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DETERMINING THE BALLISTIC CHARACTERISTICS OF HUNTING CARTRIDGES

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The object of this study is hunting cartridges. The task addressed is to determine the ballistic indicators of hunting cartridges.

The standard deviation of shot distribution on the target has been determined, as well as the area of damage by hunting cartridges and the probability of penetrating a duralumin plate.

The result of experimental studies has established that the maximum value of the standard deviation of shot distribution at the level of 8–12 cm occurs with a minimum shot weight of 32 g and a minimum shot diameter of 3.75 mm. In this case, the powder charge was an average value of 1.65 g. The area of damage was simulated by using an original software by increasing the penetration point on the target to the size of the total equivalent diameter of the most vulnerable elements of UAV with FPV piloting.

On a target with an equivalent diameter of 8 cm, the area of damage has a maximum value of 0.45–0.5 m^2 when using a minimum shot diameter of 3.75 mm. In this case, the shot weight had a maximum value of 42 g, and the weight of the powder charge was at an average level of 1.65 g. Therefore, a decrease in the diameter of the shot and an increase in the weight of the shot lead to an increase in the number of elements that hit the target, which, accordingly, leads to an increase in the area of damage.

The probability of penetrating a duralumin plate 1 mm thick was determined as the ratio of the number of shots that pierced the duralumin plate to the total number of hits in it. This value has a maximum value of 0.6–0.8 rel. units at maximum values of the shot diameter of 4.75 mm, the shot weight of 42 g, and the weight of the powder charge of 1.71 g.

The practical significance of the research results relates to the fact that they could be used to improve ammunition and means of defeat for unmanned aerial vehicles (UAVs), which are controlled using FPV piloting under combat conditions

Keywords: hunting ammunition, powder charge, shot, area of damage, probability of damage

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1. Introduction

Russia's military aggression against Ukraine has become an arena for the application of the latest technologies that significantly change the tactics of combat operations. One of such innovations is the use of UAVs, which include a wide range of aircraft of different purpose, size, and conditions of use. UAVs are becoming more widespread every year and are increasingly used both on the battlefield and in reconnaissance, artillery support, and even in conducting psychological operations. UAVs with FPV (First-Person View) piloting allow maneuvers with high precision, saving resources and reducing the risk to personnel.

FPV UAVs are unmanned aerial vehicles equipped with cameras that transmit real-time video directly to the pilot's glasses, which creates the effect of first-person flight. They allow for highly precise maneuvers, enabling a wide range of angles and details that cannot be achieved with conventional cameras. This, in turn, makes them effective for a wide range of military missions, from reconnaissance to precision strikes [1].

The military uses FPV UAVs not only for reconnaissance but also for delivering ammunition to specific locations, laying minefields, or attacking enemy armored vehicles [2]. One example of this is attacks on heavy equipment and artillery installations. FPV UAVs equipped with explosives can reduce the effectiveness of enemy artillery without endangering infantry or gunners. FPV UAVs are also actively used in these operations to destroy ammunition or heavy equipment from a distance, which reduces casualties [3].

Despite their numerous advantages, the use of FPV UAVs in warfare also presents certain challenges. One of the main challenges is the vulnerability of these UAVs to electronic warfare. However, interest in technologies that allow for the effective use of FPV UAVs is only growing. Every year, these devices are becoming more accessible, which allows even small units to use them to perform complex tactical tasks [4].

Thus, FPV UAVs have become an important element of modern military conflicts, changing the strategies and tactics of combat. They allow for precise strikes, real-time reconnaissance, reducing casualties and increasing the effectiveness of combat operations [5].

Understanding that in the future the use of FPV UAVs will only increase, and they will become an important part of the arsenal of the modern army, it is also necessary to consider the issue of countering them.

To effectively counter FPV UAVs, it is necessary to devise new technologies that would enable mass production and, if possible, at a less cost. One of these directions may be the use of a hunting shotgun and appropriate cartridges. Hunting cartridges can be used at a distance of no more than 20–50 m, and such a distance is realistic for countering only FPV UAVs from a significant list of UAVs. A hunting shotgun, unlike a rifle, fires a charge consisting of many shots instead of one bullet [6]. The difficulty of using a shotgun is that, unlike a rifle, in which the trajectory of a bullet can be predicted relatively accurately, it is quite difficult to practically track the flight of each shot separately.

Therefore, research on determining the parameters of the shot (weight, minimum diameter of the shot, weight of the powder charge), which ensure uniform distribution of the shot relative to the center of the target, is relevant. This, in turn, will allow for a higher probability of hitting the target, namely, an enemy FPV UAV.

2. Literature review and problem statement

Open access studies that consider FPV UAVs are usually of a scientific and journalistic nature. In particular, work [2] provides a general description of FPV UAVs, their operating principle and scope, without delving into the technical features of the design, the principle of hitting targets, and ways to ensure resistance to combat equipment. As a rule, such information includes commercial and military secrets aimed to avoid disclosing the capabilities of specified UAVs to a potential enemy.

Work [3] analyzes potential threats that UAVs may pose, namely physical attacks, collisions, privacy violations. The design features of UAV, typical methods of communication between its components, and some technical characteristics are considered. Information on technological advancements in the field of electronic warfare, guidance systems, software, new materials, communication technologies, avionics, etc. is highlighted. Three approaches to detecting, identifying, and tracking UAVs are described: visual, radio frequency, and acoustic. It is noted that government and military organizations keep technical information about FPV UAVs and methods for their detection and neutralization secret in order to have a strategic advantage.

In [5], an analysis of the evolution of combat clashes between UAVs in the air, on the ground and over water is carried out using an example of the war in Ukraine. It is described how tactical FPV UAVs regularly enter into "air battles" with enemy UAVs. Typical attack scenarios are characterized: collision, undermining, capture by a net and the use of small UAV interceptors. The key technical characteristics of UAV interceptors are considered: maneuverability, simplified guidance system, autonomous reactions. Examples of the use of UAV interceptors in response to FPV strikes are given, which demonstrates the beginning of the formalization of the "UAV-versus-UAV" strategy. Based on the data obtained, a conclusion was drawn about the need to design new technologies and systems to counter UAVs under modern conditions for dominance in combat theaters.

Papers that report the research on the uniformity of shot distribution relative to the center of the target when shooting from a hunting shotgun can be conditionally divided into works focused on external and internal ballistics. Work on external ballistics include studies [7–16].

In [7], it is noted that an optimal shot from a hunting shotgun is possible only when the shots fly evenly, which increases the probability of hitting the target. However, excessive scattering can lead to the fact that none of the shots will hit the target. An unsolved scientific problem is the achievement of controlled dispersion of the shot charge.

This issue was partially investigated in work [8]. The authors determined the degree of dispersion of different types of shot charge by shooting from 12-gauge shotguns with two barrels with different technical characteristics, from a distance of 10, 18 and 25 meters. As a result of the research, from 65% to 80% of the area of the pattern created by the pellets was evenly distributed relative to the center of the shot, and this percentage was maintained for shots from all three distances. The authors note that the degree of dispersion of the shots (the number of pellets that are evenly printed in the center of the shot) can be controlled and is an important factor in determining the firing range. However, the study of the firing range directly was not performed in the work.

In [9], a model for determining the firing range for rifles with a cylindrical barrel and a choke was proposed. Shooting was carried out from 12-gauge rifles with a full choke, as well as from 12-gauge and 16-gauge rifles with a cylindrical barrel. Shots were fired from distances of 75, 100, 300, 500, and 1000 cm with shots No. 2 and No. 5. For each type of rifle, statistically significant indicators of shot dispersion were found depending on the type of shot and the distance of the shot. It was noted that to determine the distance of the shot and the degree of dispersion of the shot charge, the type of rifle, the degree of narrowing of the barrel, and the type of shot should be taken into account. In this regard, additional experimental and comparative studies should be conducted for each individual type of weapon.

In order to determine the effect of barrel length on the nature of shot dispersion, the authors of [10] fired five 12-gauge shotguns, the barrels of which were gradually shortened. Six barrel length options were tested for each shotgun. Shots were fired from six different distances, with each experiment repeated three times. At all distances, a significant increase in the area of the scree was recorded when comparing the initial configuration of the shotgun with a shotgun with a changed barrel length. The study showed that the distance to the target and the presence of a choke in the barrel have a greater effect on shot dispersion than the barrel length itself. The results are at odds with an earlier study [11], in which the authors note that the barrel length (in the range from 20 to 36 inches) and the size of the shot do not significantly affect shot dispersion. The presence of a choke has a minimal effect on the degree of shot dispersion in this experiment.

The influence of the type and size of the shot on the degree of its dispersion after a shot from a hunting shotgun is also discussed in [12]. As a result of the studies, it was found that with unchanged parameters of the shotgun and the distance of the shot, the degree of dispersion of both steel and lead shot increases with decreasing shot size. The disadvantage of work [12], as well as previous papers [10] and [11], is that the studies did not take into account the influence of aerodynamic forces on the degree of dispersion of the shot.

A study on this issue is reported in [13]. The aim was to establish the degree of influence of aerodynamic forces on the formation of the shot dispersion pattern during a shot from a smooth-bore firearm. The flow structure was modeled using computational gas dynamics methods. For this purpose, a characteristic shot distribution was determined by analyzing the probability density of the location of particles. The preliminary results indicate the presence of a noticeable influence of vortex disturbances arising from the movement of front pellets on the trajectory of subsequent (rear) pellets. This phenomenon is critical for further improvement of models for predicting shot dispersion and increasing the effectiveness of target destruction.

A common drawback of the above papers [7–13] is the relatively high error in the processing of experimental data. In [7–13], multiphysical processes of the so-called clouds (swarms) of shot at different distances from the gun barrels were investigated by conducting numerous tests and experiments. To predict the degree of shot dispersion, statistical processing of the experimental results was used, which, due to the human factor, often reduces the reliability of the data.

In work [14], a more effective method for estimating shot dispersion is reported, compared to [7–13]. The authors also devised a simple technique for determining the shot distance based on the proposed method. This method makes it possible to significantly improve the accuracy of calculations.

The use of statistical analysis methods for predicting the dispersion of external ballistics shot by collecting data on the shot after firing is also highlighted in works [15, 16]. In particular, in study [15] the authors show that the Magnus effect cannot be the main mechanism of shot dispersion when fired from a rifle, as indicated in many modern studies of external ballistics. One-dimensional motion of bodies in the air, applied to shots that cover a short distance, indicates that the Reynolds number remains approximately constant throughout the flight. The distribution of shots on the target is better described by a phase-shifted Maxwell distribution in the transverse displacement space. The minimum rotation frequencies necessary for the formation of a typical scattering pattern have been determined, and it has been established that they significantly exceed the values that can be physically achieved by shots flying out of a barrel with a smooth channel. The mathematical relationships described in the cited study are generalized and universal, which makes it possible to construct modern mathematical models based on them to describe the processes and phenomena of external ballistics.

In study [16], a series of shots were fired from a 12-gauge smoothbore shotgun (Hugsan model, pump-action, chokeless, with a barrel length of 52 cm) at different distances using shot of four calibers: 2; 3.5; 5; and 8 mm. The aim of the work was to determine the distance of the shot based on the nature of the shot dispersion. 5 shots were fired from each caliber at distances of 0.7; 0.8; 0.9; 1; 2; 3; 5; 10; 15; 20; and 25 meters. The maximum distances between the shots in the vertical and horizontal directions were measured. The authors' mathematical relationships make it possible to determine the distance of the shot, knowing the length and diameter of the barrel, as well as the type of cartridge. However, the results can be used only for the specified parameters of the barrel and cartridge, as well as when firing with shot with similar geometric characteristics.

One of the first studies on the internal ballistics of a cartridge case is reported in [17]. The authors conducted many experiments and described various phenomena of internal ballistics. The disadvantage of the work is that the presented photographic experiment with a cloud of pellets, despite its high scientific value, still concerns external ballistics. Having conducted his own research, the author of work [18] notes that the parameters of the shot cloud depend on the launch conditions, such as the internal ballistics of the rifle, the properties of the cartridge case and the shot, as well as the interaction and individual characteristics of the shot. The conclusions indicate that in order to fully understand the behavior of the shot cloud, it is necessary to study all combinations of the above effects, especially to study the area near the muzzle in detail. However, conducting such studies requires significant expenditure of money and time.

More accurate calculations of internal ballistics, compared to studies [17, 18], make it possible to model by using the finite element method [19]. The disadvantage of this model is the lack of the ability to calculate the stress and deformation of the gun barrel. Also, when calculating the internal ballistics of the projectiles, the authors did not take into account the pressure of the chamber on the barrel.

In turn, such studies are reported in [20]. The authors, using the nonlinear non-stationary finite element method, performed the simulation of a 9-caliber bullet in the barrel after the shot, taking into account the pressure in the chamber, the value of which was used in the model as a load. The resulting model makes it possible to obtain data on the plastic deformation and kinematic state of the bullet, as well as the stress diagram and its distribution in the barrel over time. The numerical results describe the entire intra-barrel process, correcting the inaccuracies of real experiments that investigate the internal ballistics of projectiles. The use of simulation significantly helps engineers in the design of new systems, reducing the time for the development of small arms barrels.

Work [21] builds on the studies reported in [19, 20]. The authors performed numerical modeling of the internal ballistic behavior of the shot for rifles by combining two methods – discrete and finite elements. Multiphysical phenomena in the barrel, wad, case, and pellets were investigated. The shots were fired from a 12-gauge rifle with Italian 9½ 24 g shot with 433 pellets and American 00 shot with 9 pellets (with and without buffer). The shells were fired from two barrels – a thirty-inch cylindrical one and a full choke. A model of the complete internal ballistics of the pellets is presented until the first leading pellet reaches 1 meter from the muzzle. The goal was to compare the phenomena of shot dispersion. Also, since the barrel and wad were affected by chamber pressure, it was possible to simultaneously calculate such transient dynamic characteristics as stress/strain, barrel vibration, and wad stress/strain. According to the results of the study, the presence of a choke increased the average velocity of the 9½ shot, reducing the degree of its dispersion. For buckshot, this effect was less pronounced. Buffered buckshot also had a lower degree of dispersion compared to unbuffered buckshot. The results could be used to optimize the design of rifles and the selection of ammunition. However, in the cited work, as in previous ones, all input parameters for calculating the model were not specified. The models described above do not work under conditions of uncertainty.

In turn, the authors of [22], when studying the intraballistic cycle in the "projectile-gun barrel" model, performed an analysis of the spread of uncertainty caused by uncertainty in the input parameters. The statistical moments of the projectile parameters (mathematical expectation, variance, skewness coefficient, kurtosis coefficient) were calculated using the Bootstrap method. The estimation of the probability density function and the probability distribution function was performed using the maximum entropy method. Based on the results of the study, the authors presented a rule and a model for the propagation of uncertainty in the projectile-barrel system, taking into account variations in the uncertainty of input parameters. The proposed approach is universal and could become the basis for the construction of other models to study internal ballistics. A limitation of the cited study is the difficulty of using the results for investigating external ballistics due to a significantly larger number of input parameters for modeling.

An example of using simulated ballistics modeling of a projectile in the Ansys software environment is given in [23]. The purpose of the study was to examine the nature of deformations at different angles of fire and to establish important initial conditions for increasing the accuracy of firing at long distances at relatively large angles. It was necessary to substantiate from the point of view of physics the so-called "gun rule": when firing at an inclined surface, the projectile, as a rule, hits above the aiming point. It is noted that vertical deformations of the barrel, compared to axial and horizontal deformations, have the greatest impact on the trajectory of the projectile, and should be taken into account when firing at an angle (up or down). The results were used to design a simulator for three-dimensional analysis of the trajectory of the projectile. However, the results of the study have limited application due to the experimental conditions.

Thus, in terms of practical application, the issue of controlled dispersion of the shot is reduced to the development of a "weapon-ammunition" system in accordance with the specified efficiency indicators. According to [24], the efficiency of hunting weapons is largely determined by the characteristics of the shot cartridge. The goal is to achieve uniform and stable dispersion of pellets; moderate dispersion width, which makes it impossible to bypass the target without hitting a significant number of pellets; sufficient speed of pellets after the shot, which guarantees the target hit. Ideal dispersion involves compliance with the above conditions. At the same time, other factors also affect the end result: the type and size of the shot, the weight of the charge, and the dimensions of the target itself. This makes it difficult to achieve unanimity in conclusions and approaches to shooting.

Based on the above, it follows that the methods reported in the cited papers only partially meet the requirements for the necessary characteristics of hunting cartridges for defeating FPV UAVs. Therefore, there is a scientific task to devise a methodology for determining the characteristics of hunting cartridges for defeating FPV UAVs. This will make it possible to establish a correspondence between the technical characteristics of ammunition (shot diameter, shot charge weight, amount of gunpowder in the charge) and its capabilities to defeat drones. On this basis, it would be possible to establish guidelines that the "weapon-ammunition" system should meet when designing individual means of defeating FPV UAVs.

3. The aim and objectives of the study

The purpose of our study is to determine the ballistic performance of hunting cartridges for defeating FPV UAVs. This will provide an opportunity to determine rational values for the characteristics of hunting cartridges for defeating FPV UAVs and directions for their further improvement.

To achieve this aim, the following objectives were accomplished:

– to determine the standard deviation of the distribution of shot on the target;

– to determine the area of impact with hunting cartridges;

– to determine the probability of penetration of a duralumin plate.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is hunting ammunition.

The hypothesis of the study assumes that by determining the root mean square value of the distribution of the shot, area, and probability of damage, it is possible to characterize the effectiveness of defeating FPV UAVs by hunting ammunition. This will make it possible to determine rational values for the characteristics of hunting ammunition for defeating FPV UAVs and the directions of their further improvement.

When conducting research using experimental planning, it was assumed that the use of the *D*-optimal Box-Benkin plan would make it possible to most accurately describe the measurement results. This assumption implied deriving a regression equation that minimizes the variance between the measured values of the quantities and the resulting regression equation.

The simplification was that the experimental planning was carried out for the three, in our expert opinions, most significant factors that characterize the effectiveness of defeating FPV UAVs by hunting ammunition.

4. 2. Methodology for determining the ballistic characteristics of hunting cartridges for defeating FPV UAVs

Our study on the characteristics of hunting cartridges for defeating FPV UAVs was carried out using a multifactorial experiment according to the *D*-optimal Box-Benkin plan for the three studied factors [25]. The adequacy of the derived regression equations was assessed using the Fisher criterion. Statistical assessment of the level of variance in our results was carried out using the Cochrane criterion. The significance of coefficients in the regression equation was assessed using the Student criterion. All criteria were determined at the 95% confidence level. The value intervals and levels of variation in variable factors that were used in the research are given in Table 1.

Table 1

Intervals of magnitude and variance in the levels of the studied factors

Factor ID	Designation	Level of factor variation			Variation intervals
		−1	0	+1	
Shot diameter, mm	d_D	3.75	4.25	4.75	0.5
Weight of shot charge, g	p_D	32	37	42	5
Amount of gunpowder in the charge, g	p_C	1.59	1.65	1.71	0.06

Since the material from which the FPV UAV is made differs depending on the design (polymer, light alloys, in particular duralumin, etc.), the target material was chosen as classic for this type of ballistic research [7, 8]. Shots from a hunting rifle were fired at a target made of white paper measuring 1.5 by 2 m and a duralumin plate with a thickness of 1 mm placed directly behind it. The distance to the target was 20 m. The shots were fired in daylight, at a temperature of 20°C, and at normal atmospheric pressure. The speed of the shot charge leaving the barrel was measured by Garmin Xero C1 Pro and was 366 ± 18 m/s. It was assumed that the air speed was zero. The angle of the shot was constant, for which the rifle was stabilized.

The experiments used a hunting rifle IZH-43 (Remington Spartan 220) 12-gauge (barrel diameter 21.2 mm, barrel length 723 mm). The ammunition was charged in accordance with the experimental plan according to the *D*-optimal Box-Benkin plan for the three factors under study and the intervals of values and variations of the levels of the factors under study, given in Table 1.

The shooting was carried out in the ballistic track at the National Defense University of Ukraine, Kyiv. The shooting was carried out 1 shot at the target, after which the target was replaced with a new one, and the coordinates of the hit of individual pellets were determined on the hit target.

The coordinates of the scattered shot on the target were analyzed using the PlotDigitizer program (Sun Microsystems, USA), Fig. 1. Based on these values, the mean square deviation of the shot from the center of the shot scattering on the target was determined.

The area of damage was modeled by enlarging the penetration point on the target to the size of the total equivalent diameter of the most vulnerable elements of FPV UAV. In our studies, the equivalent diameter of the FPV UAV was taken at 8 cm (Fig. 2).

The probability of penetration was determined as the ratio of the number of pellets that penetrated the duralumin plate to the total number of hits in it (Fig. 3).

Analysis of the experimental results in Fig. 1, 2 was performed using the PlotDigitizer software (Sun Microsystems, USA).

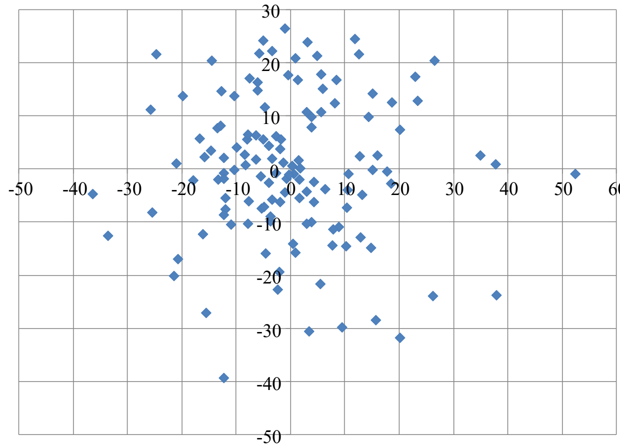

Fig. 1. Sample of scattered shot on a target with a shot diameter of 3.75 mm, shot weight of 42 g, and powder charge weight of 1.65 g

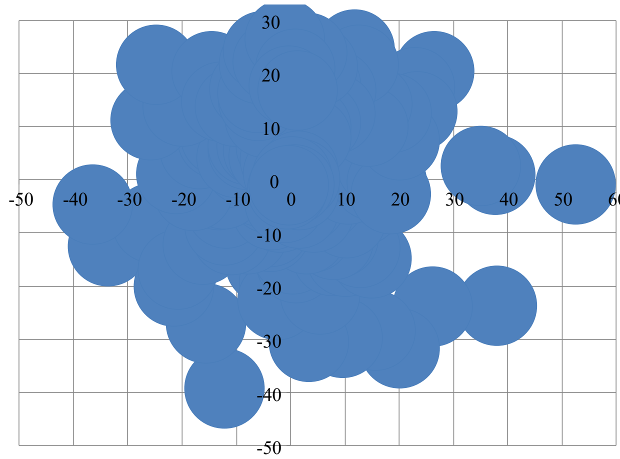

Fig. 2. Example of determining the area of damage with an equivalent target diameter of 8 cm, with a shot diameter of 3.75 mm, a shot weight of 42 g, and a powder charge weight of 1.65 g

Fig. 3. A sample of damage to a duralumin plate 1 mm thick with a shot diameter of 3.75 mm, shot weight of 42 g, and powder charge weight of 1.65 g

5. Results of determining the ballistic characteristics of hunting cartridges for defeating FPV UAVs

5. 1. Determining the standard deviation of the shot distribution on the target

The standard deviation (for three repetitions) of the shot distribution on the target depending on the values of the experimental factors is given in Table 2.

Table 2

Standard deviation in the distribution of shot on the target depending on the value of the experimental factors

Pellet diameter, mm	Weight of the charge of the shot, g	Amount of gunpowder in the charge, g	Mean of the standard deviation of pellet distribution on the target, cm
4.75	42	1.65	8.19
3.75	32	1.65	10.12
4.75	32	1.65	12.21
3.75	42	1.65	10.05
4.75	37	1.71	7.37
3.75	37	1.59	7.56
4.75	37	1.59	7.18
3.75	37	1.71	8.24
4.25	42	1.71	7.44
4.25	32	1.59	10.38
4.25	42	1.59	8.08
4.25	32	1.71	8.24
4.25	37	1.65	8.44
4.25	37	1.65	8.44
4.25	37	1.65	8.44

The regression equation that describes standard deviation in the distribution of pellets on the target, taking into account significant regression coefficients, takes the form

$$\delta = -828.687 - 0.057 \cdot d_D - 2.587 \cdot p_D + 1076.744 \cdot p_C + 1.727 \cdot d_D^2 + 0.055 \cdot p_D^2 - 326.286 \cdot p_C^2 - 0.395 \cdot d_D \cdot p_D, \qquad (1)$$

where δ is the standard deviation of pellet distribution on the target, cm; d_D is the diameter of shots, mm; p_D is the weight of shot charge, g; p_C is the powder charge, g.

The regression equation (1) is graphically illustrated in Fig. 4–6.

Thus, it can be stated that the results of determining the standard deviation in pellet distribution on the target were obtained by taking into account the given range of shot diameter, shot charge weight, and gunpowder.

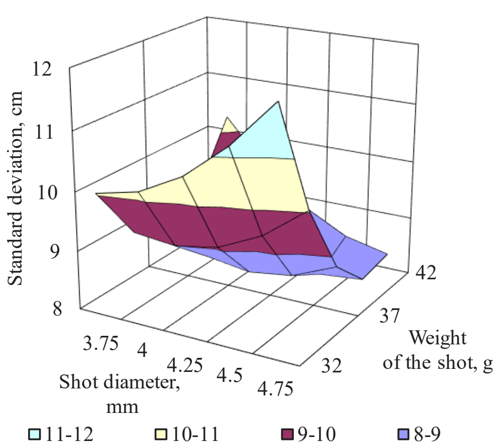

Fig. 4. Standard deviation in pellet distribution on the target depending on the diameter and weight of the pellet with a powder charge of 1.65 g

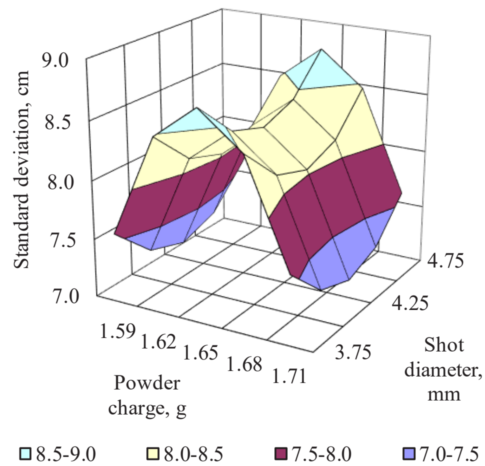

Fig. 5. Standard deviation in pellet distribution on the target depending on pellet diameter and powder charge with shot charge weight of 37 g

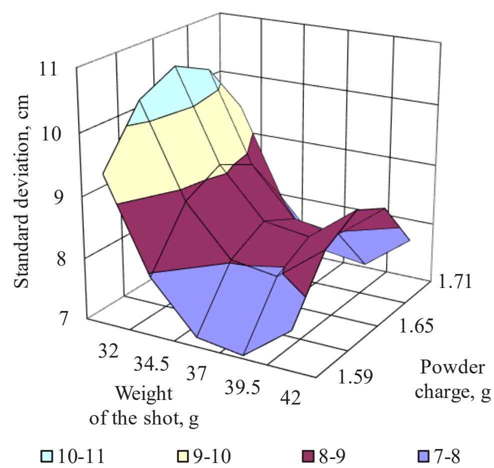

Fig. 6. Standard deviation in pellet distribution on target depending on pellet weight and powder charge at shot diameter of 4.25 mm

5. 2. Determining the area of damage by hunting cartridges

The area of damage (for three repetitions) by hunting cartridges depending on the value of the experiment factors is given in Table 3.

The regression equation that describes the target area, taking into account significant regression coefficients, takes the following form

$$S = -31.547 + 0.008 \cdot d_D - 0.141 \cdot p_D + 42.158 \cdot p_C + 0.038 \cdot d_D^2 + 0.002 \cdot p_D^2 - 12.841 \cdot p_C^2 - 0.007 \cdot d_D \cdot p_D - 0.120 \cdot d_D \cdot p_C + 0.020 \cdot p_D \cdot p_C, \qquad (2)$$

where S is the hit target area, m^2.

The regression equation (2) is graphically illustrated in Fig. 7–9.

Thus, we have obtained results of determining the area of damage to a target with an equivalent diameter of 8 cm depending on the given range of shot diameters, shot charge weight, and gunpowder.

Table 3

Area affected by hunting cartridges depending on the value of the experiment factors

Pellet diameter, mm	Weight of the charge of the shot, g	Amount of gunpowder in the charge, g	Average value of the hit area, m^2
4.75	42	1.65	0.32
3.75	32	1.65	0.47
4.75	32	1.65	0.36
3.75	42	1.65	0.50
4.75	37	1.71	0.26
3.75	37	1.59	0.36
4.75	37	1.59	0.26
3.75	37	1.71	0.38
4.25	42	1.71	0.34
4.25	32	1.59	0.38
4.25	42	1.59	0.34
4.25	32	1.71	0.36
4.25	37	1.65	0.35
4.25	37	1.65	0.35
4.25	37	1.65	0.35

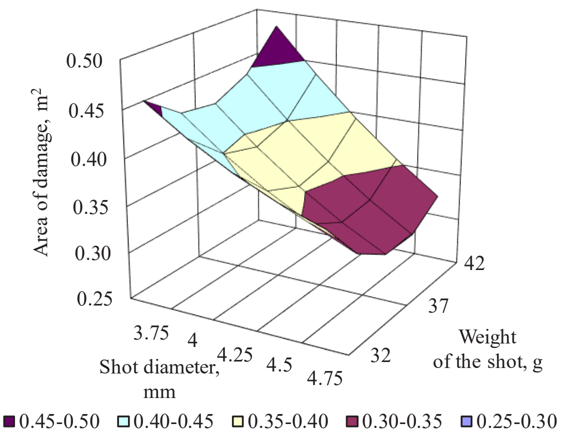

Fig. 7. Hit target area with an equivalent diameter of 8 cm depending on the weight and diameter of the shot with a powder charge of 1.65 g

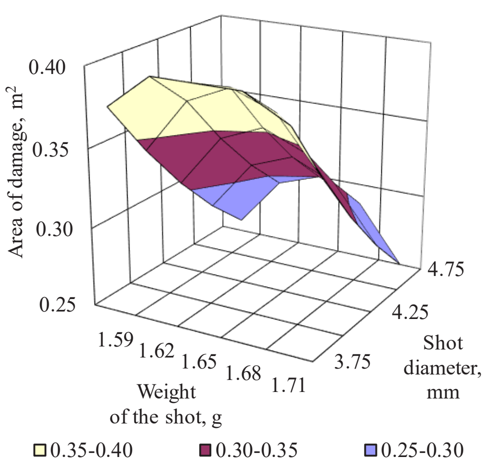

Fig. 8. Hit target area of 8 cm equivalent diameter depending on powder charge and shot diameter with shot charge weight of 37 g

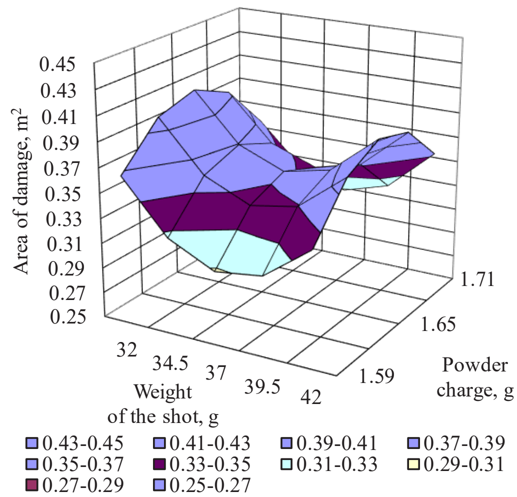

Fig. 9. Hit target area with an equivalent diameter of 8 cm depending on the powder charge and shot weight with a shot diameter of 4.25 mm

5. 3. Determining the probability of penetrating a duralumin plate

The probability of penetrating a duralumin plate (for three repetitions) depending on the values of the experiment factors is given in Table 4.

Table 4

Probability of penetrating a duralumin plate depending on the value of the experimental factors

Pellet diameter, mm	Weight of the charge of the shot, g	Amount of gunpowder in the charge, g	The average value of the probability of penetrating a duralumin plate, relative units
4.75	42	1.65	0.63
3.75	32	1.65	0.06
4.75	32	1.65	0.65
3.75	42	1.65	0.00
4.75	37	1.71	0.78
3.75	37	1.59	0.09
4.75	37	1.59	0.54
3.75	37	1.71	0.03
4.25	42	1.71	0.22
4.25	32	1.59	0.32
4.25	42	1.59	0.10
4.25	32	1.71	0.52
4.25	37	1.65	0.18
4.25	37	1.65	0.18
4.25	37	1.65	0.18

The regression equation that describes the probability of penetrating a duralumin plate (all regression coefficients are significant) takes the following form

$$\begin{aligned} P = {} & 72.528 - 7.498 \cdot d_D - 0.057 \cdot p_D - 68.357 \cdot p_C + \\ & + 0.450 \cdot d_D^2 + 0.002 \cdot p_D^2 + 18.789 \cdot p_C^2 + 0.004 \cdot d_D \cdot p_D + \\ & + 2.511 \cdot d_D \cdot p_C - 0.062 \cdot p_D \cdot p_C, \end{aligned} \tag{3}$$

where P is the probability of penetrating a duralumin plate, relative units.

The regression equation (3) is graphically illustrated in Fig. 10–12.

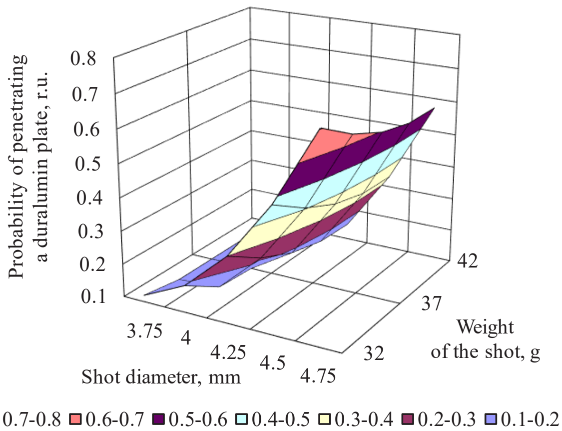

Fig. 10. Probability of penetrating a duralumin plate 1 mm thick depending on the weight and diameter of the shot with a powder charge of 1.65 g

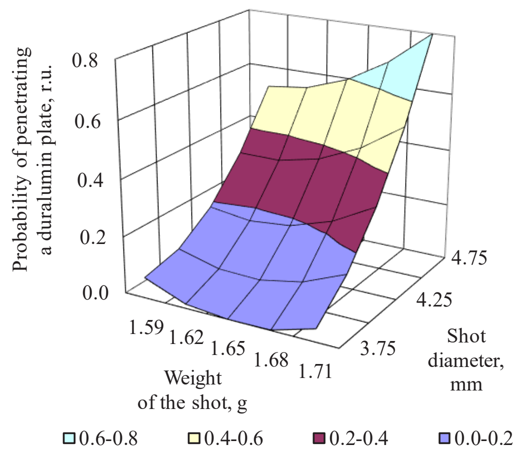

Fig. 11. Probability of penetrating a duralumin plate 1 mm thick depending on the shot diameter and powder charge with a shot charge weight of 37 g

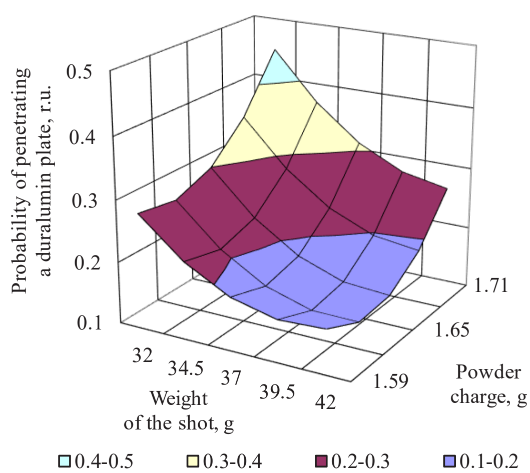

Fig. 12. Probability of penetrating a duralumin plate 1 mm thick depending on the weight of the shot and the powder charge with a shot diameter of 4.25 mm

Our results provide an idea about the influence of a given range of shot diameter, shot charge weight, and gunpowder on the probability of penetrating a duralumin plate.

6. Discussion of results based on determining the ballistic characteristics of hunting cartridges for defeating FPV UAVs

The use of hunting cartridges to combat drones is common under war conditions. The basis for such application is the experience of combat operations. There are also scientific studies on determining the effectiveness of defeating FPV UAVs with hunting cartridges [26–28].

Unlike earlier research, our study determined the characteristics of hunting cartridges for defeating FPV UAVs, namely: the mean square deviation in the shot from the center of the target, the area, and the probability of impact. This was achieved by using the design of experiments involving the *D*-optimal Box-Benkin plan for the three factors under consideration.

The plot characterizing the standard deviation in pellet distribution on the target depending on the diameter and weight of the shot is shown in Fig. 4. It demonstrates that the maximum value of the standard deviation of pellet distribution occurs at a shot diameter of 4.75 mm and a shot weight of 32 g. A smaller peak of the standard deviation in pellet distribution is observed at a shot diameter of 3.75 mm and a shot weight of 42 g. The maximum roundness of the shot on the target occurred in almost the entire range of shot diameters and at an average shot weight of 37 g. These are the parameters of the standard cartridge, and therefore the maximum roundness of the shot on the target is due to the fact that the parameters of the rifle and the standard cartridge have mutual correspondence. The deviation in the diameter and weight of the shot from the standard (average) values leads to an increase in the standard deviation in pellet distribution on the target. At the same time, the probability of hitting an FPV UAV increases.

The standard deviation in pellet distribution on the target depending on the shot diameter and the powder charge is shown in Fig. 5. It demonstrates that the maximum value of standard deviation in pellet distribution occurs at an average powder charge of 1.65 g. There are also practically identical maxima of standard deviation in pellet distribution at a minimum 3.75 mm and a maximum 4.75 mm shot diameter. The maximum roundness of the shot on the target occurred at an average shot diameter of 4.25 mm and an average powder charge of 1.65 g. The deviation in shot diameter from the standard (average) values at a powder weight of 1.65 g leads to an increase in the standard deviation in pellet distribution on the target.

The standard deviation in pellet distribution on the target depending on the shot weight and the powder charge is shown in Fig. 6. It demonstrates that the maximum value of standard deviation in pellet distribution occurs at an average value of the powder charge of 1.65 g and a powder weight of 32 g. The maximum roundness of the shot on the target was observed at an average value of the shot weight of 37 g and an average value of the powder charge of 1.65 g.

Thus, analysis of standard deviation in pellet distribution on the target depending on the diameter and weight of the shot, as well as the powder charge, revealed the following. The maximum roundness of the shot on the target was observed in almost the entire range of shot diameters, at an average shot weight of 37 g and an average value of the powder charge of 1.65 g. These are the parameters of the standard cartridge, and therefore the maximum roundness of the shot on the target is due to the fact that the parameters of the rifle and the standard cartridge have mutual correspondence. However, the probability of hitting an FPV UAV increases with an increase in the standard deviation in pellet distribution on the target. The deviation in shot diameter towards larger (4.75 mm) and smaller (3.75 mm) from the standard (average) values leads to an increase in the standard deviation in pellet distribution on the target. The maximum value of standard deviation in pellet distribution occurs at an average powder charge of 1.65 g and a shot weight of 32 g.

The impact area of a target with an equivalent diameter of 8 cm (Fig. 7–9) has a maximum value when using a minimum shot diameter of 3.75 mm, a maximum shot weight of 42 g, and a powder charge weight of 1.65 g. This value of the powder charge is a parameter of a standard cartridge, which has a mutual correspondence with the parameters of the rifle. At the same time, a decrease in the shot diameter and an increase in the weight of the shot lead to an increase in the number of elements that hit the target, and accordingly, this leads to an increase in the area of damage.

The probability of penetrating a duralumin plate 1 mm thick depending on the diameter and weight of the shot and the powder charge is given in Fig. 10–12. It has been clearly established that the probability of penetrating a duralumin plate increases with an increase in the shot diameter, shot weight, and powder charge weight. This is explained by the fact that increasing the above indicators increases the kinetic energy of the shot, and accordingly the probability of penetrating the duralumin plate.

The proposed method for determining the characteristics of hunting cartridges for defeating FPV UAVs, unlike existing ones, makes it possible to establish a correspondence between the technical characteristics of the cartridges and their functional purpose. It also provides the opportunity to design rational variants of cartridges for effective combat against FPV UAVs.

Thus, when determining the characteristics of hunting cartridges for defeating FPV UAVs, the root-mean-square deviation in shot from the center of the target, area, and probability of impact were established. The results of our study have made it possible to determine those parameters of the cartridges that would make it possible to defeat FPV UAVs to the greatest extent.

The equations derived (1)–(3), as well as the experimental dependences established (Fig. 4–12), are new in that they were obtained using the factorial design method of the experiment and such results were not reported in the reviewed literature.

The limitations of our studies include their conduct for a specific type of hunting cartridges, and the results are limited by the conditions of the experiment.

The disadvantages include the fact that the studies were conducted on the existing database of characteristics for hunting cartridges and rifles, which does not fully meet the conditions of combating FPV UAVs.

The practical significance of the research results relates to the fact that they could be used to improve ammunition and means of defeating FPV UAVs, including for use in automatic protection systems installed on combat vehicles [29] under the conditions of modern combat operations.

7. Conclusions

1. We have established that the maximum value of standard deviation in pellet distribution at the level of 8–12 cm is achieved at a minimum shot weight of 32 g and a minimum shot diameter of 3.75 mm. In this case, the powder charge's average value was 1.65 g.

2. It has been found that the impact area of a target with an equivalent diameter of 8 cm takes a maximum value of 0.45–0.5 m^2 when using a minimum shot diameter of 3.75 mm. In this case, the shot weight had a maximum value of 42 g, and the weight of the powder charge was on average 1.65 g. Therefore, a decrease in the shot diameter and an increase in the shot weight leads to an increase in the number of elements that hit the target, and accordingly, this leads to an increase in the impact area.

3. It has been established that the probability of penetrating a duralumin plate with a thickness of 1 mm takes a maximum value of 0.6–0.8 relative units at the maximum values of shot diameter of 4.75 mm, shot weight 42 g, and a powder charge weight of 1.71 g.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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