Responsive space assets for Polish Armed Forces: Feasibility study
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Abstract

This study proposes an alternative (i.e., air-assisted) system for launching payloads (micro-satellites) into space using rockets fired from Su-22 or MiG-29 combat aircraft. This paper verifies and evaluates such an air-assisted rocket system used for launching payloads to low Earth orbit (LEO) in many aspects. Mission profile and rocket drop maneuver concepts have been developed. From the adopted model of calculations and simulation results, it follows that in the considered configuration, the aforementioned aircraft will be capable of accomplishing a mission in which a payload of at least 10 kg is launched into low Earth orbit. The analyses were complemented by simulations and wind tunnel tests verifying the impact that space rockets may exert on the aerodynamic and mechanical properties of the carrier aircraft. Results of numerical simulations and wind tunnel tests to which models of the air-assisted rocket launching system were subjected indicate the rocket's impact on the aerodynamic characteristics of the aircraft and its in-flight properties is negligible. Similarly, load and strength tests to which the airframe's load-bearing structures have been subjected also failed to show any significant changes or deformations caused by the space rockets attached. The kits proposed may be deemed as the so-called Responsive Space Assets for the Polish Armed Forces. Implementation of such a system not only offers independence from countries or commercial companies providing space services but also allows us to master new capabilities in the context of deploying satellite systems for safety and defense purposes.

Keywords: air-assisted rocket launch system, defense, satellite, space, safety

1. Introduction

On July 11, 2021, Virgin Galactic (Virgin Group) completed the first commercial space flight using an air-launched rocket-powered aircraft. The air-assisted rocket system consisting of a carrier aircraft and a space rocket launched at an altitude of a dozen or so kilometers is an alternative to conventional systems that inject payloads into orbit by relying on carrier rockets launched from the ground. A few days later, on July 20, Blue Origin completed their own commercial flight in a capsule lifted by a rocket fired from a ground launcher. The payload capacity of the carrier aircraft (compared to that of a carrier rocket, such as the Falcon-9 or the

Delta IV) is a natural limiting factor, restricting payload mass to tens or hundreds of kilograms. Therefore, these systems are deemed as alternatives for launching micro- or mini-satellites.

The industrial revolution we are currently experiencing in the space sector (also known as Space 4.0), allowing us to insert increasingly advanced satellite systems, comprising primarily micro- and mini-satellites, into low Earth orbits (LEO), offers a multitude of benefits, primarily for safety and defense sectors. Observation satellites, including reconnaissance satellites that allow remote images of the Earth's surface (Liang, Li & Wang, 2012), have the largest share in such systems. Satellite imagery provides reliable information about the location and activity of the enemy, its infrastructure, including that of military and critical nature, and the geographical surroundings, thus directly affecting the assessment of the enemy's potential and improving situational awareness on the battlefield. Communication satellites are another example of a satellite system that is equally important from the safety and defense point of view. Automated command support systems used in modern conflicts require the use of both imaging and signal transmitting satellites, as these have become a key element of Network Centric Warfare (Mitchell, 2009).

According to a literature review (DARPA, 2011; Kesteren, 2013; Niederstrasser, 2018; Smolyakov, Yanakaev, Kornev & Shevko, 2018), at least 140 designs for air-assisted rocket launching systems have been developed to date, and numerous new concepts are currently under consideration. Stargazer-Pegasus by Orbital ATK (Orbital ATK, 2015) is the oldest operating system of this type. It is based on an upgraded Lockheed L1011 TriStar passenger aircraft. Virgin Orbit, a member of the Virgin Group, is working on a similar system that relies on an upgraded version of the B-747 passenger plane serving as the carrier platform.

In 2006, Boeing presented (Chen, Ferguson, Deamer & Hensley, 2006) a concept for launching a space-grade rocket piggy-backing on a Boeing F-15E supersonic fighter jet. The Responsive Air Launch system was an alternative to the "conventional" solution. An upgraded rocket based on the Pegasus design, weighing approximately 15,000 kg, was to carry a payload of up to 300 kg (approximately 2% of the total rocket mass). This was a breakthrough in terms of technology development, since similar projects appeared in the subsequent years, proposing the use of decommissioned supersonic fighter planes, such as the F-16, F-15, or the Russian MiG-29 and MiG-31 (Clarke, Cerven, March, Olszewski, Wheaton, Williams, Yu, Selig, Loth & Burton, 2007; Bartolotta, Wilhite, Schaffer, Voland, Huebner, Chen, Ferguson, Deamer & Hensley,, 2011; DARPA, 2011; Kesteren, 2013; Orbital ATK, 2015; Garcia-Cuadrado, 2017; Niederstrasser, 2018), as well as new designs (Lopata & Rutan, 2004), for space launch purposes. Recently, numerous start-ups have been established and strive to attract investors willing to fund such programs. The Spanish Celestia Aerospace is one of them. It plans to use the MiG-29 aircraft as the carrier platform. In the literature on the subject, these systems are classified as the so-called Responsive Space systems, i.e., alternative space launch solutions characterized by low costs and good levels of reliability, accessibility and mobility.

In our case, the Su-22 and MiG-29 will soon be withdrawn from service in the Polish Armed Forces. Additionally, the domestic industry sector has the potential and the experience and the scientific and technical facilities required to overhaul and modernize the aforementioned aircraft. Therefore, it seems advisable to perform a feasibility study concerned with a similar project, taking into account the potential space capabilities of the Armed Forces.

In 2021, a list of NATO air bases whose airfields are optimally suited for potential operations over the North Sea was presented at the Joint Air & Space Power conference. The 22nd Tactical Air Base in Malbork was included in that list as well (Perry & Fuller, 2020).

2. Evaluation of an air-assisted rocket system used for launching payloads into low earth orbit

The speed reached by the aircraft-based platform allows reducing the speed of the rocket required to launch an object into a specific orbit. This speed reduction is equal to the rocket-carrying aircraft's speed when the rocket's engines are fired. In systems launching cargo to low Earth orbits, separation of the orbiter from the airplane platform, occurring at transonic speeds, means that the speed of the rocket required to achieve a certain orbit may be reduced by 300÷950 m/s. It needs to be added that the angle of attack at which the rocket separates from the aircraft is important as well. It should equal at least 30°, so that the rocket does not have to perform an additional climbing maneuver. Otherwise, the rocket's engine burns additional fuel to transition into the climb phase. Furthermore, during this maneuver (at supersonic speeds) the rocket is subjected to significant lateral G-forces (loads) requiring structural reinforcement, thus increasing the mass of the rocket at the expense of its payload.

Citing the literature (Chen et al., 2006), Table 1 and Figure 1 show the simulation of a rocket taking off at an altitude of 15,000 m, with the initial (carrier) velocity of 250 m/s. Take-off from a ground launcher is shown for comparison as well. In both cases, the rocket is expected to carry 10 kg of payload into LEO at 780 km. Analysis of the data shown in the table indicates that with the given parameters, when the rocket is dropped from the aircraft at the angle of 50°, the required rocket velocity is the lowest (8,633 m/s), meaning that is 12.4% lower than the velocity of a rocket taking off from a ground launcher (9,858 m/s). Consequently, the mass of the rocket is reduced to the absolute minimum (930 kg), and has the following dimensions: 5.42 x 0.56 m (length x diameter). With the performance and capabilities of both the Su-22 and MiG-29 aircraft taken into consideration, it may be concluded that a rocket with such parameters may be carried by both planes. This means that these aircraft are capable of "launching" a space-bound payload of 10 kg into orbit at an altitude of 780 km. It also needs to be noted that references may already be found in the literature on adapting the MiG-29 aircraft to the role of a platform launching space-bound objects.

Table 1 also presents simulation results for a rocket dropped from an aircraft flying at the attack angle of 0°, i.e., performing a horizontal flight. Such a flight profile is used, in the ATK Pegasus program, due to carrier aircraft limitations.

One also needs to consider that a conventional rocket launch from the surface of the Earth requires the rocket to travel through the densest, lower layers of the atmosphere. Significant aerodynamic pressure means that considerable amounts of fuel need to be burnt before the rocket reaches the altitude from which it could be otherwise launched from the carrier aircraft. The density of atmospheric air decreases significantly as the altitude increases. At the “rocket launch” altitude of approximately 15 km that is considered in this study, it equals less than 17% of the density at ground level.

Figure 1. Space rocket launch scenarios for simulations presented in Table 1

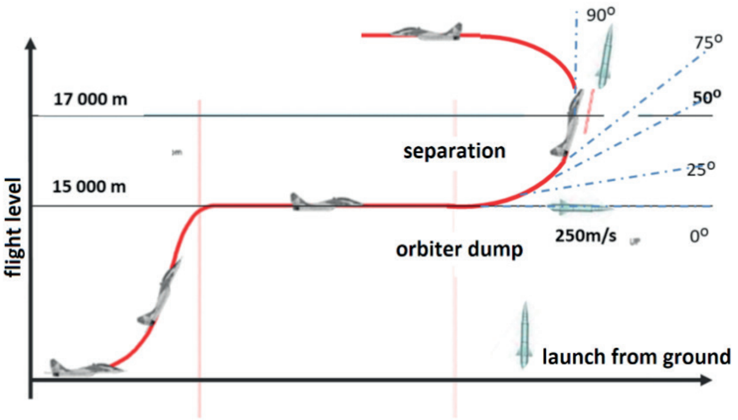


Table 1. The parameters of space rockets launched from a ground launcher and from an aircraft flying at different angles of attack (Kesteren, 2013)

Parameter	Unit	Ground launcher	Air-assisted launch for selected angles of attack:				
			0°	20°	50°	75°	90°
Rocket weight	kg	3,087	1,128	1,017	930	923	976
Rocket length	m	6.745	5.469	5.440	5.422	5.395	5.482
Rocket diameter	m	0.913	0.657	0.610	0.560	0.617	0.580
Required speed	m/s	9,858	8,851	8,687	8,633	8,718	8,716

Since there is no need for the rocket to climb through the densest part of the atmosphere using its own propulsion system, the mass of fuel required is reduced, and weight savings may be converted into an increased payload. After being launched at a significant altitude, the rocket accelerates in a thin atmosphere, so the dynamic pressure encountered is lower than in the case of a ground launch. As lower dynamic loads are exerted on the rocket, its design may be simplified, resulting in an overall weight reduction and in an optimized mission profile. In addition, gravitational interactions and drag associated with maneuvering the rocket during the flight are reduced as well.

The performance of the propulsion unit is another issue that needs to be taken into consideration – the thrust of the rocket engine needs to be optimized by specifying the correct shape of its exhaust nozzle. In rockets carrying payloads into LEO and launched at a certain altitude from the carrying aircraft, nozzles may be used that operate optimally as the ambient pressure variations are smaller. The pressure changes drastically with the increase in altitude. The largest pressure drop is observed between 0 and 12 km above ground level. When considering the flight of a rocket launched from the Earth’s surface, it should be noted that it must pass through the zone of significant atmospheric pressure changes. As mentioned above, the nozzle is designed for one specific ambient pressure value. Therefore, up to the altitude of 12 km, the nozzle will not guarantee that the exhaust gases expand optimally.

3. Operational advantages

The systems discussed here do not require the construction of any special ground-based launchers whose design would be extremely cost-intensive. The function of the launch platform is performed by the aircraft carrying the rocket. This solution guarantees great flexibility and mobility, allowing objects to be launched into an orbit of any inclination.

Air-assisted rocket launch systems may be operated independently of weather conditions as well. Conventional launches often need to be postponed to different dates due to adverse weather conditions.

Lower costs of securing the launch zones need to be taken into consideration as well. Ground-based systems require that special uninhabited safety zones be established. This is almost impossible in the conditions prevailing in Poland or in Europe. Currently, Norway owns or is building, a spaceport on Andoya Island, and a similar facility is under construction in Sweden, near Kiruna.

Most importantly, the system in question is capable of using slightly modified existing aircraft designs, including supersonic fighter planes retired from military service. Currently, the so-called 4th generation aircraft are widely withdrawn.

Gaining independence from any space providers will be another major benefit stemming from the implementation of the system. While some private companies offering commercial services (SpaceX) have entered the market, they are still dependent on government infrastructures. Furthermore, in the case of "military services," the service provider, just as any other US company, must be approved by Congress.

Independent implementation of a system guarantees that operational independence may be enjoyed as well. SpaceX, using the Falcon series rockets, is capable of launching orbital payloads weighing in excess of 10 tons. In this case, a "smaller" customer with a small load has to wait for a large shipment, or until the company "fills" the payload space. This means that launch is by no means is a Responsive Space Assets solution.

4. Conceptual shortcomings of the system

The fundamental, natural limitations of the system have the form of its small operational payload capacity that is restricted by the size and performance of the aircraft platform. The insignificant payload-to-weight ratio, estimated at 1-3% in systems of this type, means that the size of the satellite is closely related to the size and weight of the rocket by which it is launched.

The relatively cost of research and development activities and certifying the system, is a significant financial burden for small countries. Reliable data related to those aspects are difficult to find in the literature. Nevertheless, a review of the literature (Kesteren, 2013) shows that the cost of the air-assisted system equals approximately 75% of the cost of the ground-based system, which, in turn, may be estimated at approximately $15 billion. The key savings relate to the cost of the ground infrastructure and accompanying protection systems and the process of preparing and launching the space rocket. In contrast, the costs of developing and building a space rocket, including the acquisition of the aircraft platform, are comparable.

5. Evaluation of an air-assisted rocket system used for launching payloads into low earth orbit. Potential market and applications

The emergence of a market for nano- and micro-satellites (weighing from 1 to 50 kg) makes air-assisted rocket-launching platforms the optimal solution for this category of payloads. Satellites of this type are within the financial reach of not only those countries that are the tycoons of the space industry but are also within the purchasing power of individual corporations or even companies. Market analysis shows that approximately 200 nano- and micro-satellites were launched into different orbits in 2020. Furthermore, even some universities and R&D centers are interested in launching their own small satellites into space in order to serve the role of research platforms.

The load capacity of aircraft serving the role of assisting platforms is more than sufficient to lift rockets capable of launching space payloads of up to 50 kg. To date, nano- and micro-satellites have been launched as an additional supplemental payload (the so-called "piggyback") accompanying the primary payload. Thus, the timing and the target orbit depend on the requirements of the party ordering the transportation of the primary payload.

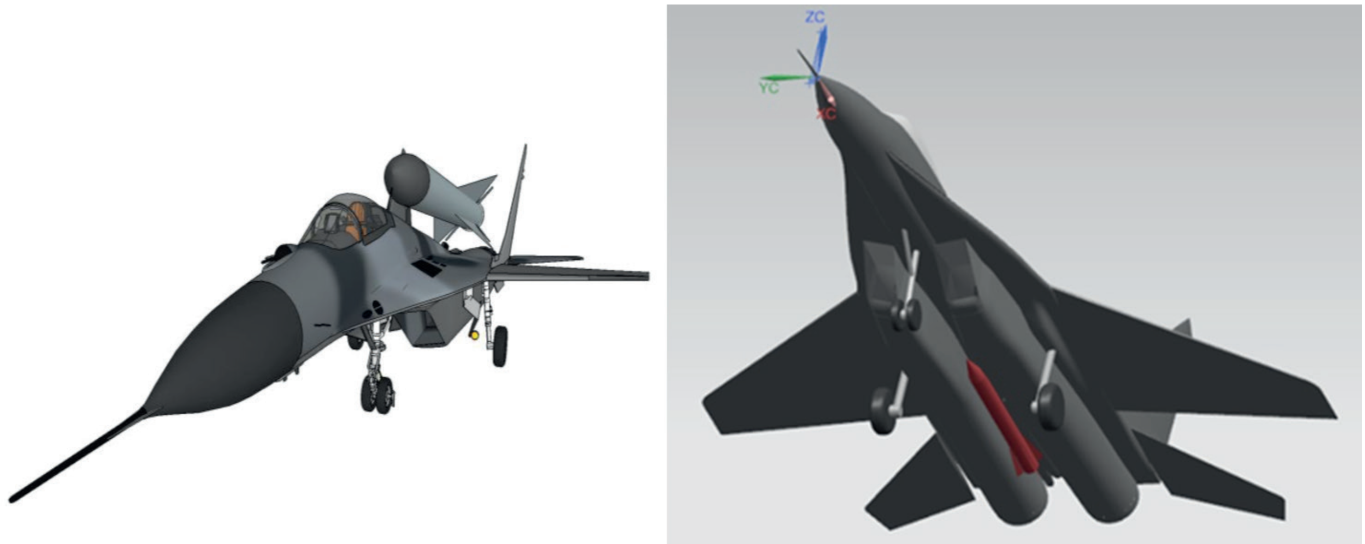
Operationally Responsive Space applications involving rapid design and construction of military satellites for their immediate launch are another segment of the market that is worth considering. Currently, the R&D phase for a classic satellite lasts between four and ten years (one to four years for a micro-satellite). It takes one to three years to perform an air-assisted launch operation, meaning that the period is comparable to the time required to design and construct a satellite. In 2007, the United States established the Operationally Responsive Space Office (ORSO), an entity tasked with building a "tactical" system of small satellites capable of offering broadly understood "support" for the armed forces. Another of its tasks consists in launching military satellites into space in an operationally responsive manner, depending on the development of the situation (hence the word "responsive" in the name of the Office). Responsive Spacelift systems are expected to be one of the key elements of the ORSO program. Such systems comprise air platforms (aircraft) and space rockets carrying a satellite into its target orbit around the Earth. Corresponding programs have also been launched in Europe (the Netherlands, Norway).

6. System concept and analysis. Configuration of system components and mission profile

As proved by the studies described above, the system's major drawback has the form of weight restrictions resulting from the payload capacity of the carrier aircraft. The aircraft's suspension points are usually located under the wings or under the fuselage, and their load-bearing capacity is limited as well. The maximum geometric dimensions of the rocket are limited by the dimensions of the aircraft itself, namely by its diameter and by the airframe's ground clearance (which is why the option of piggy-backing the rocket was considered). The length of the rocket, its weight and its location affect the balance of the aircraft and the loads to which the airframe is subjected in flight. Therefore, as previously discussed, air-assisted rocket launch systems are suitable for launching low weight, small size objects. Due to the drawbacks referred to above, it is desirable to design an optimized mission profile in order to ensure that the rocket drop maneuver may be completed safely and that the following requirements may be met:

- reaching a maximum rocket drop altitude;
- ensuring a maximum initial speed of the rocket;
- reaching the desired initial trajectory of the rocket;
- ensuring that the aircraft carrying a rocket may break away safely.

Figure 2. Configurations of the MiG-29 and the space rocket taken into consideration. Left: piggy-backing the rocket. Right: rocket suspended under the fuselage.



As indicated above, the key parameters determining the effectiveness of a space launch system relying on aircraft platforms include the following:

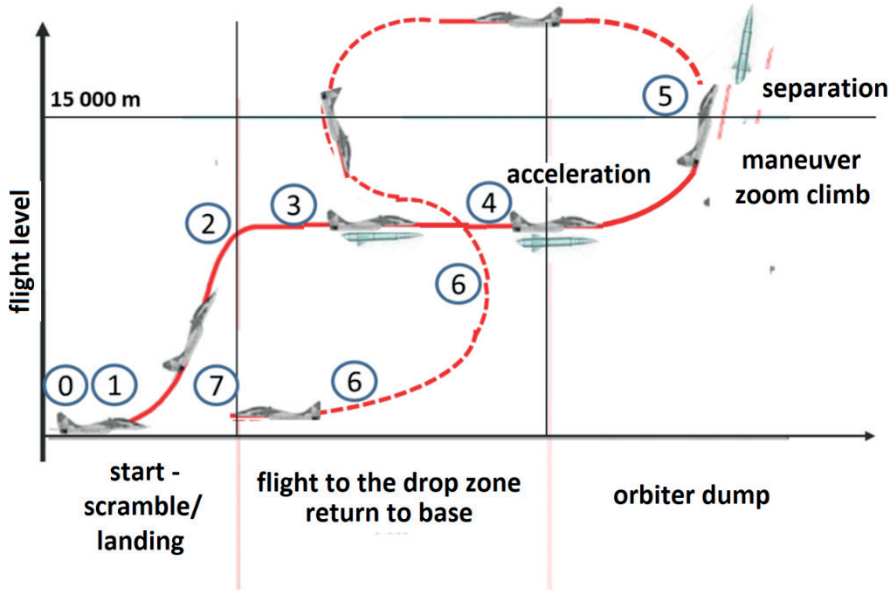
- the velocity of the carrier aircraft while dropping the payload;
- the altitude of the carrier aircraft;
- the angle of attack of the aircraft while dropping the payload.

This angle also becomes the launch angle of the space rocket. The first parameter, i.e., airspeed, is determined by the performance of the aircraft in question. For the Su-22 and MiG-29, it may be derived from their flight manuals. The same is also true for the altitude. However, an additional phenomenon known as the "energy ceiling" may be relied upon in order to increase the altitude and the velocity that may be reached by the aircraft. The energy ceiling – is the altitude achieved by an aircraft taking advantage of its kinetic energy stored by reaching its maximum velocity in level flight. While in level flight, the pilot accelerates the airplane to its maximum velocity achievable at a cruising altitude. Then, it performs a steep climb, enabling the aircraft to gain more potential energy (altitude) at the expense of losing its kinetic energy (velocity drop). In the literature, this maneuver is known as a "zoom climb". During this maneuver, the optimal rocket drop angle may be achieved simultaneously as the aircraft performs a half-loop and turns back to its base.

The mission profile proposed to perform the task is shown in Figure 3. When analyzing the mission profile, it is desirable to determine parameters such as the duration of the successive flight stages, distances traveled, and flight fuel used in each phase of the flight. The fuel (its consumption and reserves) is crucial for the success of the task at hand, as the aircraft must have sufficient fuel to accomplish the mission and return to its base. Some basic calculations of the above-mentioned factors have been performed as part of the study to answer the question of whether the aircraft under consideration are capable of performing this type of mission. For the calculations, the space rocket-related were taken from Table 1. This means that the weight of the rocket equals 930 kg, its dimensions are 5.42 x 0.56 m (length x diameter), and separation takes place at an altitude of 15,000 m, with the initial velocity (of the carrier) of 250 m/s, and its angle attack (while making the drop) amounting to 50°. The rocket is carried under the aircraft's fuselage. One should note that in the first studies of this type, the rocket was proposed to be attached on top of the aircraft's fuselage (Clarke et al., 2007). In the case of the MiG-29, such an approach would allow increasing the dimensions of the space rocket. However, an analysis concerned with the safety of the flight and of the crew indicates that placing the rocket on top of the airframe creates a considerable risk of its collision with the aircraft during separation. Subsequent analyses no longer took this scenario into consideration and focused solely on attaching the rocket to the plane's suspension points located under its fuselage.

In the case of the MiG-29, the calculations were performed based on flight manual data (Dowództwo Wojsk Lotniczych i Obrony Powietrznej, 1992), assuming that the rocket would be carried under the plane's fuselage (Figure 2), at the location of an external fuel tank, and would be attached using a special adapter. Such a solution allows using missiles with a diameter of more than 30 cm. Unfortunately, the distance between the ground surface and the rocket is the limiting factor here. It is quite low in this configuration and involves the risk of the rocket hitting the runway surface during takeoff. For the Su-22, similar calculations were performed based on the available flight manual, assuming that the rocket would be carried centrally under the fuselage or under one of the wings.

Figure 3. Mission profile proposed for an air-assisted system for launching a payload into low Earth orbit. Individual phases: 0-1 – starting engines and taxiing, 1-2 – take-off and climb, 2-3 – steady level flight, 3-4 – acceleration to supersonic speed, 4-5 – zoom climb maneuver, 5-6 – descent, 6-7 – approach and landing.



7. Simulations and studies concerned with the rocket's impact on the aircraft's aerodynamic and mechanical properties

(3D) digital models of MiG-29 and Su-22 were developed for the needs of the project. For this purpose, advanced reverse engineering tools, such as the GOM ATOS Triple Scan 3D optical scanner and the GOM Tritop photogrammetric coordinate measuring system, were used. Once recorded, the scanned data formed the so-called virtual "point cloud". Then, advanced approximation techniques available in the Siemens NX software were relied upon for smoothing definition curves and combining fragmented surface patches. That is how spatial models of both planes' aerodynamic solids were created.

For both modeling variants presented, a series of numerical calculations was performed for different airspeeds and angles of attack. The results showed that this configuration offers satisfactory longitudinal stability and good stall characteristics for high angles of attack within the entire flight envelope studied. The impact on velocity is lower than that induced by the presence of the rocket alone. The results are presented in the form of graphs with aerodynamic characteristics and color maps showing the distribution of the individual parameters within the flow fields on the surfaces of the solids studies and are supplemented with an image showing the current lines. The simulation was performed using the industry-recognized flow analysis software ANSYS Fluent. Based on the analysis of the obtained results, one may conclude that the impact the rocket exerts on the computed aerodynamic characteristics of the aircraft is negligible and that the presence of the rocket does not significantly affect the image of the flow field on the aerodynamic surface of the studied object.

Figure 4. MiG-29, comparison of basic aerodynamic characteristics: Left – lift coefficient *Cz*(*α*), right – drag coefficient *Cx*(*α*) for the MiG-29 aircraft with (CFD_A+R) and without the rocket (CFD).

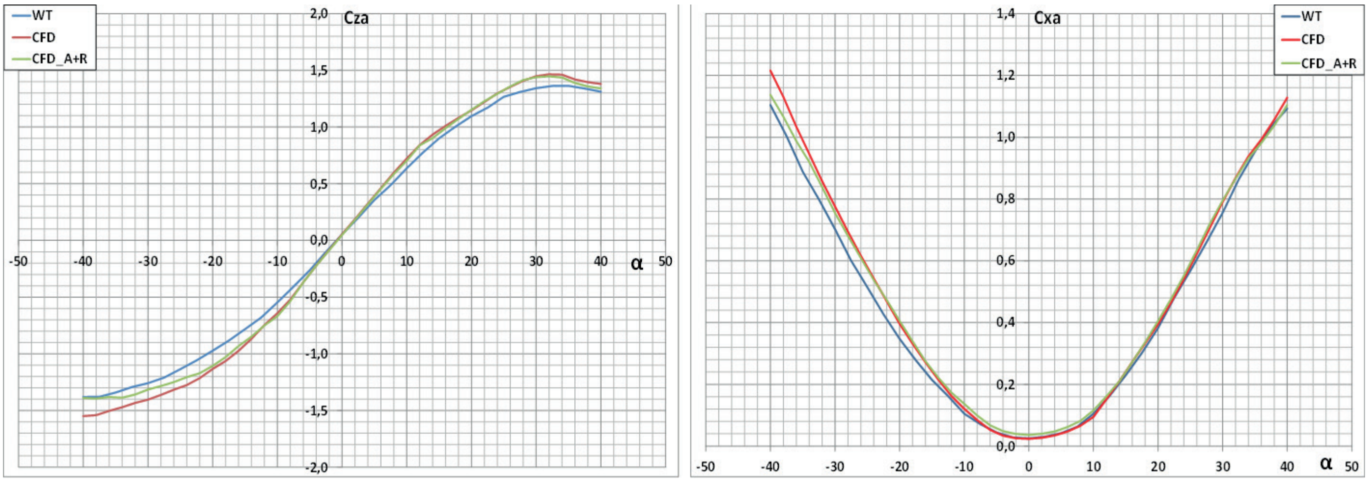


Figure 5. Static pressure distributions on the surface of the MiG-29 airframe in the configuration with the rocket, for the angle of attack α = 0° and 12°.

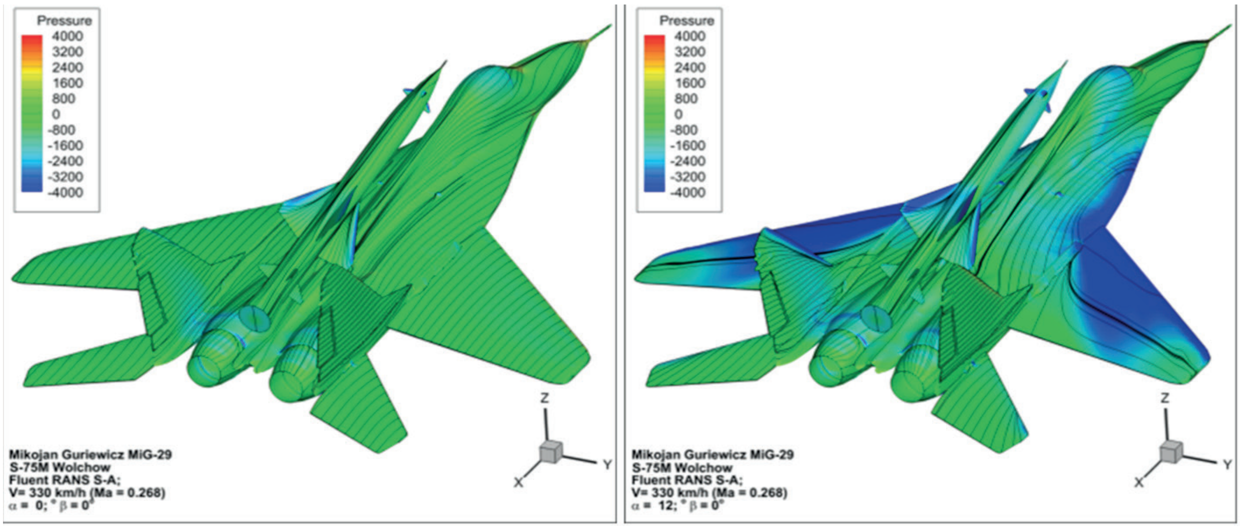


Figure 6. Su-22, Comparison of the lift-to-drag ratio as a function of the angle of attack for the Su-22 in clean configuration (CFD Su-22, left) and with the ALASA rocket (CFD Su-22 ALS, right) for different velocity values.

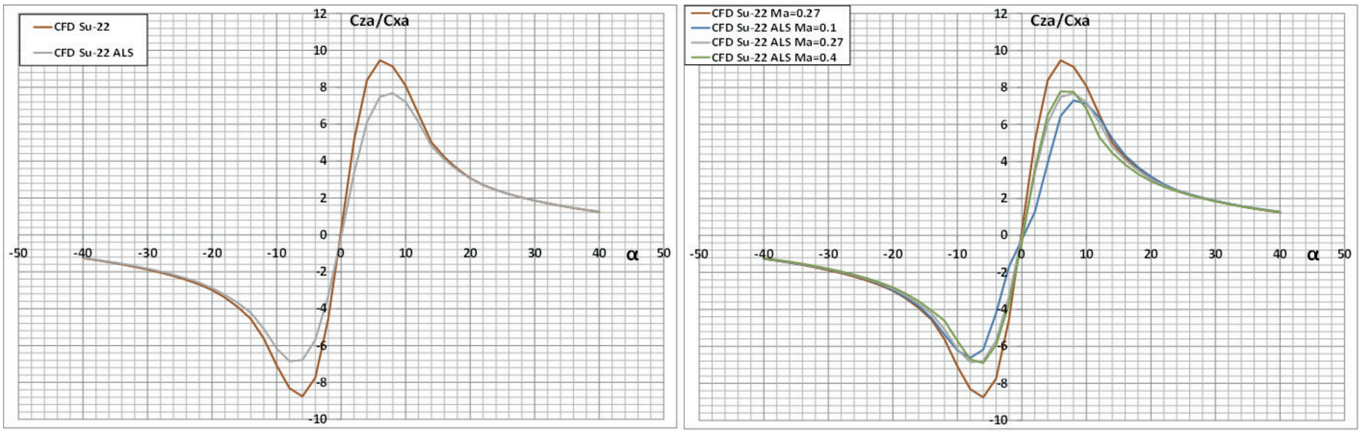
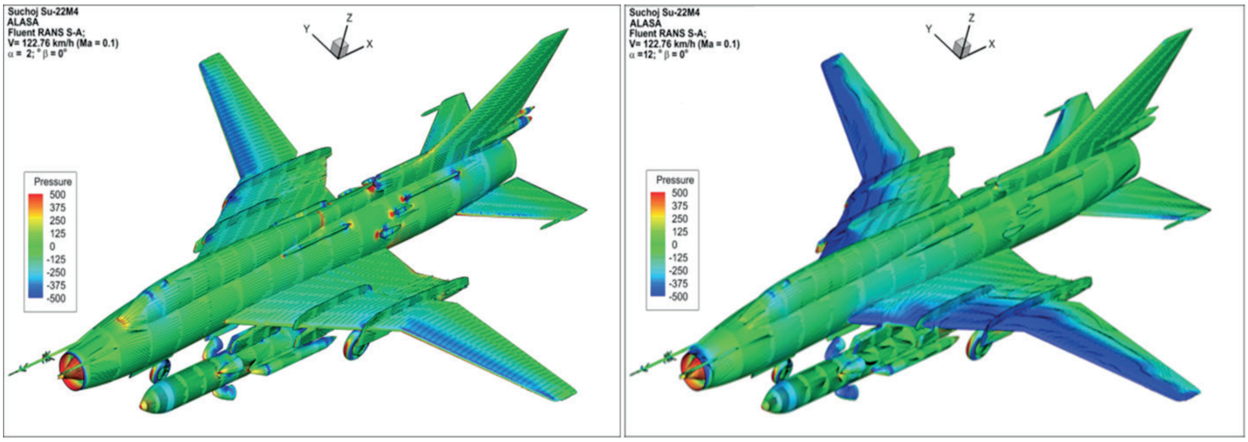


Figure 7. Comparison of changes in pressure distribution and current lines on the surface of the Su-22 with the suspended rocket, for α = 0° and 12°.



Numerical calculations were supplemented with wind tunnel tests conducted at the Military University of Technology. For this purpose, scale models of the aircraft and the space rockets were made. Using digital (3D) models, the scale models were "printed" on 3D printers for wind tunnel testing (Figure 8, 9). Most parts of the models were printed using the FDM (Fused Deposition Modeling) technology. The components were then put together, the joints were corrected, and the outside surfaces were painted. The results of the tunnel tests complied with the numerical calculations, which confirm that the rockets exert no significant influence on the aerodynamic properties of both aircraft.

Figure 8. The model of the Su-22t during wind tunnel tests.

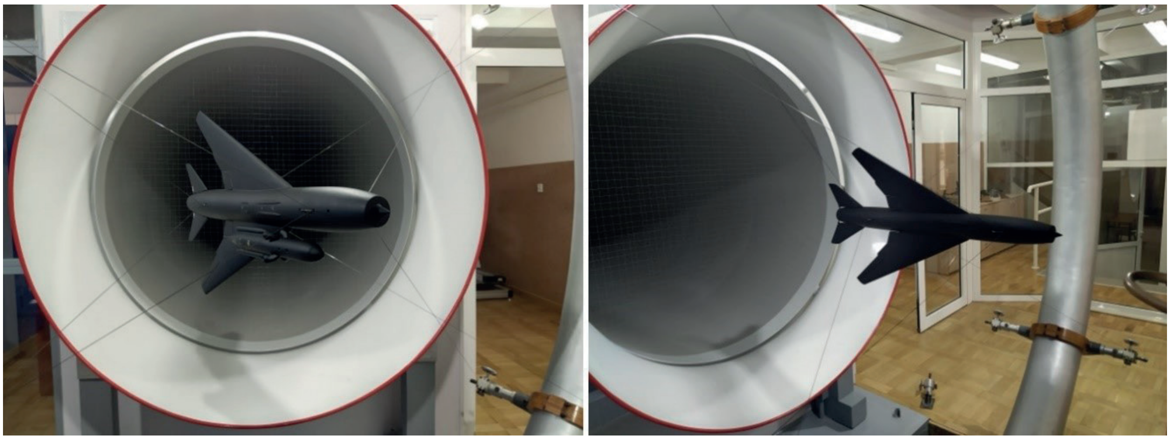
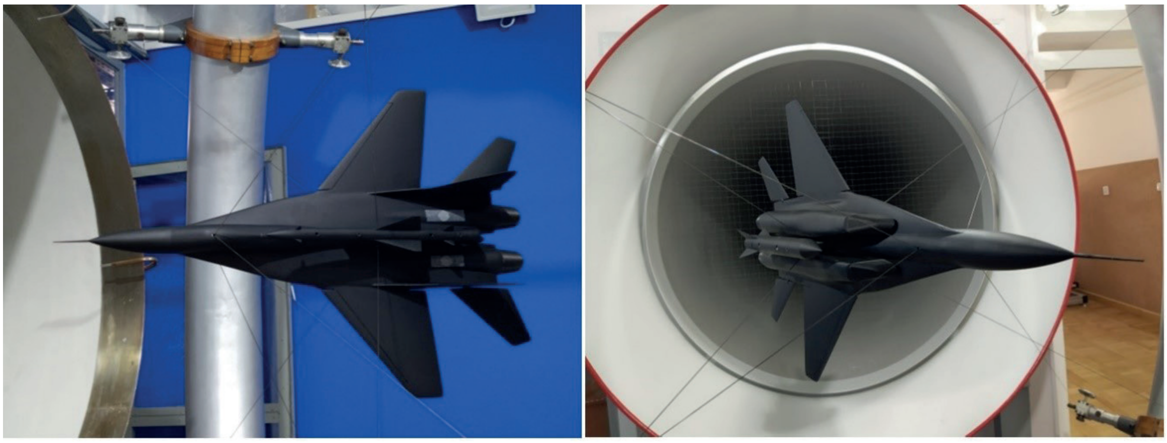


Figure 9. Model of the MiG-29 with the space rocket on top of and under the fuselage.



Discrete models of both structures were prepared using the Finite Element Method (FEM), to evaluate the stresses to which the load-bearing structure of the aircraft proposed to serve as platforms launching satellite payloads are subjected. The simulated structural properties of both models were analyzed by assessing rigidity- and weight-related parameters that are crucial for the static and dynamic performance of the structures in question. The validation analyses of MiG-29 and Su-22 models were based on the evaluation of mass distribution and on matching rigidity-related properties of the individual structural assemblies. The analyses in question involved comparing model results with the expected outcomes determined in a simplified manner. Unfortunately, the manufacturer's design documentation is not available for any of the aircraft – the exact weights of structural components and the results of factory static tests are not known. No research of this type was performed at the university due to the logistical complexity of the project and its high costs. Therefore, the values obtained for the models were related to those determined by approximate methods. Component weights were determined statistically – based on empirical formulas available in different publications. The rigidity of the model structures, in turn, was evaluated by relating numerical displacement or maximum stress values to the maximum estimated values. When evaluating aerospace structures, it is assumed that the maximum displacements of extremely loaded surface load-bearing structures usually do not exceed 10-12% of the maximum length of the structure. On the other hand, maximum stress levels should not exceed 70-75% of the values determining the break strength of the structural material (for structural duralumin the value of Rm=450 MPa may be assumed). In light of reference values obtained in the manner described above, the values achieved for FEM models of MiG-29 and Su-22 aircraft may be considered acceptable.

Figure 10. Discrete models of MiG-29 and Su-22 for analyzing structures by FEM.

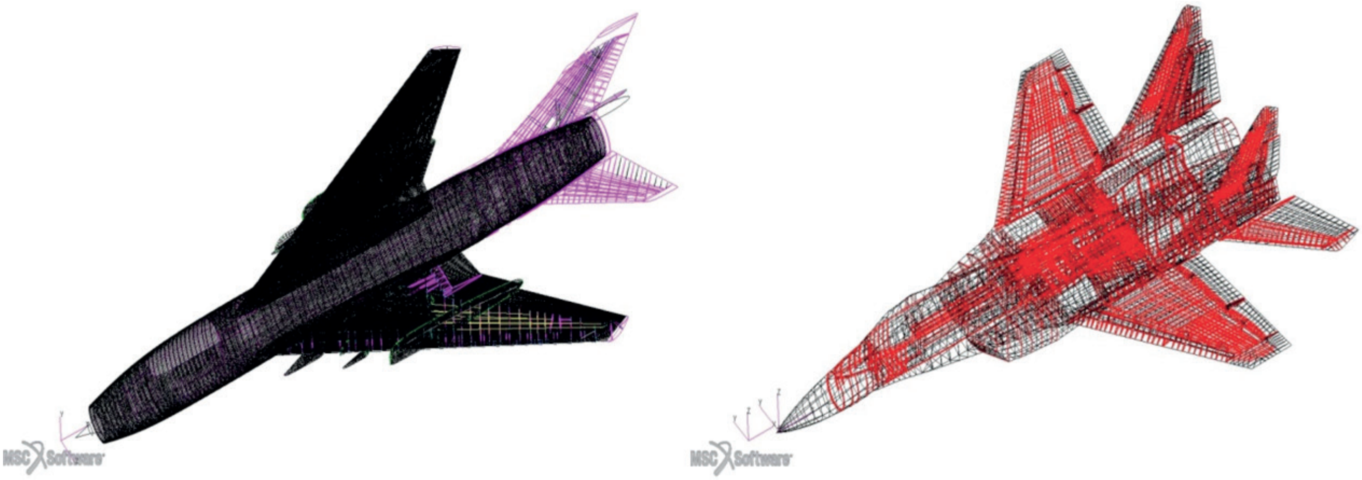


Table 2 presents an analysis of the program-related risks, with a risk weight ranging from 1 to 3 assigned to each of the aspects (6 categories) discussed in the paper. The value of 1 was assigned to the minimum risk level, while the value of 3 to the maximum risk level. The comprehensive assessment performed shows that both aircraft are characterized by similar risk rates. The risk level is relatively and equals 6 on a scale of 6 to 18 (high risk). A slightly overestimated value of 8 and thus a higher risk level was obtained for the MiG-29 under the scenario with the rocket piggy-backed on top of the fuselage.

Table 2. Assessment of space program-related risks for Su-22 and MiG-29

Evaluation of:	Risk level on scale of 1 to 3*		Comments
	Su-22	MiG-29	
Aircraft acquisition	1	1	
Capacity of the domestic industrial sector	1	1	
Space object launch concepts	1	2/1	piggy-back/under the fuselage
Threats affecting the carrier aircraft	1	2/1	piggy-back/under the fuselage
Aircraft performance	1	1	
Impact of the space rocket on the basic aerodynamic and mechanical properties of the aircraft	1	1	
Total	6	8/6	6–low risk 18–high risk

* low – 1, medium – 2, high – 3.

8. Conclusions and recommendations

The analysis of this topic shows that the proposed air-assisted rocket launch system is a feasible alternative to conventional solutions relying on ground-launched rockets, especially for countries lacking the required technologies and capabilities.

The system proposed is based on Su-22 and MiG-29, which are likely to be withdrawn from service soon and may thus become available for the space program described herein. The military airbase located in Malbork remains open, allowing aircraft to operate in the North Sea region, where the operations in question may be performed safely.

In the considered configuration, MiG-29 and Su-22 will successfully perform the task of carrying a rocket with a space-bound payload of at least 10 kg.

The results of computer simulations involving air-assisted rocket launch systems indicate that the impact of the rocket on the aerodynamic characteristics of the aircraft is negligible. The presence of the rocket does not significantly impact the airframe's flow field image and the airframe's in-flight stability. Analysis of the airframes' load-bearing structures does not show any significant changes in the magnitude and distribution of the loads and distortions which would be caused by the space rockets carried.

The risk analysis indicates that the risk affecting the success of the program is acceptable. It may be concluded that the domestic technology capabilities and repair facilities have the sufficient potential and experience to continue to maintain the aircraft in an airworthy condition, as well as to modernize and adapt them to the needs of the program.

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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