will not be possible to achieve the desired positive result of correcting the unbalance vector and it will be necessary to increase the number of planes on the projectile body to two. Therefore, for the above-described possible options for correcting the unbalance vector in only one correction plane, it is necessary to carry out:

— computer simulation of the influence of the existing unbalance on the ballistic trajectory of the projectile in order to confirm theoretical assumptions before full-scale tests (Fig. 6);

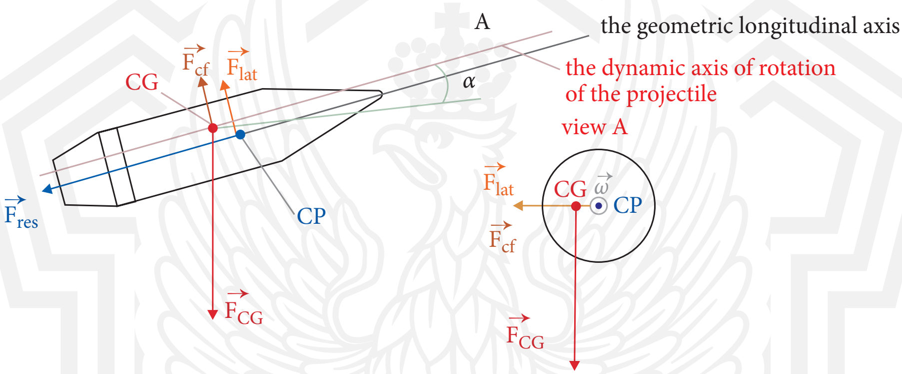

Fig. 6. Location of forces when the center of gravity of the projectile (CG) does not coincide with the center of aerodynamic pressure (CP) and the CG is on the dynamic axis of rotation of the projectile, and the CP is on the geometric longitudinal axis, which do not coincide

— the experimental full-scale tests to confirm the theoretical foundations with two different options for the selected place and plane for correcting the unbalance vector on the body of the artillery projectile in order to prepare a feasibility study and choose the best way to improve production;

— the experimental full-scale tests to confirm the theoretical foundations for improving the technical and quality indicators of the flight ballistics of the artillery projectile with a low level of unbalance after correcting the unbalance vector compared to the usual one when firing from the same gun with a rifled bore under the same weather conditions taking into account involving one unit of servicemembers with combat experience in the tests.

Prior to the start of testing, it would be advisable to obtain the results of theoretical design calculations for the strength of the projectile body in order to optimize the selection of the location of the planes and the method for correcting the unbalance vector, taking into account the equipment being used at a manufacturing plant as well as the features of the technique being applied for manufacturing the projectiles.

7. Conclusions

Despite the fact that the introduction of the additional manufacturing operation of balancing of artillery projectiles into the production will entail new financial costs for a manufacturing plant, the probability of obtaining significant benefits from this introduction is quite high. Improving the ballistic characteristics of artillery projectiles at the expense of stabilization of the lateral deflection and drift in flight when firing at a long distance from guns with a rifled bore will lead to the following:

- A decrease in the total number of projectiles to hit each single target and a corresponding decrease in the cost of logistical support with projectiles (at the expense of reducing the need for the quantity of projectiles to hit each single target).
- A reduction in the expenses for the maintenance of guns (at the expense of an increase in the inter repair period before the replacement of the tube in gun at the expense of fewer shots from one tube to hit each single target).
- Obtaining of a tactical advantage in military operations and the successful conduct of artillery fire to hit enemy's targets (at the expense of reducing the shortage in the number of projectiles of the necessary caliber).

All this as a whole implies saving the overall financial costs of artillery and gaining a tactical advantage in military operations.

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Kostiantyn Boriak https://orcid.org/0000-0003-4226-0102

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K. BORIAK

Poprawa właściwości balistycznych pocisków artyleryjskich kalibru 152 i 155 mm

Streszczenie. Istniejące metody wytwarzania pocisków artyleryjskich z kalibracją i znakowaniem tylko jednego parametru do pomiaru masy całkowitej, stosując statystycznie ważenie, nie uwzględniają dynamiki ruchu pocisku w powietrzu, a mianowicie dynamicznego niewyważenia masy na skutek nierównomiernego rozłożenia masy w całym geometrycznym kształcie pocisku. Pociski lecące po trajektorii balistycznej wirują w powietrzu z dużą prędkością kątową w zakresie 200-500 obr/min, dzięki czemu mają zbliżoną dynamikę ruchu obrotowego do obrotu sztywnych wirników. Ze względu na tolerancje produkcyjne w obróbce metalu korpusu, pociski artyleryjskie mogą wykazywać niewyważenie dynamiczne i duże niewyważenie, które może przekraczać dopuszczalną normę dla sztywnych wirników 15-20 razy i w nieprzewidywalny sposób wpływać na dynamikę pocisku, gdy porusza się on po trajektorii balistycznej. Rozwiązanie tego problemu polega na udoskonaleniu metod wytwarzania pocisków artyleryjskich poprzez wykonanie dodatkowej procedury produkcyjnej mającej na celu skorygowanie (zmniejszenie) wektora niewyważenia, co zmniejszy odchylenie boczne i znoszenie pocisków w locie, a także ustabilizowanie ich parametrów dynamicznych podczas poruszania się po trajektorii balistycznej w powietrzu, co z pewnością przełoży się na zwiększenie zasięgu pocisków i zwiększenie celności trafienia w cel. W artykule zaproponowano kilka możliwości praktycznej realizacji procedury produkcyjnej polegającej na korekcji wektora niewyważenia pocisków w jednej płaszczyźnie. Stosując metodę wyważania pocisków poprzez dodawanie brakującego metalu (masy) proponuje się umieszczenie odważnika korekcyjnego w specjalnym „rowku korekcyjnym" na zewnętrznej powierzchni korpusu pocisku, który można wstępnie wykonać na maszynie do obróbki metalu podczas ogólnej obróbki korpusu pocisku. Aby zapewnić wytrzymałość mocowania ciężarków korekcyjnych w rowkach przed wpływem ciśnienia gazów proszkowych na nie podczas strzelania z pistoletu, proponuje się wykonanie profilu geometrycznego rowka w przekroju poprzecznym w kształcie trapezu typu jaskółczy ogon. Stosując metodę usuwania nadmiaru metalu (masy) proponuje się wykonanie otworów na zewnętrznej powierzchni korpusu pocisku poprzez frezowanie (lub wiercenie). Masę i miejsce (kąt) poprawki, wymiary geometryczne oraz liczbę odważników korekcyjnych lub otworów korekcyjnych należy wstępnie określić w trakcie wyważania pocisków na stojaku. Proponuje się wprowadzenie oznakowania pocisków w pięciu klasach poprzez dwa parametry masy i ich odchyleń od normy: pierwszy to statyczny pomiar masy całkowitej pocisku, a drugi to pomiar niewyważenia masy pocisku w formie wielkości niewyważenia dynamicznego.

Słowa kluczowe: pociski, charakterystyki balistyczne, wyważanie, kalibrowanie, wektor niewyważenia
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