



STUDY ON CONFIGURATIONS OF AIRBORNE LAUNCH SYSTEM FOR DELIVERY OF SMALL PAYLOAD TO LOW EARTH ORBIT

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Abstract

The paper presents a feasibility study of airborne launch systems enabling the delivery of a small payload into low Earth orbit. The concept of a disposable rocket launched from a fighter aircraft is being analyzed. As alternatives, the paper investigates a reusable rocket plane carried by a mother plane and a three-stage system with a rocket.

Keywords: airborne launch system, rocket plane, simulation

1. Introduction

A payload can be delivered into orbit by using a space rocket launched from the ground, but that is not the only possible solution. For instance, lower Earth orbits can be reached using airborne launch systems. Analysis of benefits that are associated with air-lunching were studies in [1, 2]. This type of solution can be an interesting alternative to the offers of large space launch complexes, especially as it could be beneficial for launching small payloads. Moreover, having an air-launch to orbit system at their disposal can be essential for countries that do not have their own space transport systems or are looking for a solution that provides significant flexibility in terms of launch site and system mobility. The emergence of a market for nano- and micro-satellites (weighing from 1 to 50 kg) makes air-assisted rocket launching platforms the competitive 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. It is worth noting that this kind of system also has applications in the military domain, for example, as an anti-satellite weapon or Responsive Air Launch. 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 4 and 10 years (1 - 4 years for a micro-satellite). It takes 1-3 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)

2. State of the art

Currently, Northrop Grumman is operating on the market with the Pegasus rocket system [3], originally developed by Orbital Sciences Corporation. The system is utilizing a modified passenger aircraft (Lockheed L-1011) and a three-stages rocket (Pegasus XL) attached underneath the aircraft fuselage. Moreover, several players are working on a similar concept to bring into service either a rocket or a rocket plane that can be air-launched to orbit, for instance Stratolaunch [4] or ALOSS project [5]. A study in which collects information about currently carried out projects of such concepts is presented in [6]. However, not all commercial airborne launch system succeeded, the LauncherOne [7] is an example of system that tried to utilize a concept with a rocket fueled only by the liquid propellant but after a few attempts terminated its operations.

In the military domain, the concept of airborne launch system has been investigating for instance by the Boeing with use of F-15 as a rocket carrier [8]. Also, other studies were carried out to adapt such aircraft as F-16 [6] and MIG-31 [9] to a new role.

None of the systems operating so far have been fully reusable, the goal of this paper is to investigate different configurations of air-launch to orbit systems to address the research question of whether a reusable system for such operations can be efficient. As well as the scope of the system reusability. This paper presents the outcomes of a study on the configuration of an airborne launch system for putting a small payload into low Earth orbit (LEO). In the scope of this research, two main concepts are analyzed.

3. Concept of reusable airborne launch system

The first one assumes using a disposable rocket launched from a military fighter aircraft (Figure 1). In case of this scenario, the rocket could be attached to the aircraft either on top or under the fuselage of the aircraft. The separation process takes place at an altitude of 15 kilometers. Due to the high maneuverability of military fighter aircraft, it is possible to separate the rocket oriented parallel to its trajectory into orbit. The rocket delivers the payload into orbit and does not return, only the aircraft is a fully reusable part of the system. The mission profile presented in Figure 1 is simplified to show a general idea. More detailed flight path of the aircraft is presented in Figure 7.

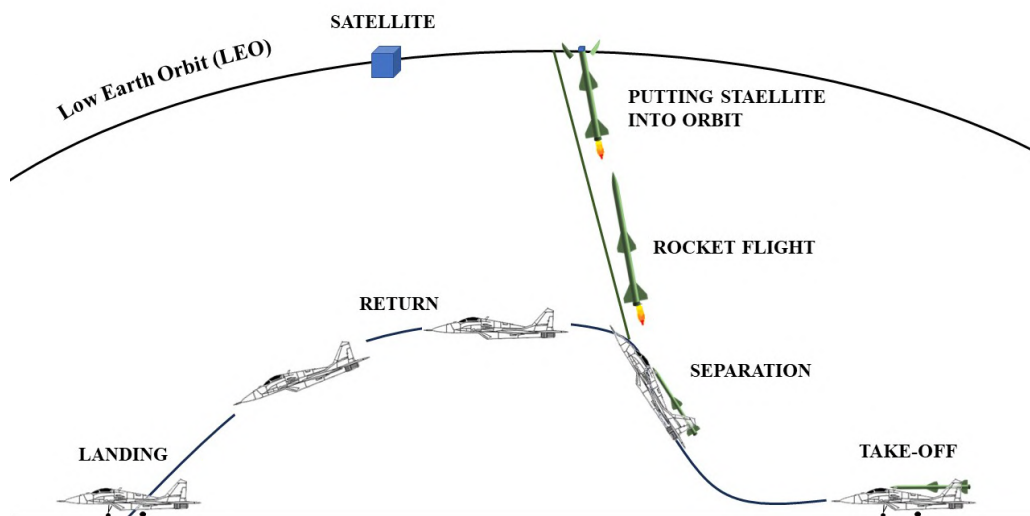


Figure 1 – Two stage system with rocket for putting small payload into orbit

Two retired supersonic aircraft were selected as a potential transport platform: MiG-29 and Su-22. To adjust the aircraft to its new mission, a dedicated mission-laden rocket is to be carried under the fuselage. In terms of safety concerns, the amended configuration of the aircraft with the ventrally mounted rocket is an acceptable solution, whereas further development which would involve payloads mounted dorsally on the MiG-29 aircraft was abandoned. In the considered configuration, both MiG-29 and Su-22 are expected to successfully complete the task of delivering a rocket with useful payload of 10 kg, which is at the least the equivalent of a nano-satellite.

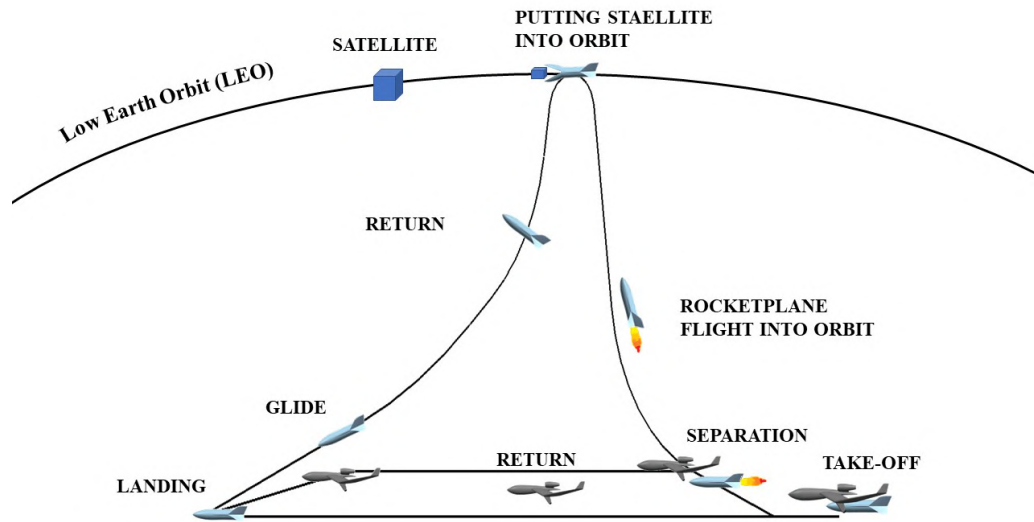


Figure 2 – Two stage system with rocket plane for putting small payload into orbit

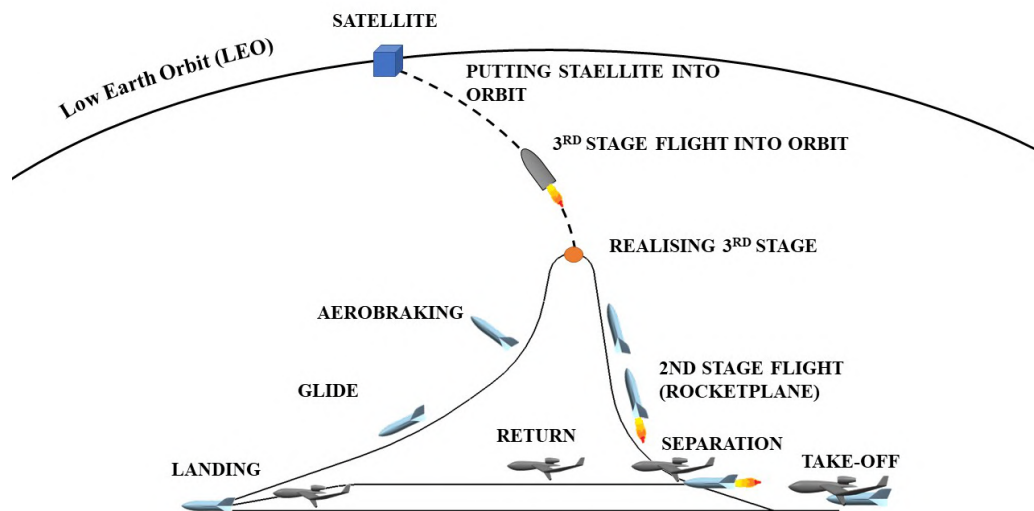


Figure 3 – Three stage system for putting small payload into orbit

The second concept engages a reusable rocket plane lifted by a mother aircraft (Figure 2) [10,11] and assuming accommodation of the system for suborbital tourist flight by adjustment the rocket-plane to unmanned flights. Both vehicles are designed in tailless configuration, during the joined flight the system looks like a conventional aircraft where the rocket plane wings are utilized as the system empennage. The mission begins from a horizontal take-off when both airplanes are connected. The separation of the vehicles takes place at about 15 kilometers. The mother plane returns to base while the rocket plane engages the rocket engine to reach the orbit where the payload is deployed. The difference from the previous concept is that after putting the payload into orbit, the rocket plane

returns to the Earth but needs a heat shield due to high temperature generated by aerobraking process expected by a high speed that is required to achieve the orbit. Moreover, the mix of above concepts was investigated that encompassing the mother plane and the rocket plane equipped with a third stage alike to a small rocket (Figure 3). In this scenario, inside of the rocket plane a third stage is installed. The beginning of the system mission looks similar to the previous scenario where the mother plane with a rocket plane attached to it performs a horizontal take-off. On board of the rocket plane the payload is installed inside of a small rocket. After the separation process, the mother plane returns to the base while the rocket plane begins to climb but it is going to perform the suborbital flight only. At the highest altitude/speed, the rocket plane deploys the third stage with a payload.

This third stage is going to be utilized for payload delivery to the orbit. In comparison to the previous case, the rocket plane does not reach the orbit which means that the heavy thermal shield is not required. The initial speed of the return flight is significantly lower than for the previous case on the other hand, an additional mass associated with the third stage is incorporated. The rocket plane is designed with a Leading Edge eXtension (LEX) which enhances the lift force due to presence of vortex lift phenomenon. The research into flight of the rocket plane in deep stall condition are presented in [12] and [13]. However, this system is not fully reusable due to the presence of a third stage.

4. Concept of the system with military airframe

4.1 Preliminary results – aerodynamic study

The first step of concept analysis required to establish the impact of the rocket on the aircraft aerodynamic to ensure that the present of the rocket does not compromise the aircraft performance. For the analysis of the aeromechanical properties of the set (aircraft-rocket), both 3D digital models for computer simulations and physical scaled models for wind tunnel tests were developed. Laser scanners were used to map aircraft geometry, the measurements were made on the Su-22 and MiG-29 aircraft. Based on three-dimensional scaled models generated in a CAD environment, physical solid models were manufactured using the rapid prototyping method, for the wind tunnel investigations. In recent years the development of new, more reliable tools for "multiphysics" calculations allowed the designers to address more problems at the very beginning (or at early stages) of the design process [14, 15]. The authors decided to use an ANSYS Fluent v.15 software based on solving partial differential equations using the finite volumes method [16, 17]. The results of initial computer simulations of air-launch-to-orbit models indicate that by using computational fluid dynamics, it is possible to effectively determine the aerodynamic properties of highly maneuverable combat aircraft with unconventional "space-bound" cargo [18–22]. The analysis of the results reveals that the rocket's influence on the aerodynamic characteristics is negligible and the presence of the carried rocket does not significantly disturb the flow around the airframe (Figure 4 and Figure 5).

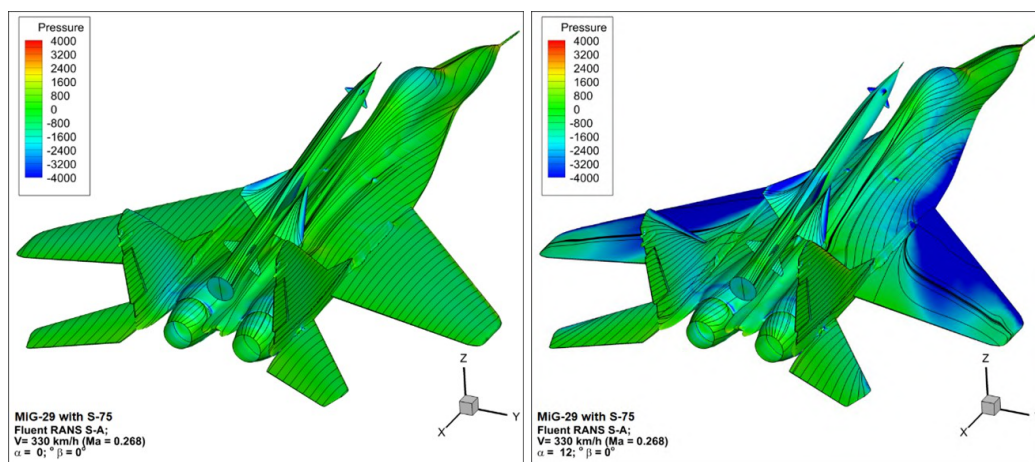


Figure 4 – Distributions of static pressure on the MiG-29 aircraft's airframe with a dorsally mounted rocket

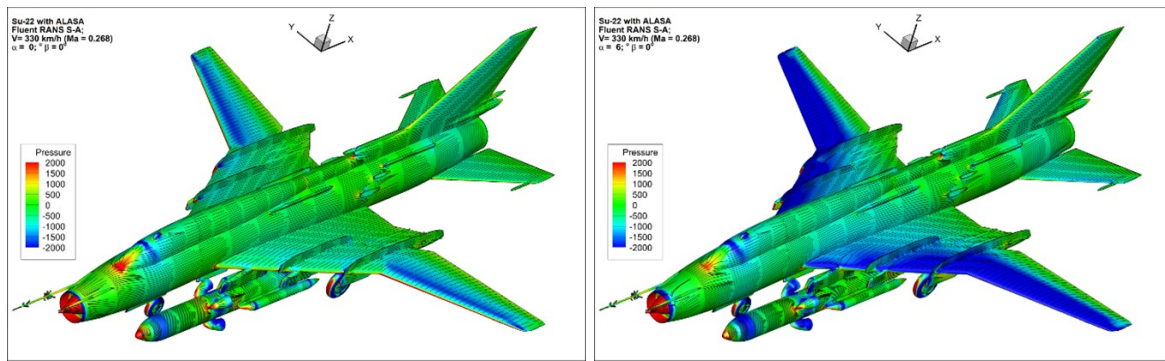


Figure 5 – Comparison of the changes in the distribution of pressure and the streamline on the surface of the Su-22 aircraft in the configuration with an ventrally mounted rocket.

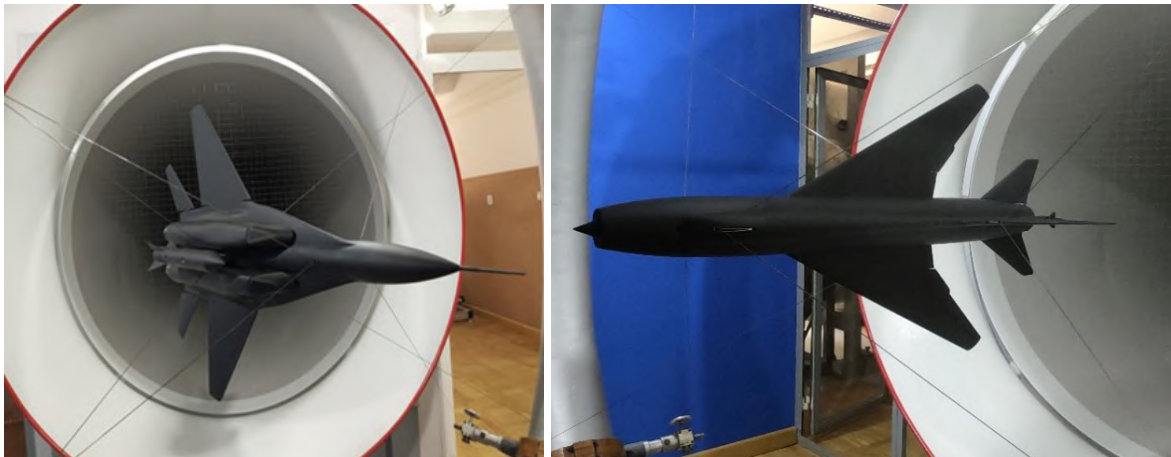


Figure 6 – Scale models of the MiG-29 and Su-22 during wind tunnel tests

Further detailed analyses of aeromechanical properties were carried out in subsequent stages of the study project. Aircraft surface models created for computer simulations are to be used to develop models for experimental research. That way, the numerical analyses and simulations were verified through experimental testing of the systems in a wind tunnel (Figure 6) of the Faculty of Mechatronics, Armament and Aerospace of the MUT. Future analysis are planned regarding reducing the net mass of the aircraft, development of a station for carrying the rocket and the space rocket itself as well as different mission scenario variants (e.g. selection of an air base, carrier rocket drop zone, etc.). But this is beyond the scope of this paper.

4.2 System Requirements - mission profile

After the concept feasibility from the aerodynamic point of view was confirmed, other aspects of system configuration can be examined. As proved by the studies, the system's major drawback has the form of weight restrictions resulting from the payload capacity of the carrier aircraft. 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 location affect the balance of the aircraft and the loads to which the airframe is subjected in flight. Therefore, the air-assisted rocket launch systems are suitable for launching low weight, small size objects. Due to the drawbacks, it is desirable to design an optimized mission profile to ensure that the rocket separation 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.

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

- speed of the carrier aircraft while dropping the payload;
- altitude of the carrier aircraft;
- 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. It may be derived, for the Su-22 and MiG-29, 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 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, the 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 maneuvers 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 7.

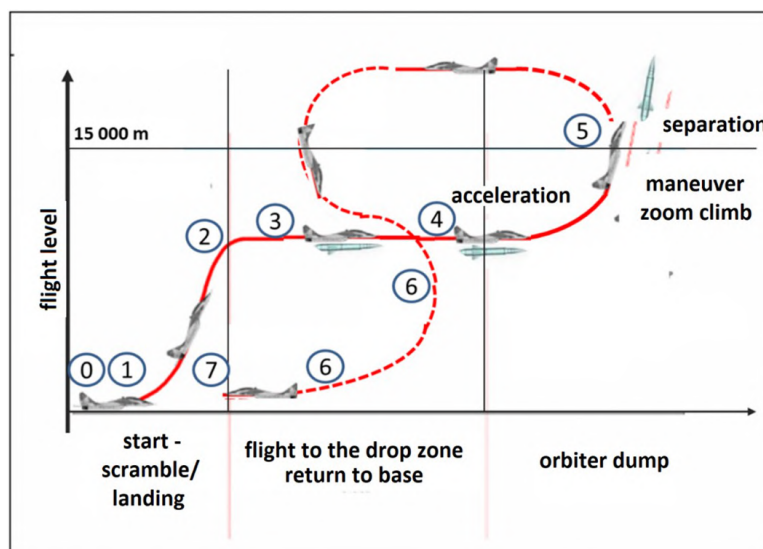


Figure 7 – Mission profile proposed for an air-assisted system for launching payload into low Earth orbit. Individual phases: 0-1 - starting engines and taxiing, 1-2 - take-off and climb, 2-3 - steady level flight, 3-4 - acceleration to supersonic speed, 4-5 - zoom climb manoeuvre, 5-6 - descent, 6-7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

When analyzing the mission profile, it is desirable to determine such parameters as duration of the successive flight stages, distances traveled, and flight fuel used in each phase of the flight. It is the fuel (its consumption and reserves) that is crucial for the success of the task at hand, as the aircraft must have sufficient fuel to accomplish the mission and to return to its base. Some basic calculations of the above-mentioned factors have been performed as part of the study to provide an answer to 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 [23], rocket's separation takes place

at an altitude of 15,000 m, with the initial velocity (of the carrier) of 250 m/s, and its path angle (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 [24].

In the case of the MiG-29, such an approach would allow to increase 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, assuming that the rocket would be carried under the plane's fuselage, at the location of an external fuel tank, and would be attached using a special adapter. Such a solution allows to use missiles with a diameter of more than 30 cm. Unfortunately, the distance between 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 take-off. 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.

5. Concept of the system with rocket plane

5.1 Mission profile - assumptions

As it was mentioned earlier the concept with the rocket plane is going to utilize the system for sub-orbital tourist flights. The take of weight maintains the same, the modifications including the payload type and different rocket engine. Within the scope of this paper only trajectory after the separation of the rocket plane from the mother plane is going to be investigated. Also, the isolated flight of the mother plane is beyond the scope of this work. The aerodynamic and trim results for this mother plane can be found in [25]. Moreover, for the purpose of this study the impact of mother plane on the rocket plane aerodynamic due to close proximity (first few seconds of the rocket plane flight after the separation) is not going to be modelled. Nevertheless the initial condition of the rocket plane flight depends on the vehicle separation speed and altitude, so computation of flight envelope with different engines was addressed. The separation speed can be faster than for the suborbital human space flight case, because the payload like satellite can undertake higher g-loads than a human flying in a tourist mission. The impact of the rocket plane separation speed on the g-load was investigated in [12]. The flight envelop (Figure 8) was computed with use of the Simulation and Dynamic Stability Analysis (SDSA) package [26] while the aerodynamic characteristics required to complete this task were obtained by the PANUKL package [27]. An exemplary pressure distribution for the joined configuration computed by the PANUKL is presented in Figure 9.

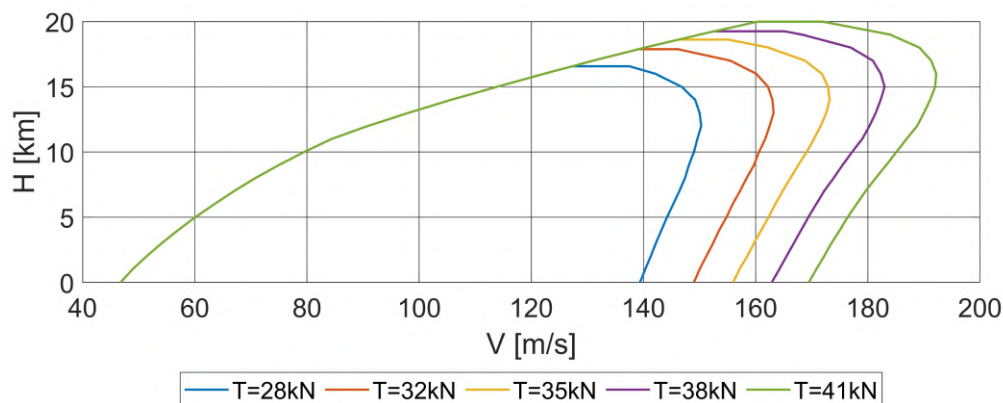


Figure 8 – Flight envelope computed by SDSA for different thrusts of mother plane engines, the legend specifies thrust of a single engine

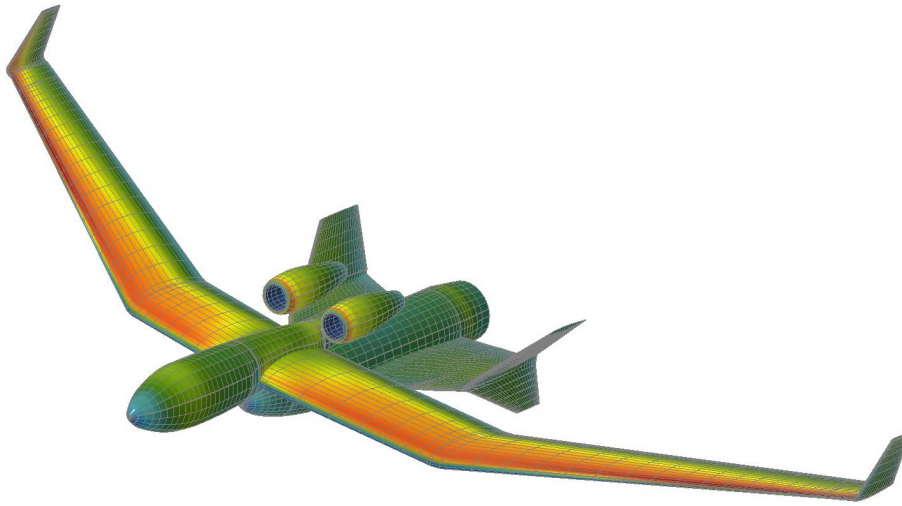


Figure 9 – PANUKL results – C_p distribution for $Ma=0.51$ and $AoA=5$ deg

5.2 Aerodynamics of rocket plane

In case of rocket plane the aerodynamic characteristics were computed with use of the MGAERO [28] software. This software uses the Euler code with multigrid acceleration in the computation of the aerodynamic coefficients of an arbitrary configuration [29]. The numerical model was comprised of a surface mesh and 7 levels of multigrid blocks. The rocket plane numerical model consisted of 20 158 on-body panels and 3 768 788 off-body panels. Exemplary pressure distribution for high Ma is presented in Figure 10, while the drag coefficient plot with respect to angle of attack is presented in Figure 11.

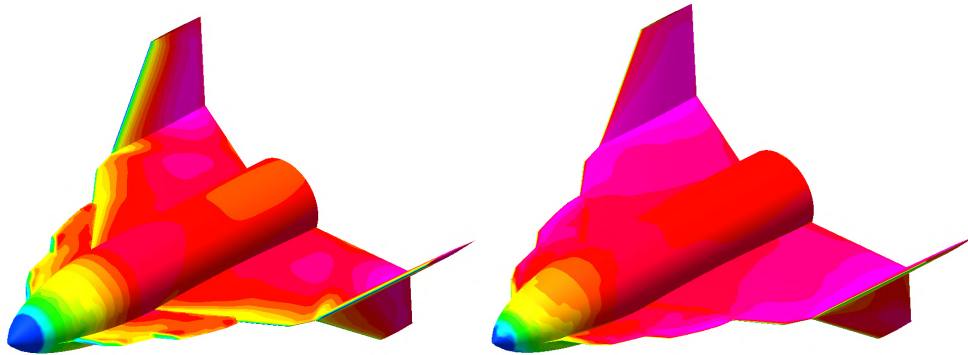


Figure 10 – C_p distribution for $Ma=2.0$: $AoA=0$ deg (left) and $AoA 10$ deg (right)

6. Flight simulation

The goal of this paper is to conduct a feasibility study regarding the airborne launch system configuration, therefore, the optimization of vehicles trajectory is beyond of this study scope. This implies that due to preliminary stage of analysis a few simplifications and assumptions are going to be made. A different mathematical models and tools were used for ascent and descent flight simulation. Within the scope of this paper, the simulations encompasses the following concepts:

- Two stage case - rocket plane lifted by the mother plane and delivers the payload into orbit
- Three stages case - rocket plane lifted by the mother plane, rocket plane carries the third stage which delivers the payload into orbit.
- Three stage rocket lifted by the military aircraft

This paper focus only on flight simulation of the rocket plane and rocket.

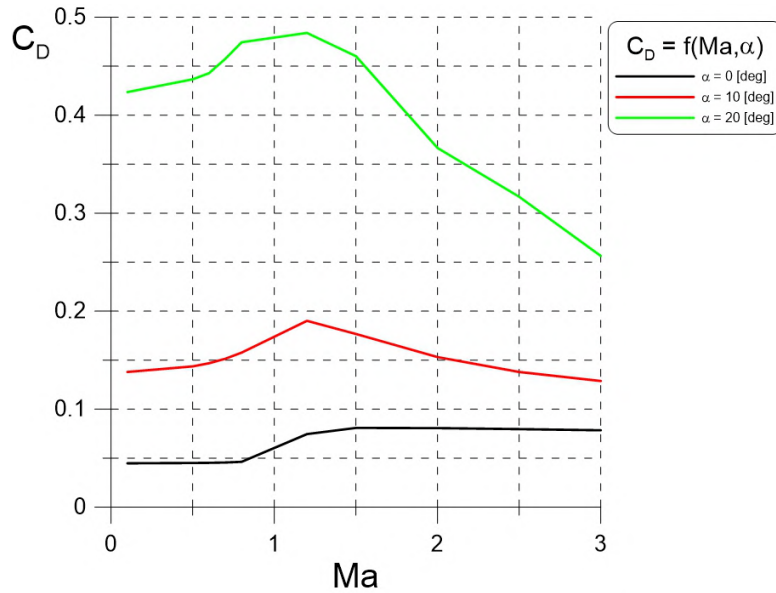


Figure 11 – Rocket plane drag coefficient versus Mach number

6.1 Numerical model of the ascent flight

Flights of the rocket plane and rocket were simulated with use of the Simulink (Figure 12). The simulation model contained the following subsystems: rocket engine, mass, aerodynamic forces, gravity, and equations of motion. By implementation of switch base block the simulation model was adapted to predict flight of vehicle which includes up to 3 stages. In case of the simulation of the scenario with the rocket plane, the rocket plane plays a role of the first stage. Aerodynamic, mass and engine characteristics for each stage were defined independently. Due to preliminary stage of the analysis a simplified model was used [30]. The implemented mathematical model describes the vehicle motion as a point mass, the aerodynamic forces where limited only to the drag. A simple gravity model which depends only on the altitude was assumed. Moreover, in the above mathematical model the Earth's rotation was neglected. Also, in the model the thrust vector control system was not implemented.

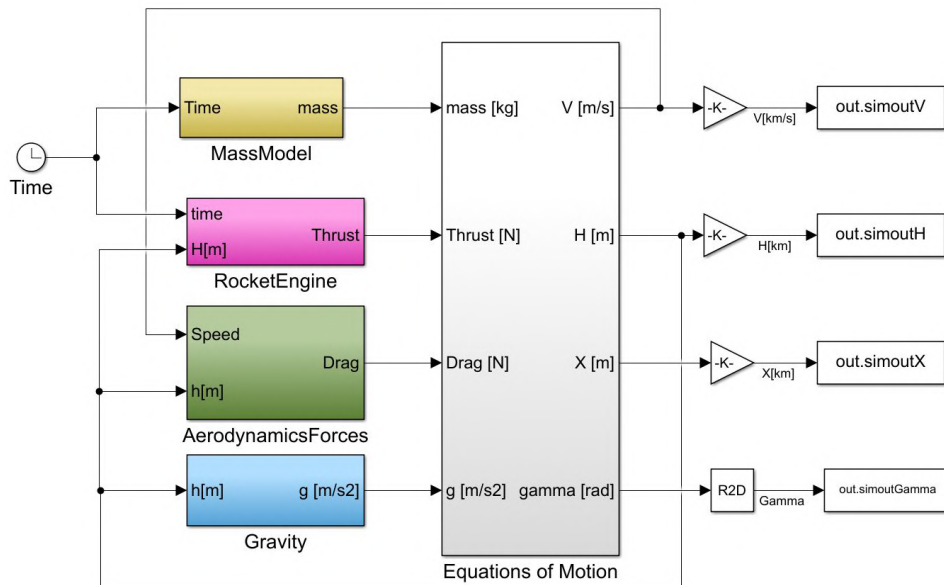


Figure 12 – Simulink model

6.2 Numerical model of the descent flight

The descend flight trajectory was simulated with use of SDSA package. The simulation were performed for the rocket plane concept because this is the only part of the system that return to Earth. The numerical model of the rocket plane is the same as was used in [31]. But the weight of the rocket plane is lower due to ejection of the payload.

6.3 Results – concept with rocket plane

Different mass arrangements were considered but the maximum initial mass of the rocket plane never exceed 4000kg including the propellant and payload mass. The mass change was associated with different payload and propellant mass, but the rocket plane empty mass was always the same in all simulations. When the rocket plane is directly flying into orbit the maximum propellant weight is equal to 2373 kg. In case when rocket plane is equipped with the rocket (third stage), the maximum mass of this additional stage is equal to 500 kg.

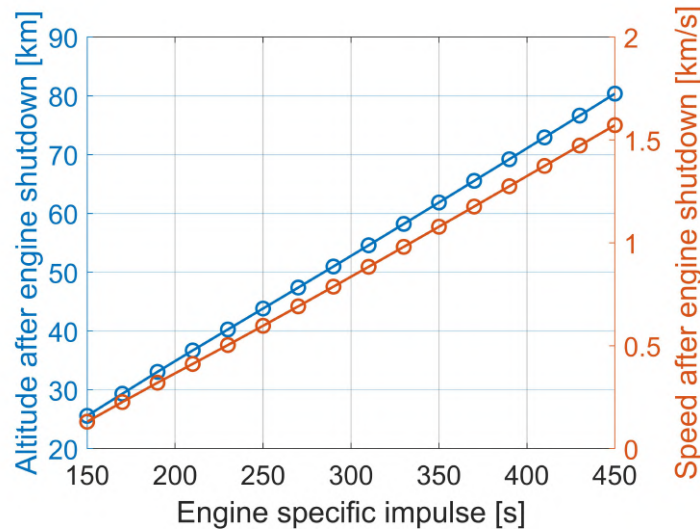


Figure 13 – Rocket plane altitude and speed just after the engine shutdown for different specific impulse.

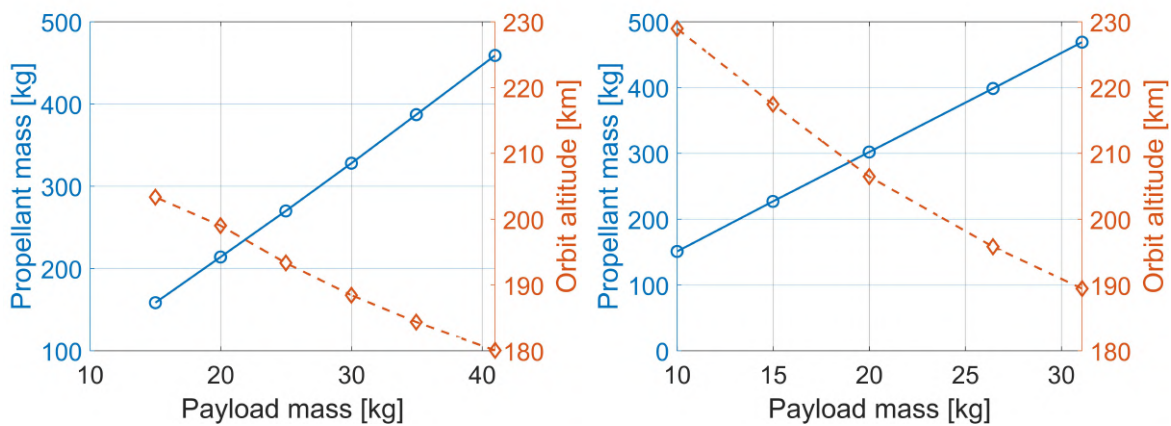


Figure 14 – Payload sensitivity study in case of separation just after the engine shutdown (left plot) and in case of coasting time (right plot). How the mass of propellant (only last stage) change with respect to the mass of the delivered into orbit. ($I_{sp}=300s$, $H_0=15km$, and $V_0=155m/s$)

The first set of results is associated with the case when the rocket plane performs suborbital flight (three stages case). For this concept two possible scenario were analyzed, the first one assumed that the third stage is released just after the rocket plane engine shutdown while the second one

assumed that the separation occurs when rocket plane speed decrease its speed. The second set of results examine the concept of the rocket plane directly flying into the orbit.

This paper shows the results of computations for different payload weight, initial conditions and engine specifications. Firstly the impact of the specific impulse on the rocket plane performance was investigated. Figure 13 shows how the rocket's plane speed and altitude just after the engine shut-down changes with respect to the specific impulse. To make the system easy to operate, the solid propellant choice would be the best but this implies the specific impulse limitation up to 300 s. Next set of simulations, were performed to compare the case of releasing the third stage just after the engine shutdown with the case when the separation occurs after speed reduction to less than 25 m/s. Based on the obtained results (Figure 14 - left), it can be observed that this design can deliver into orbit the mass of 41kg. This includes the payload and empty mass of the third stage but this is only possible if the third stage would be separated just after the rocket plane engine shutdown. If the third stage is going to be transported inside of the rocket plane and procedure of releasing would require to open the nose, then this is going to be associated with high loads acting on the rocket plane due to high speed. This would increase the structure weight and risk of the operation. Therefore, releasing the third stage after the rocket plane decrease its speed was also investigated (Figure 14 – right plot). In such a case the maximum mass that can be transport into orbit was reduced to 31 kilograms. Comparison of the engine thrust for this two scenario is presented in Figure 15. While the plot of altitude and speed versus time is presented in Figure 16. In all simulations as a target velocity increment 7.8km/s was assumed.

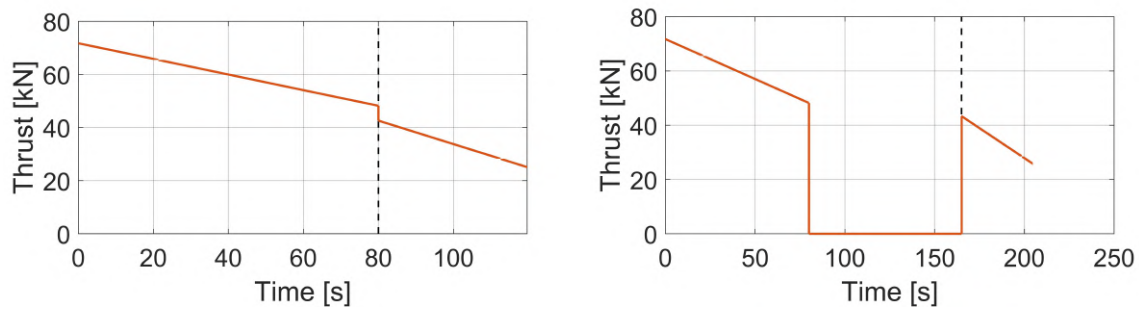


Figure 15 – Comparison of the thrust versus time for case of releasing the third stage just after the separation (left) and after the rocket plane coasting to decrease the speed (right).

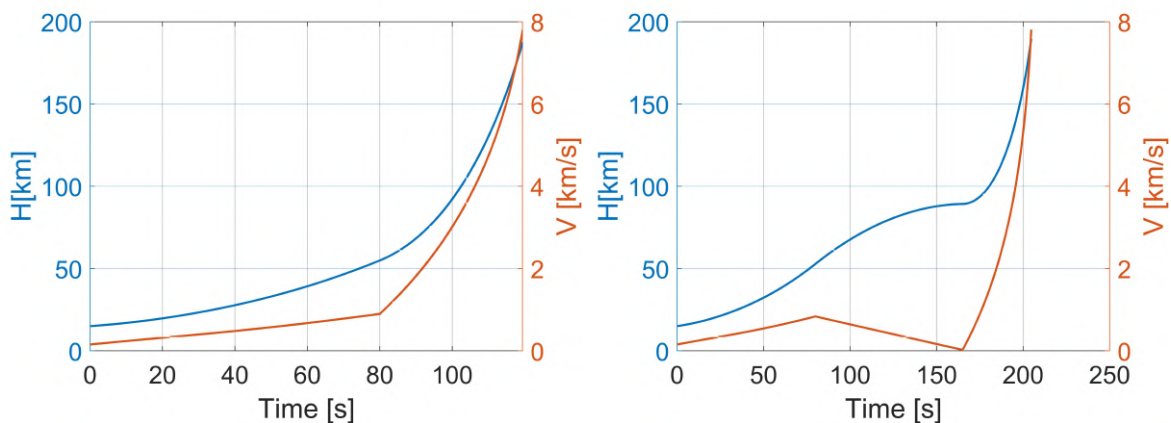


Figure 16 – Simulation of the flight for maximum payload. Plot on the left showing the case of releasing the third stage after the engine shutdown while the plot on the right is the case when the rocket plane first decelerates.

The return trajectory for the medium and low altitude was simulated with use of SDSA package. It was assumed that the simulations begins when the rocket plane achieved the altitude where the aerodynamic forces can not to be neglected. This altitude was selected based on previous studies

[13,31]. The initial speed specified in SDSA was taken based on the results of Simulink. The SDSA simulation results are presented in Figure 17. Due to low initial speed the rocket plane maximum speed indicates that heavy thermal shield is not needed. A partial thermal protection on the wing leading edge and fuselage nose should be sufficient. The maximum Mach number is equal to 3.24 and was achieved for the altitude about 32km.

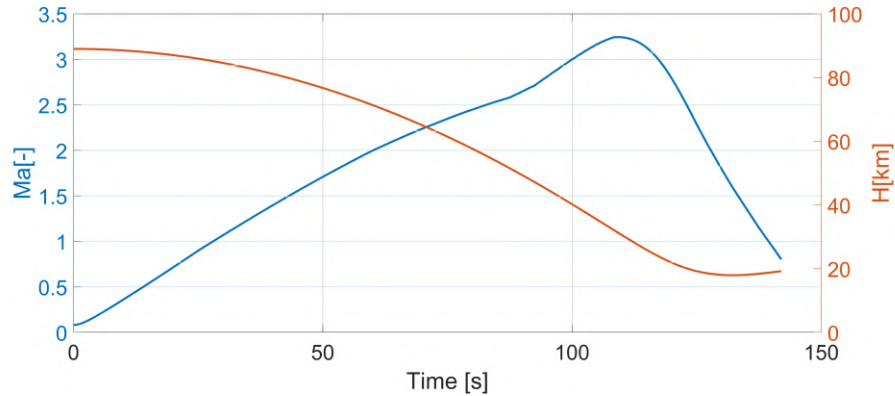


Figure 17 – Results of SDSA simulation for the return trajectory.

Next, the sensitivity study was conducted on to impact of initial speed and initial altitude of the single-stage to orbit system. For the purpose of this study, to maximize the mass of propellant, payload weight was assumed to be equal to zero. The simulations were performed for initial velocity between 155m/s to 185 m/s and initial altitude between 15-20km, results are presented in Figure 18 (left plot). All simulations were conducted for the specific impulse equal to 450s which can be assumed as the highest possible for the liquid propellant. The next set of simulation were performed for $V_0=155\text{m/s}$ and $H_0=15\text{km}$ with different initial path angle (Figure 18, right). Regardless of the initial conditions the speed increment is not sufficient to reach the orbit. Those simulations revealed that with current liquid rocket engine technology it is not possible to use a single-stage vehicle. To achieve this goal unconventional space propulsion must be developed and put into service. A hypothetical set of simulations were conducted to address the question about the engine specification that is needed to perform the mission (Figure 19). So, to achieve the orbit with the current design that would require specific impulse about 1160s. The concept of single stage design might be more feasible if the rocket plane would be equipped with two different type of engine, for example the ramjet engine. But that would require a further investigation.

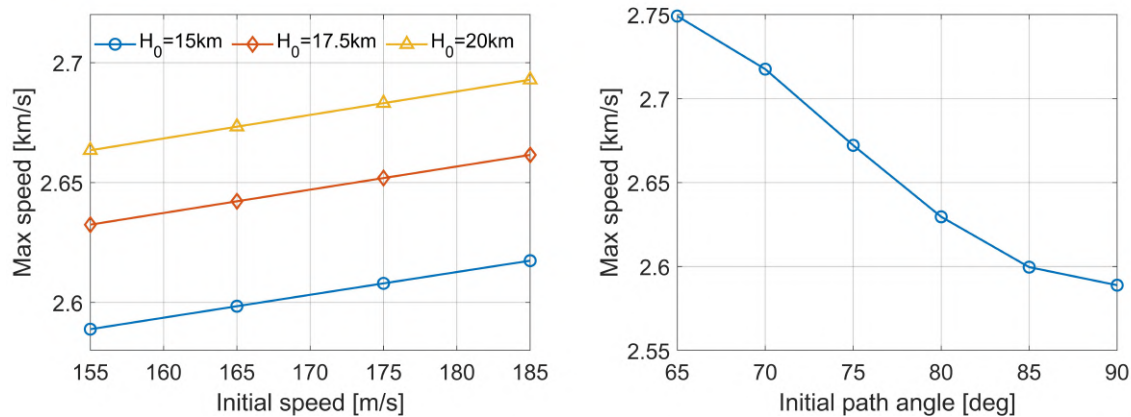


Figure 18 – Impact of the separation condition (speed and altitude) on final rocket plane speed (left). Impact of the initial path angle on the rocket plane final speed, $H_0=15\text{km}$ and $V_0=155$

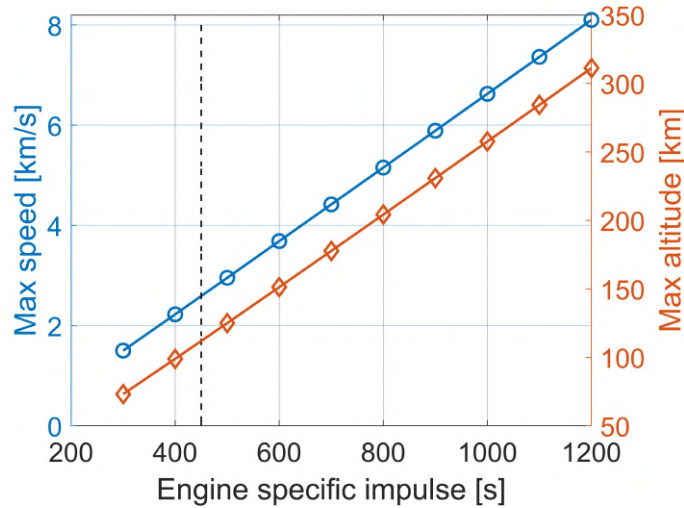


Figure 19 – Impact of the specific impulse on max speed and altitude. The dash line denote the limit of the liquid rocket propellant.

6.4 Results - concept with fighter aircraft

The analysis was conducted for three stages rocket launched from a military aircraft. Different payload weights were analyzed but the maximum rocket take-off weight was restricted by mass and the size that were established in analysis presented in section 4.2. In all analyzed cases the maximum mass of the rocket was the same, the change was associated with the propellant and the payload contribution in the mass of the third stage (Figure 20). Exemplary results for flight with the payload of 35 kg is presented in Figure 21. In this analysis, the payload mass is assumed as the sum of the satellite mass and inert mass. Based on results, it can be concluded that mass of the propellant for the military aircraft lifting the rocket is smaller than in case of the rocket plane concept.

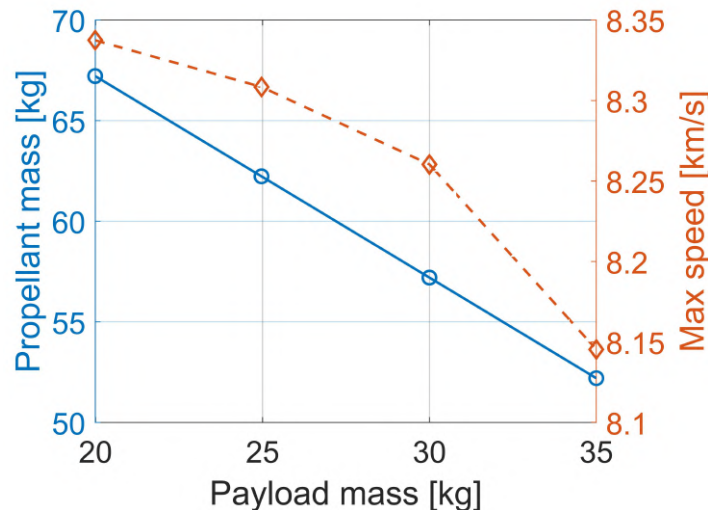


Figure 20 – Impact of the payload and propellant mass on maximum speed.

Comparison of the results for mass of 25 kilograms that is lifted into orbit by a rocket plane and by military aircraft lifting rocket is presented in Figure 22. To account for losses that were not accounted for in the mathematical model, those simulation were performed for speed increment about 8.3 km/s.

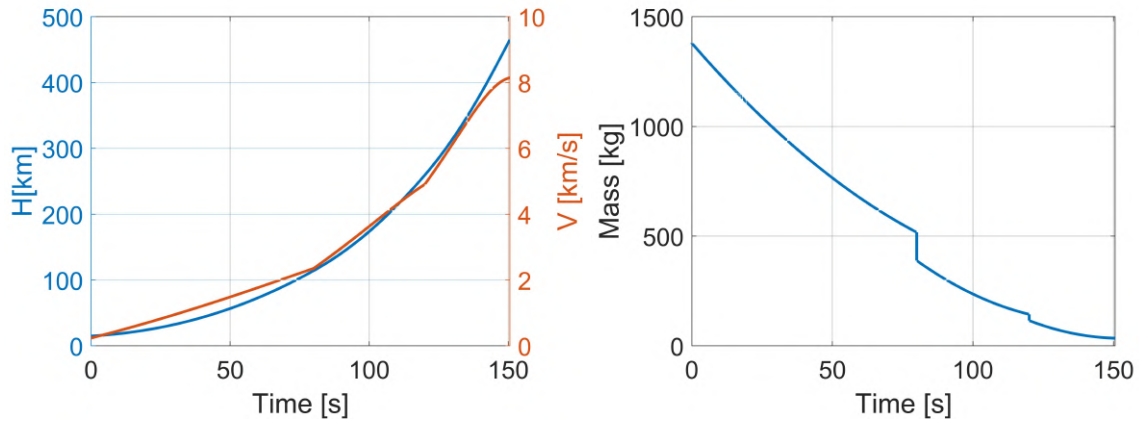


Figure 21 – Results of simulation for case of payload equal to 35kg.

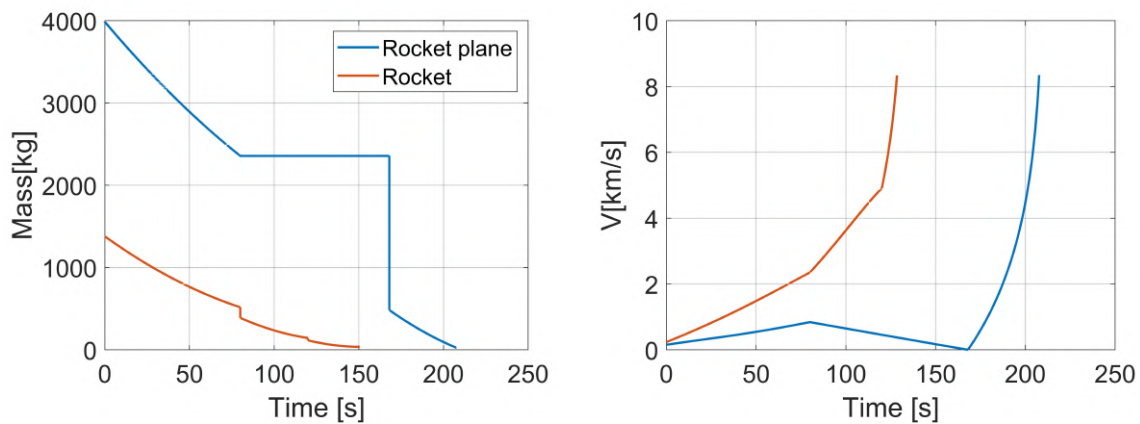


Figure 22 – Comparison of results of two concepts

7. Summary

A feasibility study was carried out for the assessment of the best possible configurations that could expand airborne launch systems portfolio. In the paper analysis of different mission profiles and weights of the payload was considered. Sensitivity study was conducted to provide insightful overview regarding the possible range of application of each system.

This study is supported by results of flight simulations acquired from Simulink and SDSA. Based on the results it can be concluded that concept of airborne launch can be competitive solution for small satellites.

In the case of the concept of a rocket plane, the scenario of direct rocket flight into orbit is not possible unless an unconventional propulsion system is developed and put into service. Alternative approach for such kind of concept could be an implementation of the set of two different engines like ramjet and rocket engine. But this requires a further evaluation.

For a rocket plane carrying an additional rocket, the maximum mass that can be put into orbit is 31 kilograms. The mass of fuel in a rocket plane concept is greater than that of a rocket carried by a military aircraft. But this study only analyzed the flight after the separation from the carrier aircraft, so to fully assess those concept more complex study is needed. Such a study should also investigate the amount of fuel required to perform the flight of the carrier aircraft. Moreover, such aspect as cost of the operation and infrastructure should be taken into account.

In conclusions, to better evaluate the concept of military aircraft and rocket plane, an optimization process is necessary, especially in terms of the trajectory design. This study should be performed using a more advanced mathematical model which is a goal of the future work.

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