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SUITABILITY OF USING DIFFERENT TYPES OF SHOTGUN SHELLS IN DEFENCE AGAINST LOW-SLOW-SMALL UAV

Ivan PEMČÁK, Jiří SKALA, Josef BAČA

Abstract: The suitability of using different types of shotgun shells for defence against low, slow and small (LSS) UAVs (Unmanned Aerial Vehicle) is investigated in this article. The basic criterion for assessing the effectiveness of shotgun fire is the hit probability and the effect of gunfire on the target. When using different types of shotgun ammunition, it is necessary to balance two conflicting requirements. First is hit probability which is affected by the number of pellets in the shotgun shell. Second is the kinetic energy of pellets which is affected by their size and speed. The theoretical procedure for determining the optimal types of shotgun ammunition depending on the distance and resistance of the target is demonstrated.

Keywords: Hit probability; Kinetic energy of pellet; UAV; Buckshot; Birdshot; Shotgun dispersion.

1 INTRODUCTION

Today, the use of unmanned aerial vehicles (UAVs) is widespread in both civilian and military applications. Increasing the availability of these devices to the general public also means an increased security risk. For companies, in terms of industrial espionage, and for the armed and security forces, in terms of reconnaissance and direct attack. In this article will be discussed defence against micro UAV of Class I. [1] Properties of this subclass of UAVs are described in Table 1.

Tab. 1 Properties of Micro Class I. UAVs

Weight of UAV	Operating Altitude	Mission Radius	Payload
< 2.00 kg	< 90 m	< 5 km	0.2-0.5 kg

Source: author.

Defence against UAVs is currently composed form many different methods. These methods range from control signal jamming, GPS scrambling, taking control of the device, to the physical capture or destruction of the device. Signal jamming may become less and less effective in the future, due to the implementation of autonomous systems that do not rely on GPS signal or operators input. Therefore, it is necessary to have the means for physical destruction of UAVs. One way of physical destruction is the use of small arms fire. And one of the most common groups of handheld weapons for defensive purposes is the shotgun. The effective range of most shotgun shells is limited by the relatively low initial velocity and high dispersion of the pellets cloud. At the same time, shotgun ammo offers large variability between individual types of rounds, differing in the number of shots, their size, material and initial speed.

This article was created in collaboration with the Department of Weapons and Ammunition, University of defence Brno. This article is one of a series dealing with the detection and elimination of UAVs. [2][3]

2 DETERMINATION OF BASICS PARAMETERS

Two types of cartridges were chosen for comparison in this article. In American terminology, these are the 12 gauge #4 Buckshot and the #1 Birdshot. Equivalent designation of used ammunition is 12/76/6,09mm SB and 12/70/4,00mm SB. Cartridges are displayed in Fig. 1. Properties of the cartridges used are described below in Table 2.

Fig. 1 #1Birdshot (left) and #4 Buckshot (right) shels
Source: author.

Tab. 2 Ammunition properties

Type	Number of pellets	Pellet diameter (mm)	Weight of one pellet (g)	Initial velocity (m/s)
#4 Buckshot	41	6,09	1,32	370
#1 Birdshot	111	4	0,323	380

Source: author.

The number of pellets and their weight was determined by delaboration of used ammunition. The initial speed of the cluster of shots was provided by the manufacturer of ammunition. [4][5] In both cases, the pellet was made from lead. The cartridges were chosen with regard to their availability and its use in the Czech army.

3 DETERMINING THE PROBABILITY OF TARGET DESTRUCTION

The basic precondition for destroying the target is its hit with sufficient number of projectiles with sufficient energy. It is not certain, that pellet form shot will hit the target. Therefore, it is necessary to first determine the hit probability. Simulation method will be used to determine the hit probability. In this paper, is considered as the target of a commercially available drone DJI MAV 2. Whose 3D model is used for creation of image of drone in a target plane Fig. 2. For this paper was chosen random orientation of drone. In this image, drone is divided into two areas.

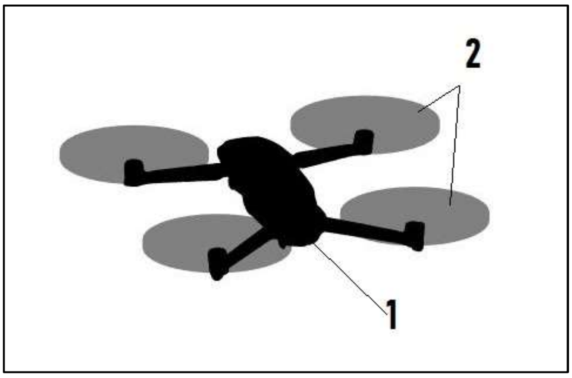

Fig. 2 Used drone image - DJI MAV 2
Source: author.

The first area consists of the drone body itself,. I assume that a single shot of any size with kinetic energy greater than $E_{k,\,lim}$ will ensure destruction. The second area consists of rotor spaces. Which is the entire space where the rotor moves. It would be impractical to simulate firing with individual rotors in different positions, so this simplification is introduced. As a result, the rotor is not necessarily hit when rotor space is hit. To facilitate the calculation, I assume that the probability of the rotor blade being hit in case of hit rotor space is P_{rot} = 0.2. This problematic will be detailly investigated in future studies. For purposes of this article, this simplification is acceptable. Also in this case, the kinetic energy necessary to eliminate the propeller and thus the entire drone is considered to be $E_{k,lim}$. Combined hit probability for entire drone $P_{1,2}$ is calculated as

$$P_{1,2} = P_1 + P_2 P_{rot}. \quad (1)$$

Where P_1 and P_2 are probabilities for hitting each part of drone.

3.1 Determining the probability of hit

To determine the probability of hitting the target when firing a cloud of projectiles, it is necessary to determine the characteristics of the dispersion of the cluster of shots depending on the distance, this dependence is known as „pattern“. To do this, experimental shootings were carried out. For this experiment was used Beneli M3T with 19.75 inches smoothbore barrel with cylinder bore (without choke). Targets were analysed using Matlab code. [6]

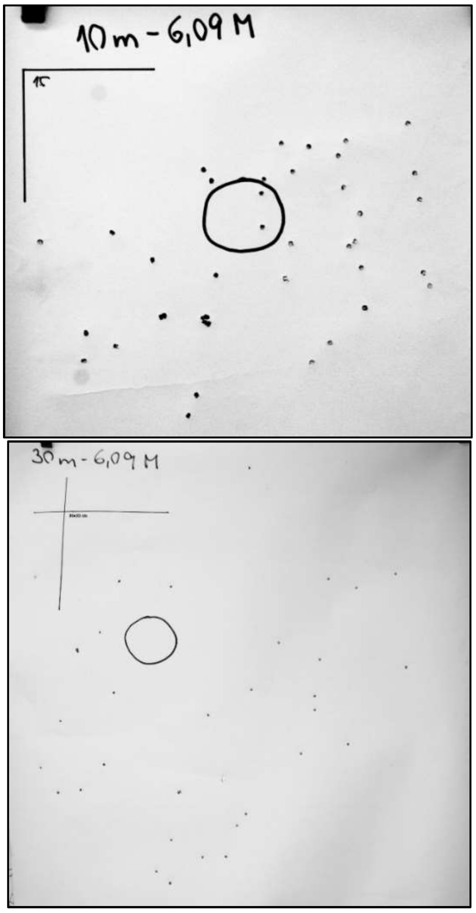

Fig. 3 Pattern for #4 Buckshot at 10m (top) amd 30m (bottom)
Source: author.

In Fig. 3 are shown targets after one shot of #4 Buckshot at distances 10m and 30m with circle with 10cm in diameter used as aiming point. Note that in both cases, the midpoint of impact is shifted to the right and bottom. This shift was also observed in other targets. It is result of imperfect zeroing of the weapon. It is a systematic mistake removable by correctly zeroing of the weapon.

In this article, I will not take into account the error of the shooter or the error of aiming the weapon. The aiming error also includes an error of determining distance and lead. This issue is described in previous articles in this series [1] [2].

Distribution of hits corresponded to the normal distribution. This was confirmed by analysis carried out in Matlab using Shapiro-Wilk parametric hypothesis test of composite normality with $\alpha = 0.05$. [3] Furthermore, it can be assumed that when shooting shotgun horizontally at short distances, σx, σy will be the same. Thus, the scattering pattern should have a circular characteristic. Minor deviations from this assumption observed in Table 2 are possibly caused by an insufficient number of conducted experiments. The following characteristics were determined and used for calculations.

Tab. 3 Standart deviation of shots from center of pattern

Standard deviation from the centre of pattern in mm (σ_x, σ_y)			
Type	10m	20m	30m
#4 Buckshot	120, 89	213, 213	235, 263
#1 Birdshot	77, 85	176, 161	244, 332

Source: author.

For further calculations were standard deviation approximated by first degree polynomial equations. Values of 0 for both σ_x and σ_y were added at 0m distance for proper approximations. Equations for dispersion with 95 % confidence bounds are shown below.

$$\sigma_{x,\#4\ Buck} = (7.98 * x + 22), \quad (2)$$

$$\sigma_{y,\#4\ Buck} = (9.13 * x + 4), \quad (3)$$

$$\sigma_{y,\#1\ Bird} = (8.31 * x), \quad (4)$$

$$\sigma_{y,\#1\ Brid} = (10.72 * x - 16{,}4). \quad (5)$$

Results for #4Buckshot were further verified by another experiment. In which was fired at square target of size 0,6m x 0,6m at distance 10m – 50m in 10m increments. Two independent targets were used. Number of hits in each target was counted. Hit counts were compared with simulation of fire at target 0,6m x 0,6m using Monte Carlo method with 10000 individual experiments for each distance. Results of simulation are compared in Tab. 4. Shot at Target 1. at 50m distance was admitted as shooters error.

Tab. 4 Hit count ouf #4 Buckshot

	Distance to target (m)				
	10	20	30	40	50
Target 1	41	36	21	11	3
Target 2	41	38	14	12	9
Simulation	41	33	22	15	10

Source: author.

Due to the insufficient number of experiments for proper statistical evaluation, I consider these results to be satisfactory for this article. With the obtained dispersion parameters, it was possible to simulate, the probability of hit for individual target zones for both types of shells. The centre of dispersion pattern was aimed at the centre mass of drone.

In Fig. 4 are shown results of one simulation for #4 Buckshot in distance 10 and 30 meters. Each red point represents one pellet hit in target plane.

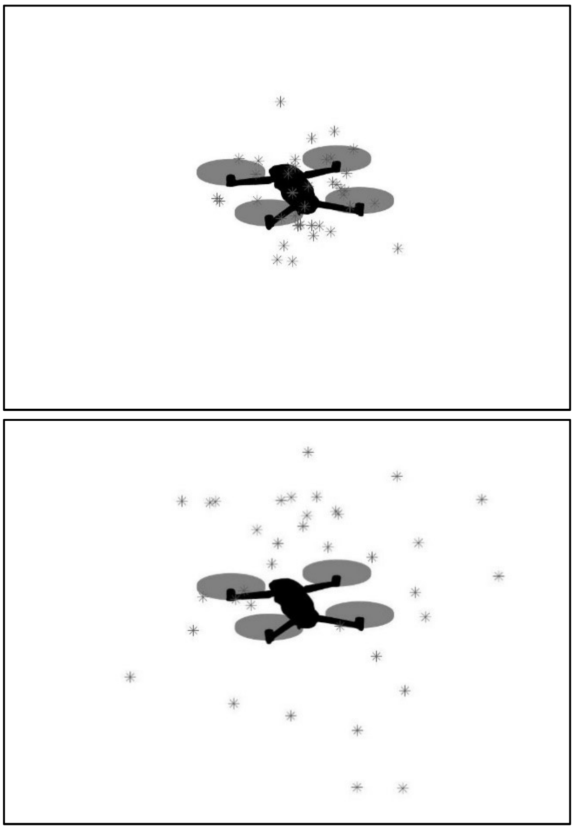

Fig. 4 Dispersion simulation in 10 (top) and 30 meters (bottom)
Source: author.

Simulations were carried out using Monte Carlo method with 10000 individual experiments for a given distance with a step of 5m. In each experiment was examined the state of target. If at least one pellet hit was observed in first zone, the target was considered to be destroyed. When pellet hit second zone, then was tested dependent probability of hitting rotor blade.

If rotor blade was hit, then the target was destroyed. With large number of experiments the frequency of successful destruction of the target is equal to the probability of destruction.

The results of the simulations are shown in Fig. 5.

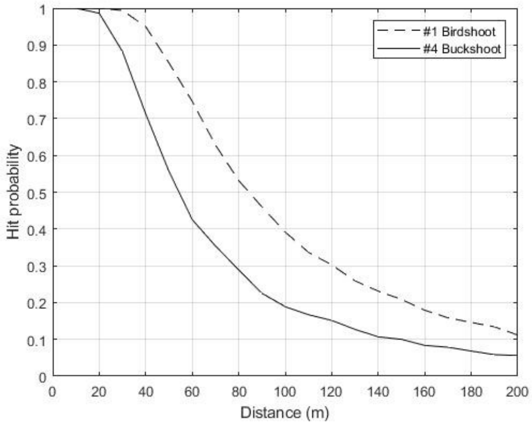

Fig. 5 Combined hit probability for both types of ammunition
Source: author.

It is clear from the results, that the use of #1 Birdshot is more advantageous in terms of hit probability. For example, at 50 m has the #1 Birdshot probability $P_{\#1\ \mathrm{Bird},\ 50} = 0.84$ when for #4 Buckshot it is only $P_{\#4\ \mathrm{Buck},\ 50} = 0.45$. However, the energy of the projectile must be taken into account when assessing effectiveness of fire.

3.2 Determination of projectile energy

For the needs of this paper, the energy of individual projectiles was considered to be equal its kinetic energy

$$E_k = \frac{1}{2}mv^2. \tag{6}$$

Where m is mass of single pellet and v is instantaneous speed of projectile. The calculation of the speed of projectile fired from firearms is one of the basic tasks of external ballistics and is described in detail in the literature [7] [8]. Since the shotgun pellets are spherical, it was possible in this article to use the simplified calculation method presented by E.J. Allen in publication "Approximate ballistics formulas for spherical pellets in free flight" [9]. Equation 6. Calculate speed of single pellet at given distance and is divided into three parts depending on Mach's number of projectile.

$$v = \begin{cases} \dfrac{0{,}92 M_0 v_s}{(0{,}92 + 0{,}0375 M_0) e^{\left(\frac{0{,}69x}{k_z}\right)} - 0{,}0375 M_0} & for\ 0 < x \le x_1 \\ \dfrac{-0{,}1956 v_s}{0{,}965 e^{\left(\frac{-0.12225(x-x_1)}{k_z}\right)} - 1{,}128} & for\ x_1 < x \le x_2 \\ \dfrac{0.2926 v_s}{0{,}495 e^{\left(\frac{0{,}3135(x-x_2)}{k_z}\right)} - 0{,}077} & for\ x > x_2 \end{cases} \tag{7}$$

where:

$$x_1 = 1{,}44928\, k_z \cdot \ln\left(\frac{0.80417 M_0}{0.92 + 0.0375 M_0}\right), \tag{7}$$

$$x_2 = x_1 + 1{,}05173 k_z\ , \tag{8}$$

$$k_z = \frac{D\rho_p}{\rho_a}, \tag{9}$$

$$M_0 = \frac{v_0}{v_s}, \tag{10}$$

where v_0 is initial velocity of projectile, v_s speed of sound, D is diameter of projectile, ρ_p is density of projectile material, ρ_a is density of air and x is distance from muzzle. For this paper values were chosen as:

$$\rho_p = 11{,}3\ \mathrm{g \cdot cm^{-3}},$$

$$\rho_a = 0{,}0012\ \mathrm{g \cdot cm^{-3}},$$

$$v_s = 340\ \mathrm{m \cdot s^{-1}}.$$

The dependence of speed on the flight path was determined by analytical calculation. The calculated speeds correlate with the observation and are shown in Fig 6.

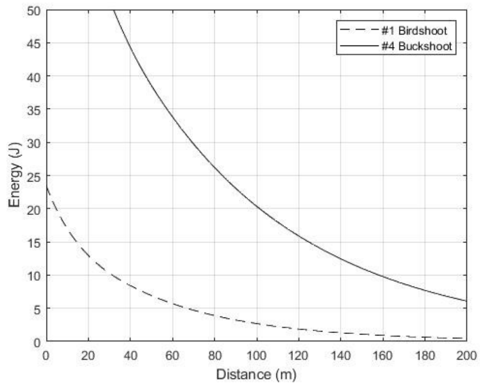

Fig. 6 Kinetic energy of individual pellets for both types of ammunition
Source: author.

Required kinetic energy needed for drone destruction is considered to be $E_{k,\lim} = 10$J. The value was chosen on the basis of practical experience. It can be seen from the speed profiles that #1 Birdshot has kinetic energy only 6.9 J at 50 m, which is less than the estimated limit energy $E_{k,\lim} = 10$J. In contrast, #4 Buckshot with 38J of energy is certainly capable to destroy intended target.

4 DESIGN OF THE OPTIMAL SHOTGUN LOAD FOR A GIVEN DISTANCE

The calculated results show that the # 4 Buckshot is too powerful for its intended purpose because its kinetic energy does not correlate with the probability of a hit. With the obtained outputs, it is possible to theoretically design the optimal load with the maximum probability of hit and sufficient energy at the selected distance of the engagement. To demonstrate this case, we choose a distance of 100m.

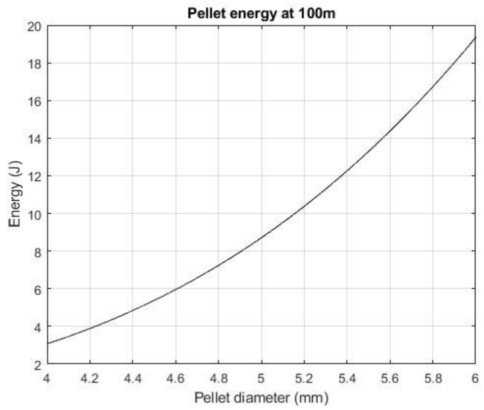

Fig. 7 Pellet energy at 100m
Source: author.

Using formula from the previous paragraph, it is possible to numerically quantify the kinetic energy of a pellet at a distance of 100 m with initial speed $v_0 = 370\ \mathrm{m \cdot s^{-1}}$, depending on its the diameter. This v_0 is the most common among powerful heavy high-brass loads. Iteration step is selected as 0.01mm. The resulting energies are shown in Fig. 7.

When energy E_k = 10J is required at a distance of 100 m, a pellet with a diameter should be D = 5,15mm. This shotgun load is closely related to the not very widespread ammunition marked as AAA Buckshot. This load is currently difficult to obtain and is usually manufactured only for chambers of length of 70mm and shorter, while the described # 4 Buckshot is designed for more powerful systems with a chamber length of 76mm. Therefore, some data from the # 4 Buckshot are used for the theoretical load calculation. For purpose of this paper this theoretical load will be called AAA Buckshot 12/76. It is expected that the total weight of the shots will be the same, as are used for optimal load calculation. The total weight of pellets in the cartridge is given by the relation

$$m_s = c_p * m_p. \tag{11}$$

Where m_s is the weight of all pellets in cartridge, c_p is the number of pellets in the cartridge and m_p is weight of one pellet. Substituting the data from Tab. 1 for #4 Buckshot we get $m_{s,\#4}$ = 54,12g. By expressing and substituting the equation is obtained:

$$c_{p,AAA.12/76} = \frac{m_{s,\#4}}{m_{p,AAA}}, \tag{12}$$

Where $$m_{p,AAA} = \frac{\pi * D^3}{6} * \rho_p, \tag{13}$$

It can be assumed that the initial speed of the pellet cloud will be the same for #4 Buckshot and designed AAA Buckshot 12/76.

Tab. 5 Properties of eperimental load

Type	Number of pellets	Pellet diameter (mm)	Weight of one pellet (g)	Initial velocity (m/s)
AAA Buckshot 12/76	66	5,15	0.808	370

Source: author.

By reducing the diameter of an individual pellet and maintaining the total weight of all pellets in the cartridge, the cartridge will naturally contain a larger number of pellets. This will consequently also increase probability of successful hit. For calculation was used dispersion properties of # 4 Buckshot. Based on experience, this simplification can be used for preliminary analysis. For exact verification scatter pattern, it is necessary to perform experimental shooting, which is outside the scope of this article.

The simulation results using the values for AAA Buckshot 12/76 are shown in the following graph.

It can be observed that the limit energy of 10J is reached at a distance of 100m. At this distance there is a probability of hit $P_{\text{AAA Buck 12/76, 100}}$ = 0.37. For comparison $P_{\text{\#4 Buck, 100}}$ = 0.20.

5 CONCLUSION

This article presents possible way of evaluating effectiveness of shotgun fire. It can be stated that at the specified parameters, the use of #1 Birdshot ammunition is ineffective for distances exceeding 30m. Birdshot ammunition in general can only be used effectively for a very short distance. At the same time, it can be stated that the use of ammunition #4 Buckshot at a distance of 50 m still guarantees the probability of hitting $P_{\text{\#4 Buck, 50}}$ = 0.5 with more than enough energy for the effect in the target.

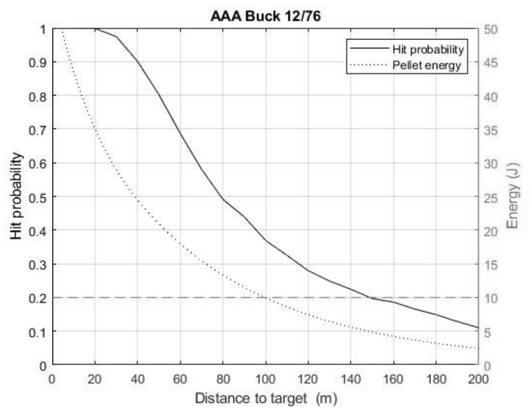

Fig. 8 Energy of pellet and hit probability of theoretical AAA Buckshot 12/76
Source: author.

Furthermore, the procedure for determining the optimal load for a given distance of 100 m was demonstrated. In which sufficient energy $E_{k,lim} = 10J$ is still provided for destruction of chosen target. If desired maximal distance would be lower, even smaller diameter pellet could be used resulting in higher hit probability. Simultaneously with increasing resistance of the targets and required kinetic energy of pellet, the question arises of using larger shots, for example popular #00 Buckshot, even at the cost of a lower hit probability. Which then have to be adequately balanced by a larger number of shooters, or several rounds fired at given target.

In this article the dispersion characteristics of the Benelli M3T shotgun and used ammunition used were significantly simplified, for exact application it is necessary to exactly confirm their specification and experimentally verify the presented results.

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Dipl. Eng. Ivan **PEMČÁK**
University of Defence
Kounicova 65
662 10 Brno
Czech Republic
E-mail: ivan.pemcak@unob.cz

Dipl. Eng. Jiří **SKALA**
University of Defence
Kounicova 65
662 10 Brno
Czech Republic
E-mail: jiri.skala@unob.cz

Dipl. Eng. Josef **BAČA**
University of Defence
Kounicova 65
662 10 Brno
Czech Republic
E-mail: josef.baca@unob.cz

Ivan PEMČÁK graduated in Weapons and ammunition engineering from University of Defense, Czech Republic in 2018. After two-year as an ordnance officer in a light infantry battalion of Czech armed forces, he returned to the University of Defense as Ph.D. candidate. His field of research is fire control systems, target hit probability and weapon design.

Jiří SKALA graduated in Weapons and ammunition engineering from University of Defense, Czech Republic in 2020. He is currently employed at Prototypa-ZM, s.r.o. as an experimental shooter and technician. In parallel with work, he is working on his PhD at the Department of Weapons and Ammunition His field of research is weapon design, operation and maintenance.

Josef BAČA graduated in Weapons and ammunition engineering from University of Defense, Czech Republic in 2017. He serves in the military repair facility in Jaroměř, where he specializes in the repair of fire control systems. His field of research is fire control systems, target acquisition and optical system design.