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An Attempt to Assess the Performance of Modern Combat Aircraft

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Abstract

Recently, the so-called fifth generation (5th) aircraft have been introduced into the air forces, including the already implemented American F-22 and F-35, the Russian Su-57 and the Chinese-made J-20. Little is known about the latter, but the first squadron of Su-57 is being formed, which will ultimately replace the fourth generation (4th) Su-35 aircraft. Nowadays, in global political turmoil, the mentioned aircraft can pose a real threat to NATO defense systems. Therefore, the performance of Russian 4th and 5th generation combat aircraft has been evaluated. This is quite interesting because the aircraft comes from the same Sukhoi design bureau, and the experience of the predecessor was utilized to develop the new one. Thus, it was possible to assess the impact of modern technologies and design methods on the performance of the new generation combat aircraft. To evaluate the performance of the aircraft, the method based on the so-called Energy Maneuverability theory was used, based on the method cited, the Swiss company ALR Aerospace has developed a commercial program that is used in the process of modern aircraft design. The program was utilized in this study to determine the performance and assess the capabilities of the 4th and 5th generation combat aircraft. The essential aircraft's data for the cited program were taken from relevant military portals, the aircraft manufacturer's website, monographs on the design of combat aircraft, papers, and even confidential sources. However, some of the aerodynamic parameters were obtained by comparing the aircraft used by the Polish Air Forces (F-16 and MiG-29) with a similar mission profile or parameters and performance. The outcomes of work can be helpful, for example, at the stage of air threat assessment and simulations and anti-aircraft defense systems.

Keywords: aeronautical engineering, advanced combat aircraft, aircraft performances, assessment and evaluations, Energy -Maneuverability method

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1. Introduction

Recently, the so-called fifth (5th) generation aircraft have been introduced into the air force, including the already implemented American F-22 and F-35 aircraft, the Russian Su-57 and the Chinese-made J-20 (Beresnevicius et al., 2023; Deptula et al., 2019; Harrigian et al., 2017; Shaw, 1985). Little is known about the latter, but the first combat squadron of Su-57 aircraft is being formed, which will ultimately replace the fourth-generation Su-35 aircraft. For obvious reasons, the performance of the Su-57 remains unknown. These aircraft may pose a real threat in the current unstable political situation. As a result, the work assessed and comparatively analyzed the performance of the fourth and fifth generation of Russian combat aircraft to determine whether a new generation aircraft can pose a threat and challenge for the anti-aircraft defense systems.

The concept of assessing the performance of combat aircraft by analyzing flight parameters such as air speed, range, altitude, and load factor was developed in the 1960s by American pilot-engineer John Boyd (Coram et al., 2002; Wilson, 2017) and was intended to assess the performance of Soviet combat aircraft during the Vietnam War. In the initial phase of the conflict, the Russians introduced into service a new third (3rd) generation supersonic fighter the MiG-21, which in air-to-air combats clearly outperformed its American counterparts, the F-101 Voodoo and F-4 Phantom. Available reports show that American losses were 5:1, that is, five F-4 planes were shot down for one MiG-21.

John Boyd and the mathematician Thomas Christie (Wilson, 2017; Coram et al., 2002) developed a method called Energy-Maneuverability (E-M) that allowed to determine and assess aircraft performance essential for air combat maneuvering, dog fights, i.e., air speed, altitude, climb rate, turn radius, based on available structural load factors (G factors). In the professional literature, it is called the energy method because it allows one to determine the energy, or more precisely, the energy reserve available to the aircraft in a specific phase of flight, required to perform maneuvers. The method allowed us to determine and analyze the performance of Soviet and American fighters and to find and identify flight regimes where American aircraft dominated, having better maneuverability, i.e., a higher climb rate and turn rate. Figure 1 presents a chart demonstrating the performance envelope (speed-altitude) for the F-4 and its counterpart MiG-21. The chart shows the areas where the MiG-21 had a higher climb rate than the F-4 and vice versa. On this basis, an air combat tactic was developed in which American pilots were to avoid fighting in areas where Soviet aircraft dominated, and as a result, losses were significantly reduced to 1: 3 for Americans.

The method was used in the 1970s to design fourth (4th) generation American multirole aircraft: F-15 and F-16. Moreover, they are still being used today to assess the combat capabilities of modern aircraft, including Rafale, Typhoon, Gripen, F-22, and F-35 (Raymer, 1992; Roskam, 2004; Whitford, 2004; Ball, 2003; Ye-Fan, 2014). The dynamic characteristics of aircraft may be helpful, for example, in the stage of threat classification and optimal guidance and control of anti-aircraft defense systems, both combat aircraft and anti-aircraft missile systems (Bużantowicz et al., 2018; Krenc et al., 2018, 2019).

This paper is structured in the following way: the research methods are described in the next section, and the results are obtained, followed by their evaluation, and the summary and conclusion are presented in the last section.

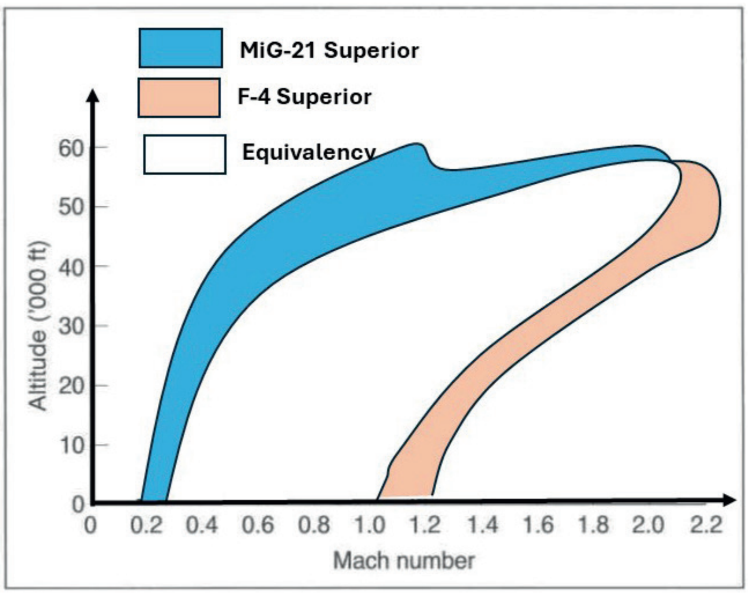

Figure 1. Assessment of combat aircraft performance: MiG-21 versus F-4 Phantom. Source: the authors' own work.

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2. Assessing the method for aircraft maneuvering performance

The performance envelope mentioned above is derived from the flight envelope known in aviation. In the literature, unlike the latter, it is also known as a "Doghouse plot," which is a graph with curves arranged in a shape like a "doghouse" (Fig. 2).

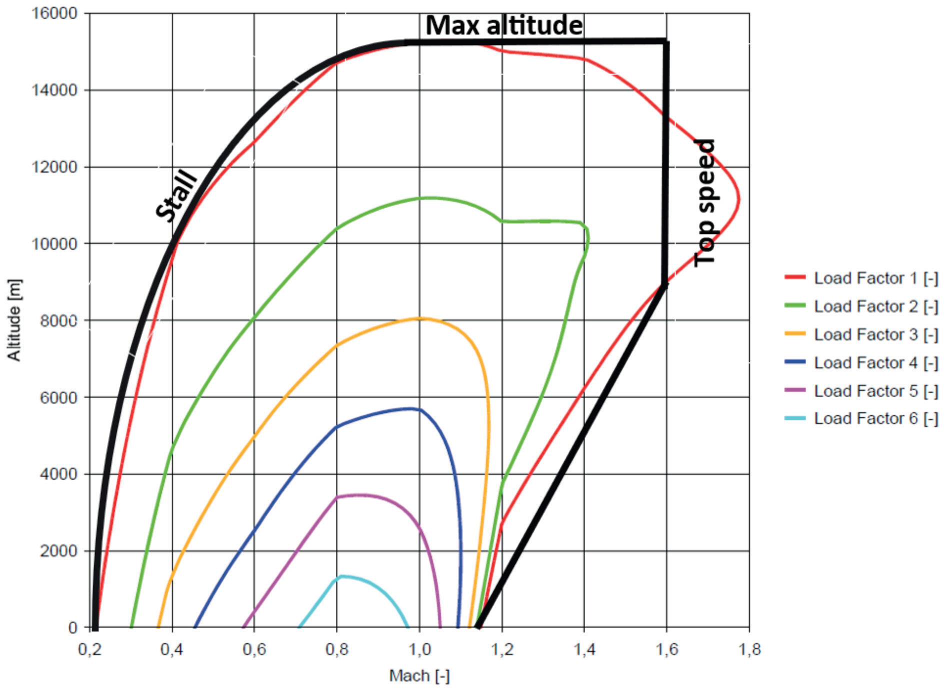

Figure 2. Structure of the envelopes of the Doghouse plot for various load factors. Source: the authors' own work.

The envelopes represent the permitted altitude ranges of the steady flight altitude as a function of the air speed (Mach number) for various values:

1. the specific excess power (SEP) or rate of climb;
2. the load factor (n);
3. the turn rate.

An explanation is required regarding the rate of climb, which is a conventional performance parameter here due to the analogous unit (m/s). In the literature (Jung et al., 2021), this parameter is called a specific excess power, abbreviated as SEP or P_s and is determined using the following formula:

$$\mathbf{SEP = (T - D)V/W} \quad (1)$$

where: *T = thrust of the propulsion system, D = drag of the aircraft, V = airspeed, W = weight of the aircraft (mass).*

It expresses the excess thrust of the aircraft in relation to its weight and is interpreted as the ability of the aircraft to perform maneuvers and acceleration. The entire area under the envelopes (Fig. 2) represents the conditions in which the aircraft can fly with 'reserve' thrust, that is, the pilot has excess thrust at his disposal and, consequently, a sufficient climb rate to perform maneuvers. For example, the aircraft depicted with a black envelope can fly up to an altitude of approximately 15,000 m, at which it reaches the so-called absolute ceiling (no excess thrust, and the rate of climb equals zero). The right side of the graph is limited by the maximum speed (top speed) Ma = 1.6 and the strength of the airframe structure (the lower, oblique part of the envelope). The left side of the envelope is the minimum airspeed, i.e. the so-called aircraft stall speed. The curve shows the performance of the aircraft at the load factor of n = 1. The remaining curves in the figure were determined for flights with a higher load factor (n = 2–6). This means that for n = 6 (high maneuverability), the aircraft can only fly in the limited velocity range from 0.7 to 0.9 Ma and with an absolute ceiling of up to 1800 m. However, flights outside the performance envelope are possible. For example, when the aircraft

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is diving, it can achieve higher speed, using gravity as a source of additional energy. Similarly, higher altitudes can be achieved by accelerating and then climbing, a maneuver known as a zoom climb. The left side of the chart describes the minimum speed of the aircraft and the stall speed.

The load factor, or G-load, abbreviated as n, is the ratio of the aircraft lift to its weight and represents a global measure of the stress ("load") to which the structure of the aircraft is subjected:

$$\mathbf{n = L/W} \tag{2}$$

where: *L = aircraft lift, W = aircraft weight (mass).*

The higher n values, the better aircraft maneuvering performance. For modern fighters, n is about 9.

The turn rate or angular velocities of turn is the rate of directional change, i.e., in turning flight, the number of degrees of heading change per unit of time (usually measured in seconds).

Calculations were performed for the Russian 4**th** generation multirole combat aircraft and its successor, 5**th** generation aircraft (Fig. 3). For obvious reasons, the performance of the latest aircraft remains classified. Therefore, the task of the research was to assess and comparatively analyze the performance of the above-mentioned combat aircraft. This is quite interesting because the aircraft come from the same Sukhoi design bureau, and the experience of the predecessor was utilized to develop the new one. Thus, it was possible to assess the impact of modern technologies, design methods, and computational techniques CAD on the new generation combat aircraft performance. Furthermore, based on Boyd's concept, it was possible to identify "strong and weak" flight regimes of the fighters.

Essential data were taken from the relevant military portal (Jane's Group, *Jane's All the World's Aircraft*), the aircraft manufacturer website, monographs on combat aircraft design (Raymer, 1992; Roskam, 2024), articles (Kozakiewicz et al., 2018; Sutrisno et al., 2019; Zalewski et al., 2000), and even confidential sources. However, some of the aerodynamic parameters were obtained by comparing aircraft used by the Polish Air Forces (F-16 and MiG-29) with a similar mission profile or parameters or performance. The engine parameters were obtained by converting the characteristics available in the literature in proportion to the maximum values provided in the literature. In addition, the rapid development of reliable calculation tools has made it possible to obtain information about aircraft aerodynamics using the Finite Volumes Method. Various scientific papers (Bridel et al., 2021; Goetzendorf-Grabowski et al., 2023; Kowaleczko, 2003; Krzyżanowski, 2009; Olejnik et al., 2020; Shayak et al., 2024) show the possibilities of using numerical methods to obtain general information on the aerodynamic characteristics of aircraft or their parts.

Performing the reverse engineering method without having the real object or its model poses the risk of underestimating or overestimating the aircraft performance. However, a critical validation of the results by referring them to the operational missions of the fighters makes it possible to assess their reliability. In this context, reliability is provided with respect to the approximate values of the parameters studied and trends in changing characteristics depending on the input variables.

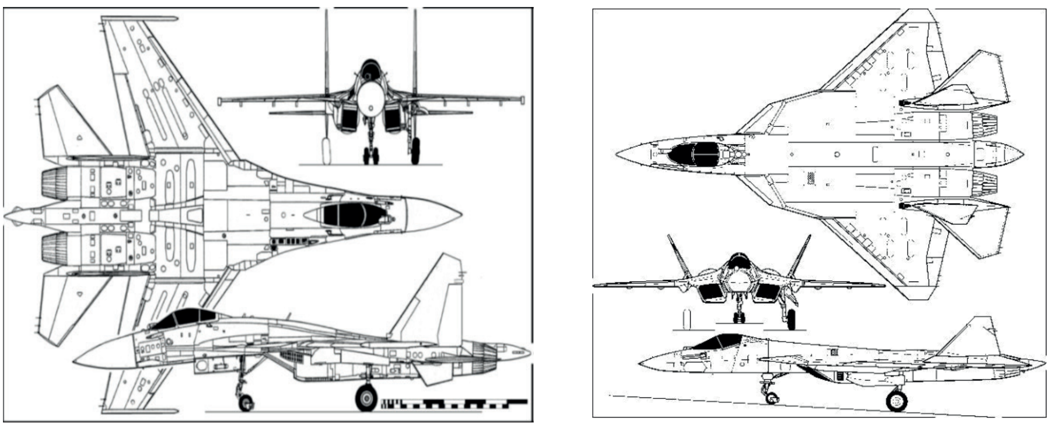

Figure 3. Modern combat aircraft: 4**th** on the left and 5**th** generation on the right. Source: Jane's Group. (2023).

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3. Analysis of combat aircraft performance

This section describes the results of the performance assessment of Russian-designed aircraft in the context of the three essential parameters:

1. the load factor (n);
2. the specific excess power (SEP);
3. the turn rate.

The performance mentioned is important from an air-to-air combat point of view, including a dogfight and air-to-surface combat (the maneuver of target approaching, operating, and escape from the anti-aircraft defense threat zone). Calculations were carried out in the ALR Aerospace Aircraft Performance Program. Based on the software procedures, the necessary input data, i.e., aircraft parameters and performance, were identified to build a numerical model (ALR Aerospace, 2002).

3.1. Load factor

This subsection presents the performance envelope calculations results as a function of the load factor for the 4th generation fighter aircraft and its 5th generation successor, as determined using the Aircraft Performance Program.

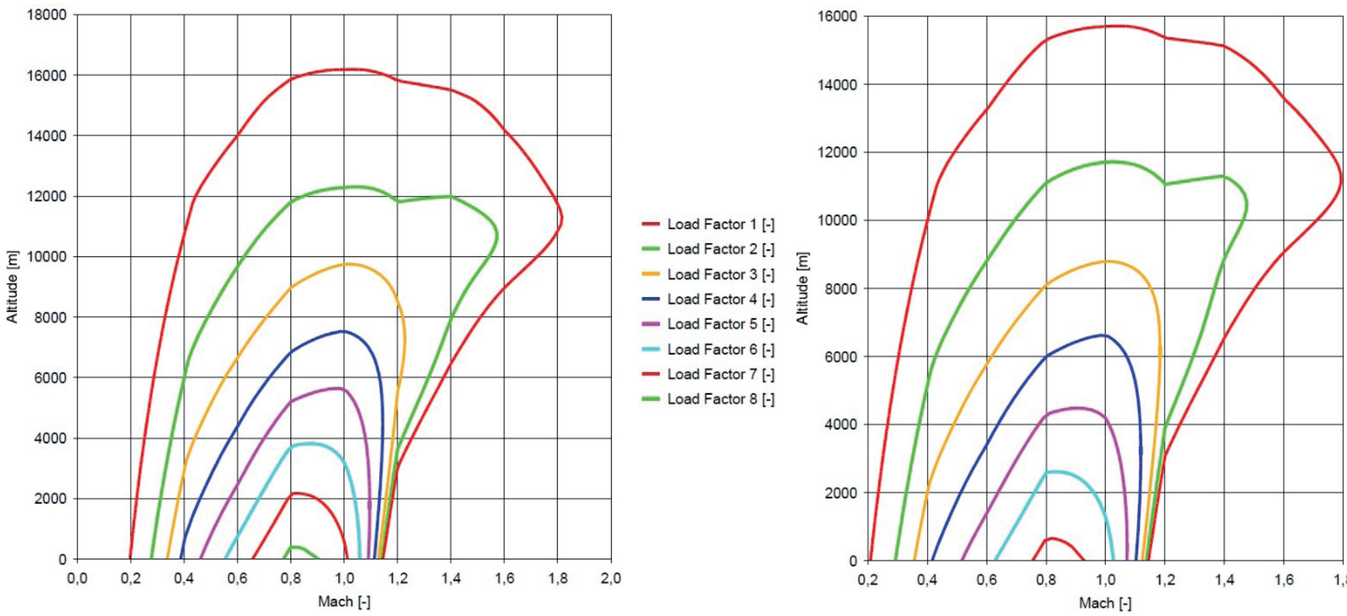

Figure 4. Performance envelopes of the 4th generation aircraft for various load factors and typical combat missions, on the left: air combat (Air-Air), on the right: attacking ground targets (Air-Ground). Source: the Authors' own work.

Figure 4 demonstrates the performance envelopes for a 4th generation aircraft, i.e., altitude – air speed (Mach number) for various load factor values and combat missions. The Air-Air variant means air operations, i.e., combating enemy aircraft, dog fight, while Air-Ground means attacking ground targets, i.e. the use of warfare to attack ground targets, which is associated with an increase in the take-off weight of the specific aircraft by 4000 kg, i.e. up to 34,000 kg. The load factor n = 1, 5 and 6, constituting different values of the permitted load factor. Flight with a load factor of n = 1 means steady, level flight of the aircraft without the possibility of maneuvering. The higher the value of the above-mentioned factor, the better the maneuverability. Factors n = 5 and 6 (according to the pilot manual) are recommended for combat operations (air or ground), the aircraft has sufficient energy reserves, and the pilot can perform maneuvers. The analysis of the curves demonstrates that these operations are carried out to an altitude of 5000 and 4000 m and a speed up to Mach 1.1. A further increase in the factor value, that is, an increase in maneuverability, 'forces' the pilot to operate at a low altitude and in a narrow speed range. Moreover, for the assault variant, the maximum allowed load factor value is 7.

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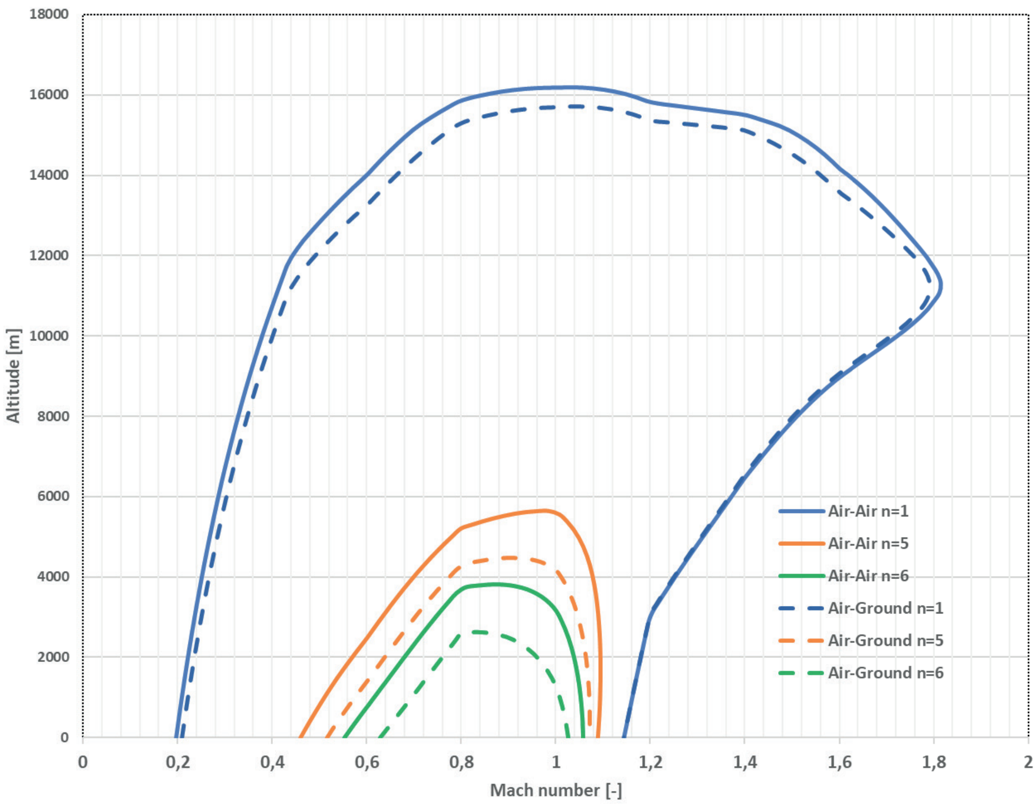

Figure 5. Performance envelopes of the 4th generation aircraft for combat missions and recommended load factor (n) values. Source: the authors' own work.

The analysis of the curves (Fig. 5) demonstrated that the increase in aircraft weight (dashed lines) depending on the payload configuration (armament) had a slightly negative impact on the maneuverability of the aircraft. The pilot must operate at a slightly lower altitude but maintain the entire flight speed range.

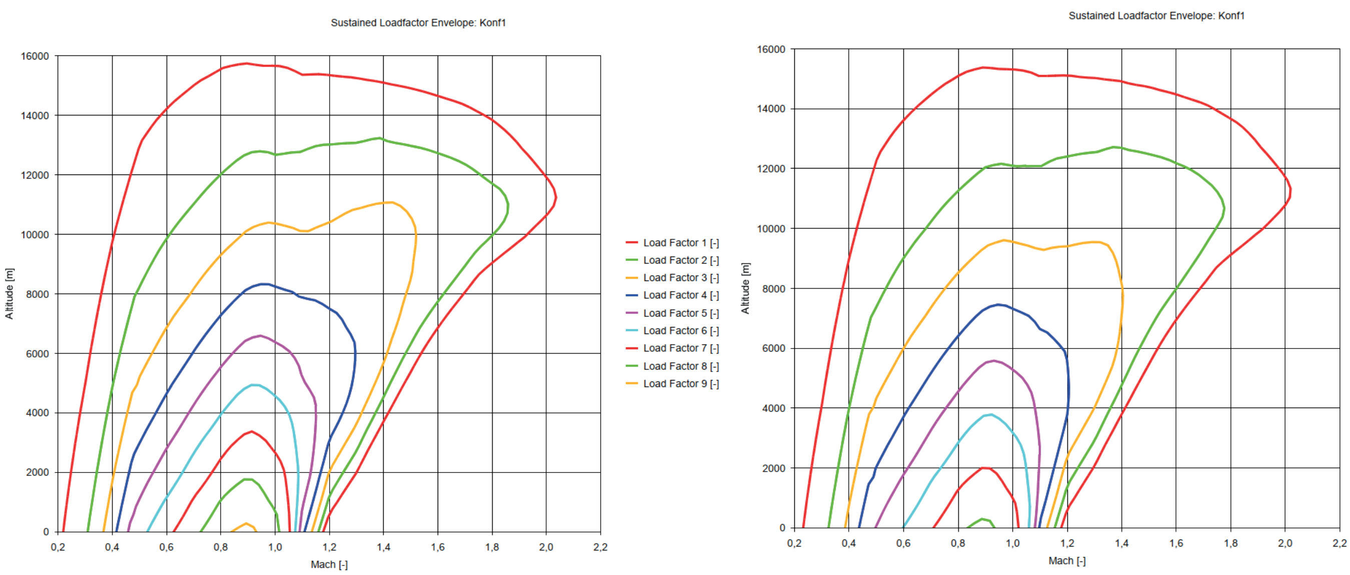

Figure 6. Performance envelopes of the 5th generation aircraft – various load factors for typical combat missions, on the left: air combat (Air-Air), on the right: attacking ground targets (Air-Ground). Source: the authors' own work.

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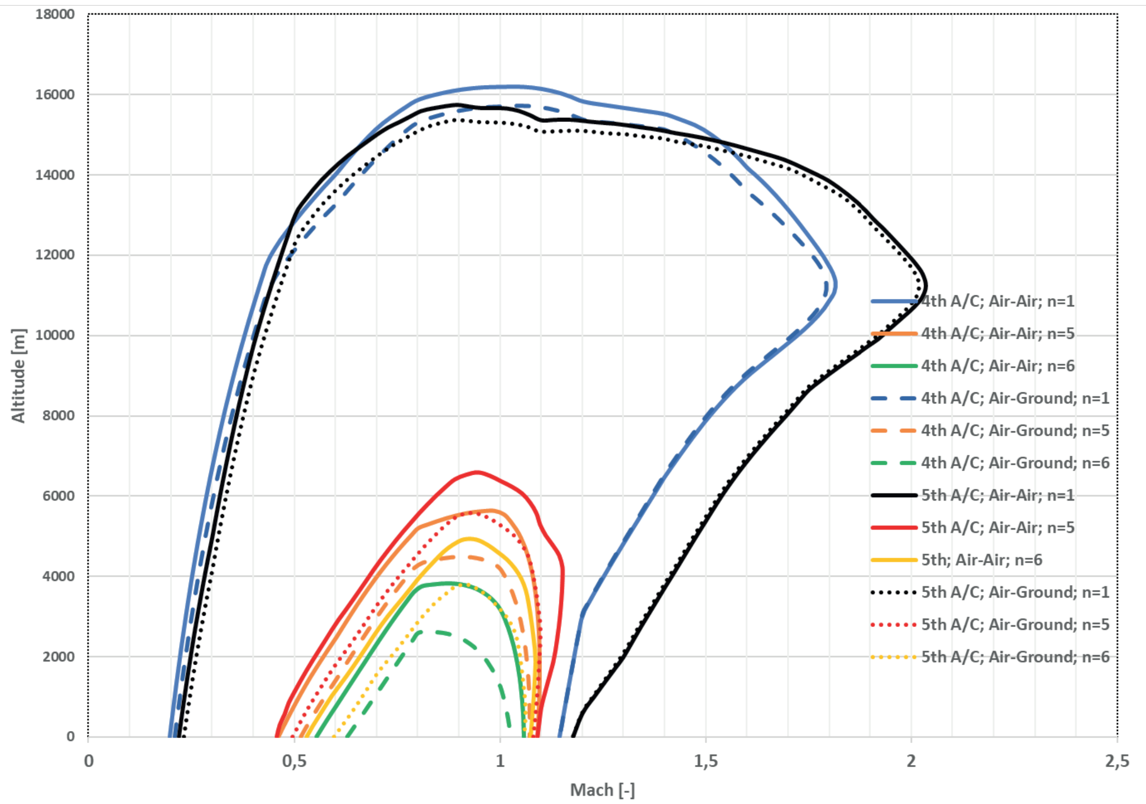

Figure 7. Performance envelopes of the 4th and 5th generation aircraft (A/C) for combat missions and recommended load factors (n). Source: the authors' own work.

Figure 6 demonstrates analogous characteristics of the 5th generation aircraft. The curves are similar; the envelopes are presented in Figure 7 to compare the aircraft. The analysis of the curves demonstrates that the new aircraft is slightly superior to its predecessor because the 5th generation aircraft, despite its higher take-off weight, has a slightly higher specific power (0.70 for the 5th and 0.68 for the 4th generation). Moreover, the essential armament (Air-Air variant) is carried in the weapons bays, which reduces aircraft drag. This is especially observed at a higher load factor of n = 5 and 6, where a higher energy reserve is 'required' from the aircraft.

3.2. Specific excess power

The next aspect of the considerations was the assessment of the specific excess power (SEP) of the fighters, with similar Air-Air and Air-Ground configurations (Figs. 8-10).

The analyzed performance curves of the 4th generation aircraft as a function of SEP (Fig. 10) depending on the mission type are like those for the load factor. However, in comparison, the new aircraft clearly dominates (Fig. 11). This aircraft, with SEP = 200 m/s (which can be interpreted as a climb rate), can fly in a wide range of speeds from 0.5 to 1.0 Ma with flight altitudes of up to 3000–4000 m, depending on the configuration. It should be emphasized here that this is a typical range for air to surface operations.

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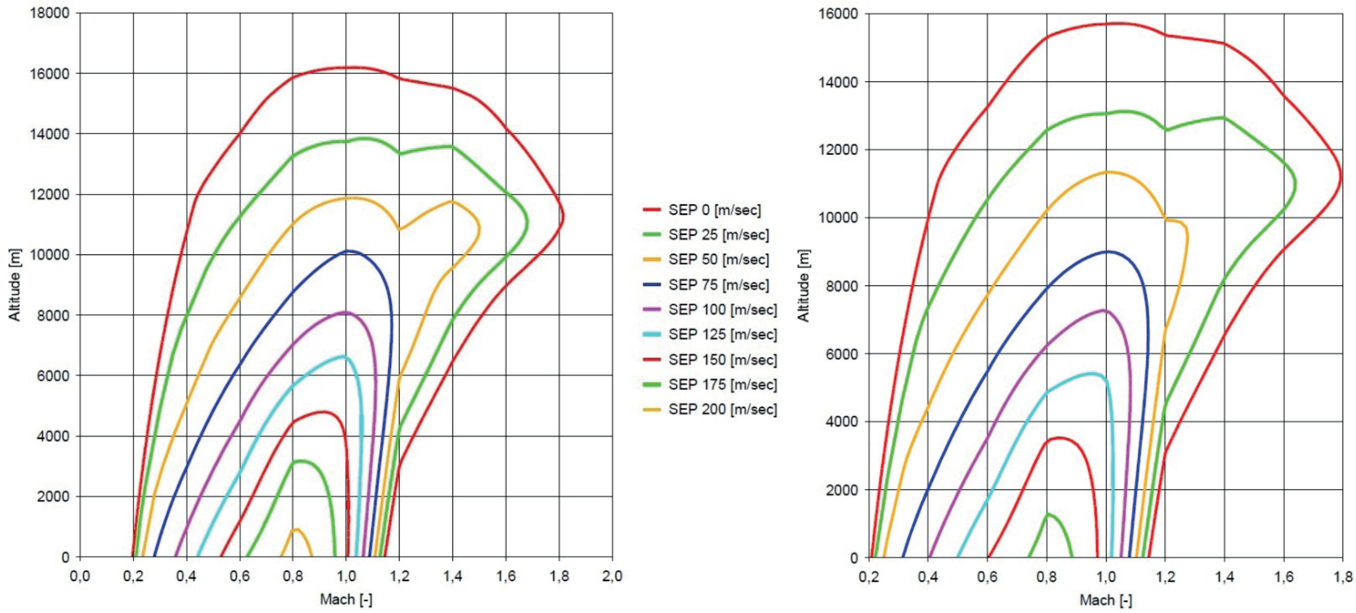

Figure 8. Performance envelopes of the 4th generation aircraft – SEP for typical combat missions, on the left: air combat (Air-Air), on the right: air-to-surface mission (Air-Ground). Source: the authors' own work.

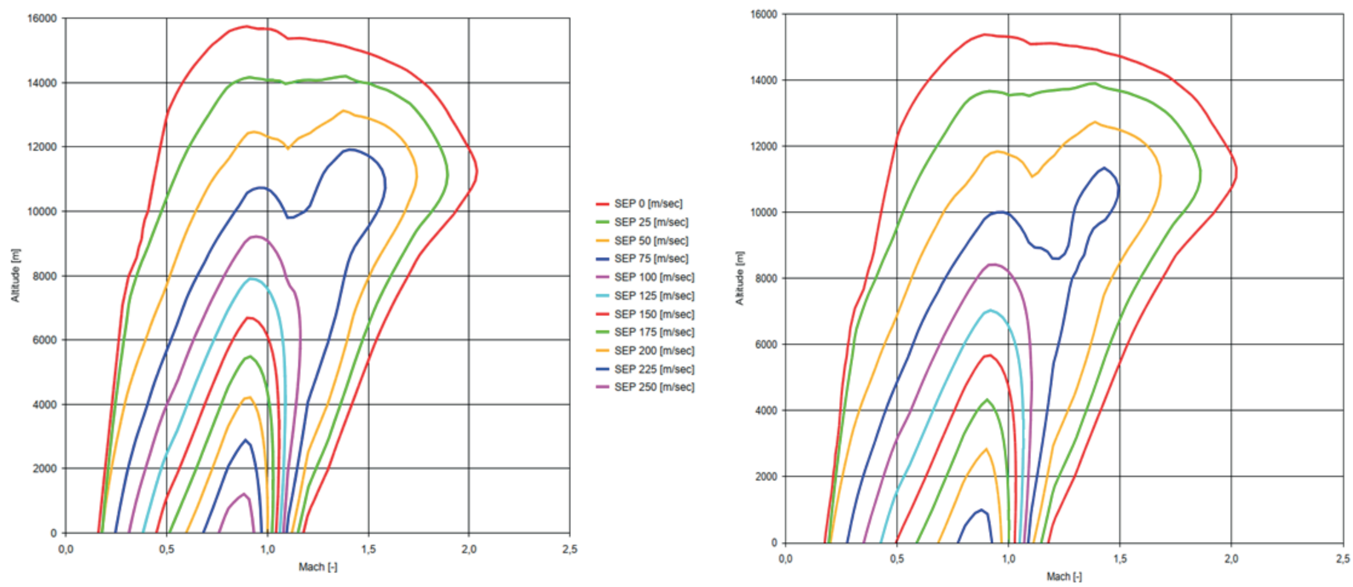

Figure 9. Performance envelopes of the 5th generation aircraft – SEP for typical combat missions, on the left: air combat (Air-Air), on the right: air-to-surface (Air-Ground). Source: the authors' own work.

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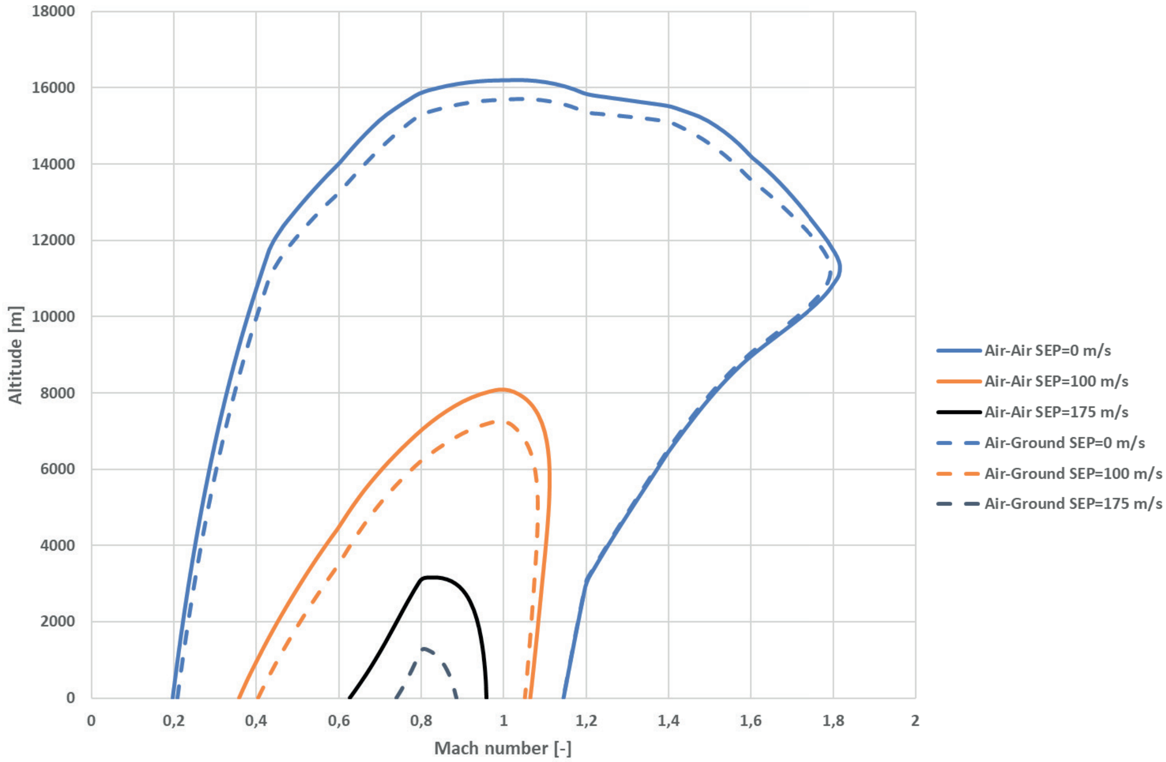

Figure 10. Performance envelopes of the 4th generation aircraft for various specific excess power (SEP) values. Source: authors' own work. Source: the authors' own work.

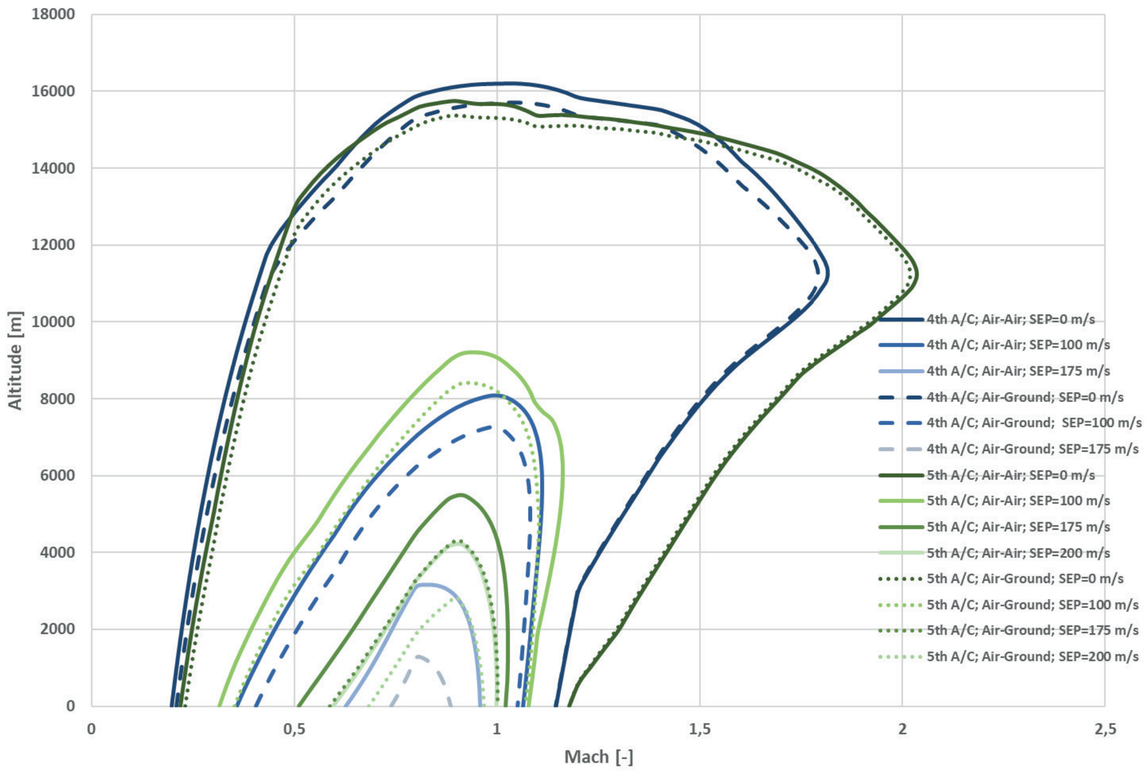

Figure 11. Performance envelopes of the 4th and 5th for combat missions and various specific excess powers (SEP). Source: the authors' own work.

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3.3. Turn rate

The chart in Figure 12 shows the envelopes of the turn rate or angular velocities of the turn at various flight altitudes (in the same configuration). For comparison purposes, the angular velocity envelopes are summarized in Figure 13. The charts were made for a flight altitude of up to 4000 m (for typical air operations). At this altitude, the angular velocity of turn decreases. The aircraft loses its maneuvering performance, which is dictated by the decrease in air density. Therefore, the aircraft loses its maneuverability. Similarly to the SEP analysis, the advantage of the new generation aircraft at low and medium altitudes is apparent. This can be explained by the use of more advanced aerodynamics and a more effective flight control system. However, at an altitude of 4000 m, the properties are comparable.

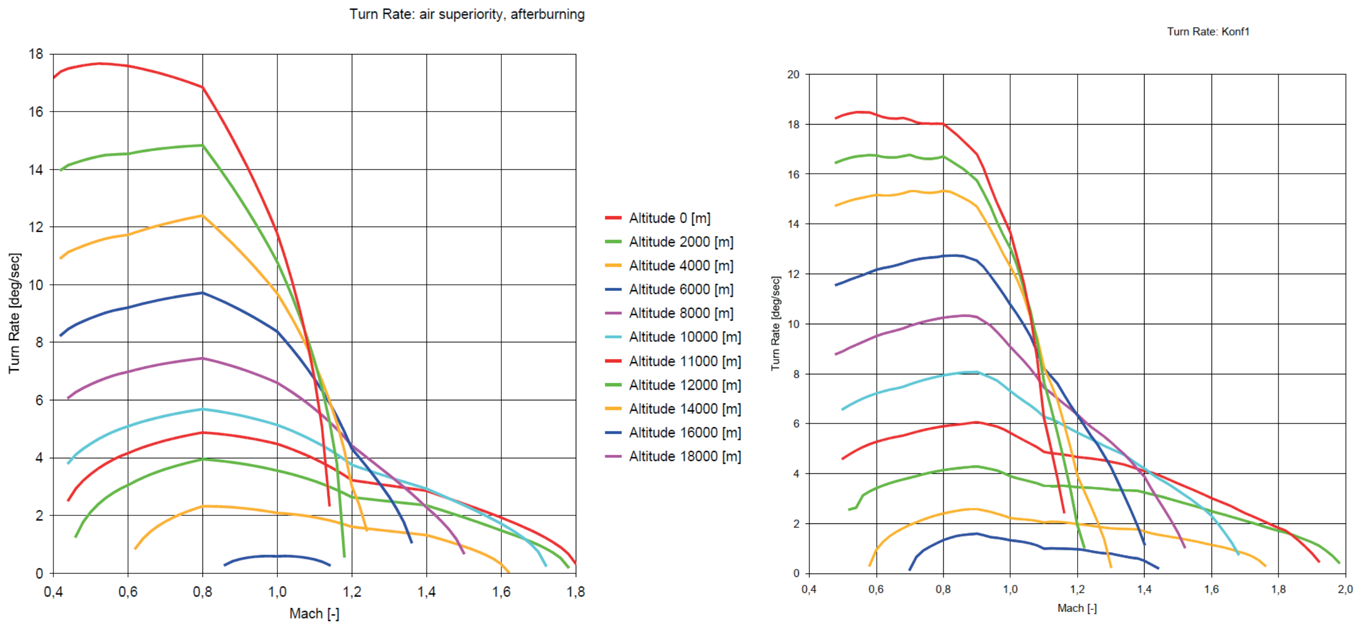

Figure 12. Performance envelopes of the 4th generation (left) and 5th generation (right) aircraft – turn rate at different altitudes, for the Air-Air configuration. Source: the authors' own work.

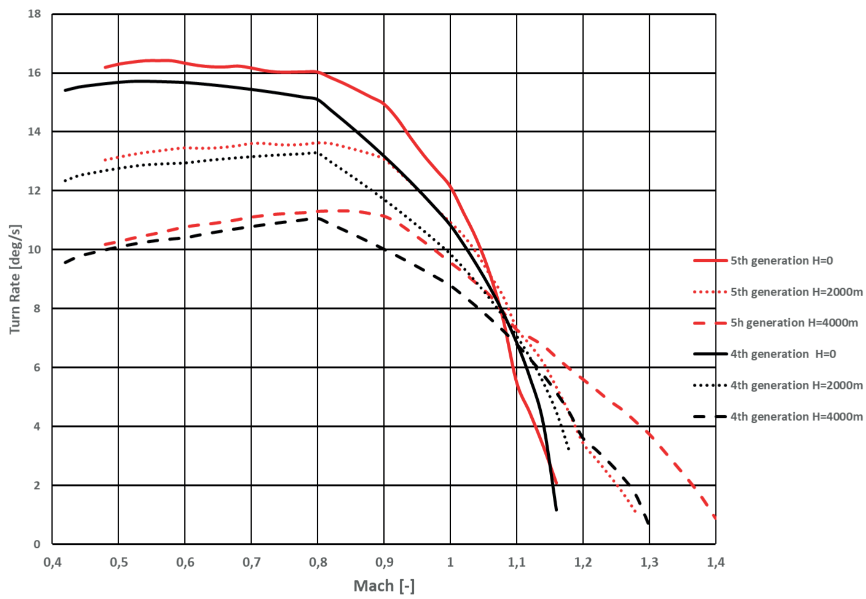

Figure 13. Performance envelope – turn rate for aircraft of the fourth and fifth generations combats for various altitudes (H). Source: the authors' own work.

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4. Reliability evaluation of the results

When performing a reverse engineering task, using comparative methods, one should consider whether the obtained results represent the capabilities of a real aircraft (for example, by relating them to known NATO designs) or by referring them to assumptions resulting from the operational purpose and operating environments.

In the case of new generation aircraft, the combat operational purpose should be considered, considering not only cost but aircraft survivability on the battlefield: detection by the enemy systems and the effectiveness of anti-aircraft defense systems. As described above, the maneuvering parameters at low and medium altitudes are qualitatively better than those for the older 4th generation aircraft, while at higher altitudes, these values are similar. On the one hand, this is the result of the new design (state of the art in aerodynamics) and new emerging technologies, such as thrust vectoring, while conceding better maneuvering parameters is justified by the intended use of the aircraft.

Considering the mission safety, aircraft production costs and the effectiveness of modern anti-aircraft defense, the 5th generation aircraft should not expose itself to enemy fire while performing its mission. Thanks to the 'stealth' properties and the systems used to detect the enemy, the combat duel on the modern battlefield takes place in the radio-electronic domain, in which the decisive factor is the earlier detection and targeting of the adversary, the appropriate means of warfare and the departure of the danger zone. It should be noted that even a fifth-generation aircraft, if targeted by enemy air defense, has a small chance of avoiding being hit. Active protection measures combined with the maneuvers performed to increase the chance of survival but do not significantly impact the probability of being hit.

Based on the above, it can be assumed that the results obtained are consistent with the intended use of the 5th generation aircraft and are considered qualitatively correct. Bearing in mind that the values of the obtained permissible air speed on the load envelope are similar to those that can be found in the analyzed literature, one can also assume that they are comparable to real values.

5. Summary and conclusions

1. The Boyd-Christie energy manoeuvrability method applied to determine the so-called performance envelope of the aircraft in the 'doghouse' variant is still suitable for evaluating and comparing aircraft, including those that are currently being introduced into operation.
2. In the case of the new combat aircraft where some data are not available or classified, reverse engineering allows us to assess and recreate necessary input data and parameters for calculations.
3. The performance parameters determined by the Boyd-Christie specific excess power, load factor, and angular velocity of turn, describe the manoeuvring performance of the aircraft.
   Through their analysis and interpretation, it is possible to indicate the 'so-called' critical flight ranges where the aircraft shows high performance and high manoeuvrability. For example, when attacking ground targets and ranges where, the pilot will attempt to avoid an attack due to 'weak' dynamic properties or low manoeuvrability.
   These ranges were determined for the aircraft analysed, which is important in the current situation and can be used to develop, for example, dogfight tactics for allied aircraft to combat potential adversary fighters (Boyd's original idea) or to create scenarios and models for ground-based anti-aircraft systems.
4. To summarise the assessment of the selected 4th and 5th generation combat aircraft in terms of performance, the advantage of the new generation aircraft is clearly visible at low and medium altitudes. This can be explained by the use of more advanced aerodynamics and a more effective flight control system. However, at an altitude of 4000 m and above, the properties of the aircraft are comparable.

Declaration of interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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