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PERFORMANCE OF AIRCRAFT CANNONS IN TERMS OF THEIR EMPLOYMENT IN AIR COMBAT

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Abstract:

The article deals with the combat use of aircraft cannons in close-range aerial manoeuvering combat in terms of their usage and combat effectiveness. The specifics of air combat manoeuvering are analyzed as well as of Gatling cannons - the general formula can be applied to all cannons and a manoeuvering target. The emphasis is laid on the calculation of the probability of kill by a cannon burst, while particular factors, which influence this probability, are analysed. The further part compares the performance of chosen air cannons in terms of muzzle energies of variously long cannon bursts as well as the possibilities of cannon fire application of the most spread or perspective fighters. The conclusive part evaluates the chosen fighters in terms of the number of 1-second bursts they are able to deliver as well as of the overall muzzle energy of all their carried projectiles.

1. Introduction

Altough aircraft cannons are generally belonging among the oldest aerial weapon systems intended for air target destruction, they are still used today and present an important and widely used means of destroying both aerial and ground targets. They have been implemented into airplanes since the First World War. However, at that time they were usually manually-loaded single-shot weapons. During the time between the world wars, the designers concentrated on the refinement of machine guns, while cannons were slightly neglected. Though, during the Spanish Civil War, the German Messerschmitt Bf 109 with a 20mm cannon demonstrated distinct superiority over the Soviet fighters, which were equipped only with machine guns.

2. Employment of Aircraft Cannons in Air Combat

The major advancement of aircraft cannons was brought by the Second World War. While on the beginning of the war, the dominant weapon had still been the machine gun, the 20mm cannons became a common armament in the year of 1945. Even some bigger calibers (30, 37 or 45mm) were not rare and a few weapons with a caliber, which is typical rather for artillery guns, appeared (American 75mm or German 55mm cannons). Despite these weapons had devastating effect for the target, they had not been overly spread because of their excessive recoil force. Aerial automatic guns played a key role during the Korean conflict. In the sixties of the 20^{th} century, after the introduction of air-to-air guided missiles, a ply for excluding aircraft cannons from the fighter aircraft’s armament appeared. However, because of the low reliability of the guided missiles of that time and due to the fact, that the pilot had nothing left to defend himself by after all the missiles had been fired, the aircraft cannon became a component of the new versions of those airplanes (F-4E) again and it was additionally installed into the original versions.

It appears that the percentage of gun kills diminishes conflict to conflict. For instance, all shootdowns achieved by Israeli fighters during the Six Day War were reached by cannon. Though during the Attrition War, the percentage of gun kills dropped to 70%. This portion further subsided to only 30% in the Yom Kippur War, while in the Lebanon Interdiction in 1982 it was just 7%. During the years 1982-1990, no aerial victory by any Israeli fighter was achieved by air cannon.

During the Falklands War (1982), only four of all shootdowns scored by British fighters were achieved by cannon, the rest was reached by air-to-air guided missiles. Likewise, the USAF scored only two gun kills during the Operation Desert Storm. However, despite of these statistics, the importance of aircraft cannons should not be underestimated. In particular, this is reflected by the experience of USAF in Vietnam.

During this conflict, the airplanes equipped with aircraft cannon (F-105 Thunderchief, F-8 Crusader) achieved significantly better score than aircrafts armed only with guided missiles (F-4 Phantom II). The F-105D scored 27.5 kills (mostly MiG-17), from which only two were achieved by guided missile. The F-8 proved to have the best kill-to-loss ratio (6:1) among all U.S. aircraft throughout the war. The average score of USAF fighters during the years 1965-1968 was just 2.15:1, while the US Navy was slightly better with the score of 2.75:1. The number of achieved aerial victories by aircraft type is shown in Table 1. The term "manoeuvre" in this table refers to an aerial victory, which was achieved without the use of weapon systems (e.g. the adversary collided with terrain during the air combat) [7].

Tab. 1.

Shootdowns by USAF in Vietnam by particular aircraft type and weapon

ACFT/WEAPON	AIM-7	AIM-9	Cannon	Manoeuvre	*Total*
F-100	0	0	1	0	*1*
F-105	0	3	28	0	*31*
F-4B,C,D,J	56	62	11	1	*130*
F-4E	11	8	6	1	*26*
F-8	0	14	5	0	*19*
A-7	0	0	1	0	*1*
Total	*67*	*87*	*52*	*2*	*208*

The aircraft cannon plays an important role especially in those cases, in which the visual identification of the target is necessary. This forces the pilot to approach to the target to a very close range, which in fact can be smaller than the minimum range for a succesful missile launch. These situations can occur also in peace during fulfillment of the tasks of anti-air defense (AAD) and NATINADS. From the fighter pilot's point of view, there are three areas regarding aircraft cannons, which are the most important: the combat effectiveness of aircraft cannons, their firing envelope and the possibilities of defense manoeuvring against a gun attack. This paper will analyse the first area [4], [7]..

3. The specifics of air combat and of Gatling cannons employment

The air combat manoeuvring (ACM) has some traits, which influence the manner of aircraft cannon employment in it and the cannon's combat effectivness. The ACM is typical by frequent manoeuvring of the fighter aircraft and the target, while the manoeuvres are usually conducted with a high G-load. The change of the plane of manoeuvre is also very common. The attacking airplane can be positioned in any aspect angle with respect to the target. As a result of these conditions, high-deflection shots and snapshots are very common. Further, the time for aiming and for the burst itself is very limited. The length of burst is usually not greater than 1.0 or 1.5 second.

The weapons working on the Gatling principle reach their maximum rate of fire only after a certain amount of time, which they need for spin-up of their set of barrels to the maximum angular velocity. This spin-up lasts usually from 0.3 to 0.55 seconds depending on the particular weapon. Weapons which are externally-powered (M61) have a significantly longer period of spin-up than weapons, which's set of barrels is spun by an internally gained force (GSh-6-23). The necessity of spin-up lowers the number of fired projectiles during the burst (as a burst we consider an interval between pushing the trigger until firing of the last projectile). Therefore it is necessary to include the spin-up time into the calculations. However, a certain run-up time is required also for other cannons than Gatlings (e.g. revolver guns). But in these cases, the run-up time is so small (about 0.05 seconds), that we can neglect it.

4. Methodical calculation of the combat effectiveness of aircraft cannons

For the purpose of evaluation of the combat effectiveness of aircraft cannons, methodics of calculation was developed. The equation (5) was adopted from [9].

The aircraft cannon's combat effectiveness in ACM is characterized by the probability, with which a burst destroys the target under certain previously stated conditions (engagement parameters) such as range, time of burst, aiming error, target shape etc. The probability of kill by a cannon burst (P_k) can be expressed as a quotient of ***energy of the burst*** and of the ***medium energy necessary for killing the target***, multiplied by the ***probability of hit***, as stated in (1)

$$P_k = P_z \cdot \frac{E_b}{E_z} \quad , \qquad (1)$$

where P_k is the probability of kill, P_z is the probability of hit, E_b is the energy of burst, E_z is the medium energy necessary for target destruction.

The medium energy necessary for killing the target is a parameter of the target. It is "the number of megajouls", that we need to deliver to the target to be able to consider it destroyed. It depends on the thickness, slope and protection features of the target's surface. These parameters can differ in dependance on which part of the target aircraft is hit. Further, most airplanes (targets) have so-called vulnerable areas. If one of these areas is hit, the probability of disabling the whole aircraft is obviously higher, than if the shot hits an other part of the target. Under real conditions, it also appears, that the fired projectiles tend to have bigger overall effectiveness if they are concentrated on a smaller area, than when they are spread and solitarily hit different parts of the target. This effect is usually referred to as density of fire. However, quantification of these phenomena is so complicated, that its introduction into the analytical solution of P_k would lead to an excessive complexity of the calculation, while the practical value of its results would not be much increased due to the immense number of factors on which it would be dependent. Therefore, we will consider a target of constant ballistic parameters all over its surface in the further calculations and we will also seclude the effect of density of fire in order to achieve an acceptable level of simplification.

The energy of burst can be expressed as the overall energy of all fired projectiles, as in (2)

$$E_b = n_v \cdot E_i \quad , \tag{2}$$

where n_v is number of fired projectiles, E_i is the energy of every single projectile.

The energy of a projectile has two components (kinetic and chemical) and is therefore a sum of them, as stated in [3]

$$E_i = E_k + E_{ch} \quad , \tag{3}$$

where E_k is the kinetic energy of a single projectile at the time of impact, E_{ch} is ihe chemical energy of a single projectile.

The kinetic energy is gained during the shot and usually diminishes during the flight of the projectile towards the target as a result of aerodynamic drag. Therefore it is necessary to consider the kinetic energy at the time of impact, not at the time when the projectile leaves the barrel. The impact velocity depends also on the relative speed of the fighter aircraft and the target. The flight speed of the attacker also influences the initial velocity of the projectile and its aerodynamic drag. The size of the kinetic energy is stated in (4)

$$E_k = \frac{1}{2} m_i v_c^2 \quad , \tag{4}$$

where m_i is the mass of the projectile, v_c is the impact velocity of the projectile.

The chemical energy is a result of the fragmentation effect of the *HE* component and the incendiary effect of the *I* component of the projectile. The effort to analytically determine its size or to make a comparison between kinetic and chemical energy is very complicated. Let's analyse the effect of a delay-fuzed HE-I cannon projectile. Firstly, such projectile causes damage by its kinetic energy at the moment of impact on the target. Afterwards, it penetrates deeper, where the HE component explodes and causes further damage. This blast produces lots of shell fragments, which inflict another damage by their kinetic energy. Finally, the incendiary (I) component inflicts further chemical effect (fire) to the target. Now it is clear, that it is almost impossible to analytically determine the size of the chemical energy, which depends on the design of the projectile and the fuse and on the structure of the target's surface. Therefore we have to use an empiric formula, which gives us the amount of chemical energy in dependance on the portion of high-explosive (HE) or incendiary (I) component in the projectile. This relation is shown in (5)

$$E_{ch} = 10 \cdot \frac{m_{HEI}}{m_i} \cdot E_k \tag{5}$$

where m_{HEI} is the mass of the HE-I components.

By substitution of (4) and (5) to the original formula (3), we get the final formula for the energy of a single projectile (6)

$$E_i = \frac{1}{2} m_i v_c^2 \cdot (1 + 10 \cdot \frac{m_{HEI}}{m_i}) \quad . \tag{6}$$

The number of fired projectiles in a burst is dependent on the cannon's rate of fire, length of burst and eventually on the spin-up time, as shown in (7)

$$n_v = \frac{k}{60} \cdot (t - \frac{t_r}{2}) \tag{7}$$

where k is the theoretical rate of fire [min^{-1}], t is the length of burst, t_r is the time necessary for spin-up (in the case of Gatling cannon).

By substitution of (6) and (7) to the formula (2), we get the final formula for the energy of burst (8)

$$E_b = \frac{k}{60} \cdot (t - \frac{t_r}{2}) \cdot \frac{1}{2} m_i v_c^2 \cdot (1 + 10 \cdot \frac{m_{HEI}}{m_i}) \tag{8}$$

The determination of the probability of hit is also a complex subject. In a real situation, we have a target of a certain shape, which is being attacked from a particular aspect angle. Therefore, the target always presents a different area. The dispersion pattern of the projectiles differs as well, since it is dependent on the relative velocity of the fighter aircraft and the target and on the nature of the manoeuvre, which is being performed. If the closure was zero and the attacker was not manoeuvring, the dispersion pattern would have a circle shape. The mutual position of the target and the dispersion pattern depends on the aiming error, which is caused by pilot during the aiming process. As a result, the dispersion pattern and the target overlap (either completely, partialy or not at all). Hence we can conclude, that the probability of hit can be expressed as a quotient of the area of the overlap and the area of the whole dispersion pattern, as stated in (9)

$$P_z = \frac{A_{\text{int}}}{A_{fig}} \quad , \tag{9}$$

where A_{int} is the area of the intersection of the target and the dispersion pattern, A_{fig} is the area of the whole dispersion pattern.

If we substitute (8) and (9) to the original formula (1), we get the final formula for the probability of kill by a cannon burst (10)

$$P_k = \frac{\frac{A_{\text{int}}}{A_{fig}} \cdot \frac{k}{60} \cdot \left(t - \frac{t_r}{2}\right) \cdot \frac{1}{2} m_i v_c^2 \cdot \left(1 + 10 \cdot \frac{m_{HEI}}{m_i}\right)}{E_z} \quad . \tag{10}$$

Hence we can see, that the P_k depends linearly on the length of burst, projectile mass, HE-I content portion and on the rate of fire. It decreases with increasing spin-up time and depends quadratically on the impact velocity. The P_k is also influenced by other factors including cone of fire, target shape and size, medium energy necessary for target destruction, range of engagement and manoeuvring of the attacking aircraft and the target.

5. Theoretical comparison of chosen aircraft cannons

With regard to the specifics of ACM mentioned above, three different length of burst were chosen: 0.50, 1.00 and 1.50 second. The aircraft cannons, which were chosen for the comparison are those ones, which are used on the most spread or perspective fighters. The resulting muzzle energies of burst (E_{b0}) are shown in Figures 1 to 3.

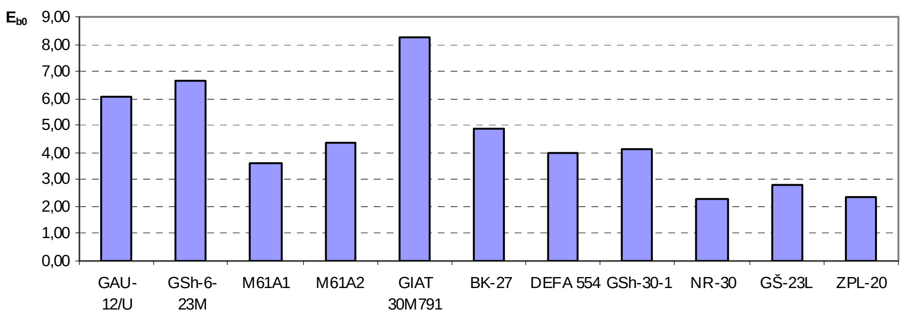

Fig. 1. Comparison of energies of 0.50-second bursts, values are in MJ

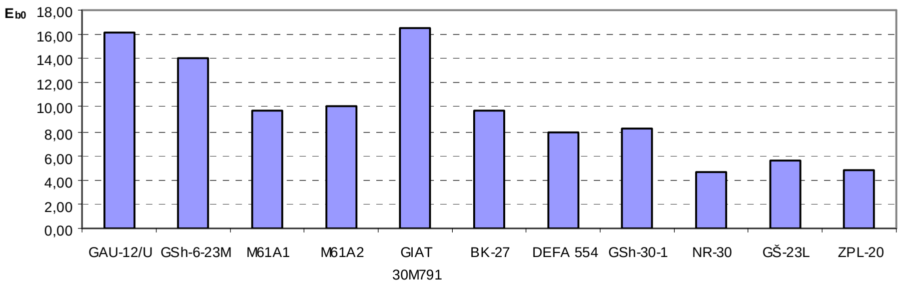

Fig. 2. Comparison of energies of 1.00-second bursts, values are in MJ

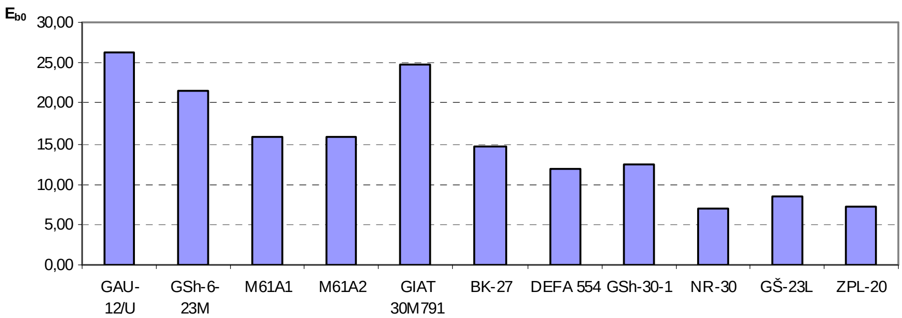

Fig. 3. Comparison of energies of 1.50-second bursts, values are in MJ

Tab. 2.

Overall energy of all carried projectiles [MJ]

Aircraft	**Air cannon**	**Ammunition capacity**	**Number of 1 sec. bursts**	**Overall muzzle energy of all carried projectiles**
F-14	M61A1	675	6.1	74.5
F-15A,B,C,D	M61A1	950	8.6	104.9
F-15E	M61A1	512	4.7	56.5
F-16	M61A1	515	4.7	56.9

F/A-18A,B,C,D	M61A1	570	5.2	63.0
F/A-22	M61A2	480	4.8	55.6
F-35A	GAU-12/U	182	2.6	52.6
F-35B	GAU-12/U	220	3.1	63.6
F-35C	GAU-12/U	220	3.1	63.6
AV-8B	GAU-12/U	300	4.3	86.8
Su-27	GSh-30-1	150	6.0	49.7
MiG-21	GSh-23L	200	3.5	19.9
MiG-23	GSh-23L	250	4.4	24.9
MiG-29	GSh-30-1	150	6.0	49.7
MiG-29M	GSh-30-1	100	4.0	33.1
MiG-31	GSh-6-23M	260	1.6	24.3
Tornado IDS	BK-27	360	12.7	122.9
Tornado ADV	BK-27	180	6.4	61.5
Mirage 2000	DEFA 554	250	8.3	66.0
Rafale	GIAT 30M791	125	3.0	49.7
JAS-39	BK-27	120	4.2	41.0
L-159 (1 gun pod)	ZPL-20	224	5.2	24.5
L-159 (2 gun pods)	ZPL-20	448	5.2	48.9
L-159 (3 gun pods)	ZPL-20	672	5.2	73.4
Average		***341***	***5.7***	***56.6***
2nd Generation		***333***	***6.6***	***60.8***
3rd Generation		***376***	***5.3***	***59.1***
4th Generation		***215***	***3.7***	***45.6***
5th Generation		***276***	***3.4***	***58.9***
American		***457***	***4.7***	***65.8***
Russian		***185***	***4.3***	***33.6***
European		***207***	***6.9***	***68.2***

Knowing the parameters of a particular aircraft cannon (including muzzle energy of a single projectile) and the ammunition capacity of its carrier, we are able to determine the number of bursts (e.g. 1 second long bursts) the airplane is able to deliver as well as the overall energy of all projectiles it carries. The results of our own calculations are shown in Table 2. It presents the possibilities of cannon fire of the most spread or perspective fighter airplanes.

The parameters of chosen aircraft cannons and projectiles, which were used in the comparison are listed in Table 3. These data were used in the calculation of muzzle energies and the number of bursts a fighter is able to deliver [3,8,10].

The evaluation of aircraft cannons utilizing the formula (10) is very difficult because all necessary characteristics for all cannons – especially the dispersion of hits in the target, the external ballistics characteristics – are not known. Therefore it is acceptable to use for the evaluation of cannons the formula (11) derived on the base of (10) i.e. to evaluate and to compare the cannons according to the total muzzle energy of fired burst.

$$E_{b0} = \frac{k}{60}\left(1-\frac{t_r}{2}\right)\frac{1}{2}m_i v_0^2\left(1+10\frac{m_{HEI}}{m_i}\right) \quad (11)$$

In comparison with the formula (10) the impact velocity v_c is replaced in the formula (11) by the muzzle velocity v_0.

Tab. 3.

Parameters of aircraft cannons and projectiles used in the comparison

Air Cannon	**Projectile**	**Projectile mass**	**Muzzle velocity**	**HE-I component portion**	**Rate of fire**	**Spin-up time**
		[g]	[ms^{-1}]	[%]	[min^{-1}]	[s]
GAU-12/U	PGU-25	180	1097	16,7	4200	0,4
GŠ-6-23M	23x115	176	715	10,8	9500	0,1
M61A1	PGU-28	98	1036	11	6600	0,4
M61A2	PGU-28	100	1050	11	6000	0,25
GIAT 30M791	30x150B	275	1025	17,5	2500	0
BK-27	27x145B	260	1025	15	1700	0
DEFA 554	30x113B	275	840	17,2	1800	0
GŠ-30-1	30x165	400	860	12,4	1500	0
NR-30	30x155B	410	780	12,1	1000	0
GŠ-23L	23x115	175	740	10,8	3400	0
ZPL-20	20x102	100	1020	11	2600	0

6. Conclusion

It turned out, that though the significancy of aircraft cannons in air combat diminishes due to the exercitation of the BVR (Beyond Visual Range) combat doctrine, their place within the fighter aircraft's armament is irreplaceable. This is i.a. acknowledged by the fact, that the aircraft cannon remains a standard armament of the most modern fighters such as the American F/A-22 Raptor, which is generally considered a typical BVR fighter aircraft, but also of European airplanes such as Rafale, Eurofighter or Gripen. The major advantage of aircraft cannon is its multipurposeness, since it can be used against both aerial or ground targets, which can be of either point or surface character. In ACM, the aircraft cannon gains importance especially in those cases, in which the fighter manages to approach the target to a very close range, from which the probability of kill by a guided missile is too low. These cases can occur in war when both sides have survived the BVR phase of the air combat, but also in peace during fulfillment of the tasks of anti-air defense (AAD).

Basing on the above mentioned mathematical equations, a comparison of several chosen aircraft cannons in terms of burst energies was made, which is considered the greatest contribution of this article. According to this comparison, the French 30mm GIAT M791 revolver cannon (standard armament of the Rafale aircraft) proved to have the highest combat effectiveness under the conditions of ACM among all compared aircraft cannons. Its success stems from the great mass of its projectile, high HE-I content portion, high muzzle velocity and average rate of fire. The Russian 23mm GSh-6-23 proved to have an above-average performance too as a result of its unsurpassed rate of fire and a very short spin-up time (achieved by its internal power conception). Gatling cannons (with the exception of GSh-6-23) proved to have very poor performance during bursts which lasted 0.5 seconds and less, thanks to their necessity of spin-up. This is the main reason why revolver cannons (e.g. BK-27, DEFA 554) are generally more suitable for ACM employment than Gatling guns. The most important factors, which influence the probability of kill are the mass of the projectile, content portion of HE-I components, muzzle velocity and rate of fire. Further, ACM being typical by a very short length of burst makes the spin-up (run-up) time a significant factor too.

As we can see in Table 2, the average number of 1-second bursts a fighter airplane is able to deliver is 5.7, while the average overall energy of all carried projectiles is 56.6 MJ. From the comparison of various fighter aircraft generations and regions of origin, it is possible to conclude, that the possible number of bursts tends to decrease in time, while the overall energy remains more or less the same. The Russian and former Soviet aircraft appear to have the lowest ammunition capacity. Further, they are able to deliver lower number of bursts than their American and European counterparts and they have much lower overall energy of all carried projectiles. These facts degrade their combat effectiveness in ACM. In contrast to the Russian and European approach, the American conception bets on the large ammunition capacity. Yet, the number of bursts and the overall energy is still lower than of the European fighters. The best approach seems to be the one chosen just by European designers. Airplanes such as Gripen, Rafale, Mirage or Tornado have much lower ammunition capacity than American fighters. However, they are able to deliver much more 1-second bursts than American and Russian airplanes (6.9 compared to 4.7 and 4.3). Also the overall energy of all carried projectiles is the highest (68.2 MJ compared to 65.8 and 33.6 MJ). The achieved results of mutual aircraft cannon comparison can be also used for evaluation during a possible selection or replacement of armament for combat helicopters since the production of some already used cannons is over and a replacement is being seeked.

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