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

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Abstract

This paper considers of two possible concepts of the airborne launch system. The first project consists in utilizing a retired supersonic aircraft like MIG-29 or Su-22 to adjust them to carry a rocket with small satellite payloads to Low Earth Orbit. The second project assumes adaptation of the rocket plane originally developed for suborbital space tourist flights. The rocket plane is going to be converted into unmanned vehicle which carries inside a small rocket that delivers a payload into an orbit. This paper outlines sensitivity analysis for different mission profiles as well as payloads and propellant mass. Using a simple mathematical model allowed for robust analysis of many scenarios. Simulations were performed with use of the Simulink and SDSA package.

Keywords: airborne launch system, flight simulations, unconventional configurations

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, low Earth orbits (LEO) can be reached using airborne launch systems. But such flights are associated with a payload weight limits and the use a traditional space rocket allows for the delivery of heavier payload. Nevertheless this type of solution can be an opportunity for a low-cost space launch for example in case of research carried out by universities. Moreover it is a chance to access the space in case of countries or stakeholders without the space launch complex in their disposal. The aim of the paper is to conduct study into two different concepts and perform sensitivity study of payload mass, propellant mass, engine characteristics on the mission profile. It is a continuation of the research presented in [1].

2. State of the art

In 2006, Boeing presented [2] a concept of launching a space payload rocket by utilizing a Boeing F-15E combat aircraft as an alternative *Responsive Air Launch* to the conventional method (Figure 1). The modified rocket based on the Pegasus rocket with a total mass of approx. 15,000 kg could carry a payload of up to 300 kg (about 2% of the total mass of the rocket). That was a turning point in the development of the technology because analogous concept designs appeared in the following years in which decommissioned supersonic aircraft [3]-[6] were proposed as rocket carriers. For instance, in the Netherlands a similar study was conducted to analyse the process of launching microsatellites from the F-16 aircraft [7]. The analyses indicated that the fighter aircraft could launch a space rocket of a total mass of 930 kg, with a useful cargo capacity of approx. 10 kg, into LEO up to an altitude of 500 km. In our context, the Su-22 and MiG-29 (with comparable performance capabilities) will soon be withdraw from the Polish Air Force. As Polish national industry and research institutions have experience in the modernisation of both the aircraft, there would occur an occasion to start a development project to adopt those aircraft withdrawn from military duty to missions of launching carrier rockets.

Figure 1 - Evolution in the configuration of Boeing's air-launch-to-orbit systems, on the left: F-15 Global Strike Eagle with a rocket on top of its fuselage, on the right: F-15E ALASA with a rocket underneath the fuselage.

3. Configuration of the airborne launch system

In this paper two different concepts of the airborne launch system were considered, but both involve utilization of an aircraft that lift the next stage of the system up to 15 kilometers above sea level. Detailed description of each concept can be found in section 3.1 and 3.2.

3.1 Concept with the fighter aircraft

For the purposes of the project, several configurations of the aircraft-rocket system were analyzed, i.e., with the rocket placed above or below the fuselage, and under the wing (Figure 2).

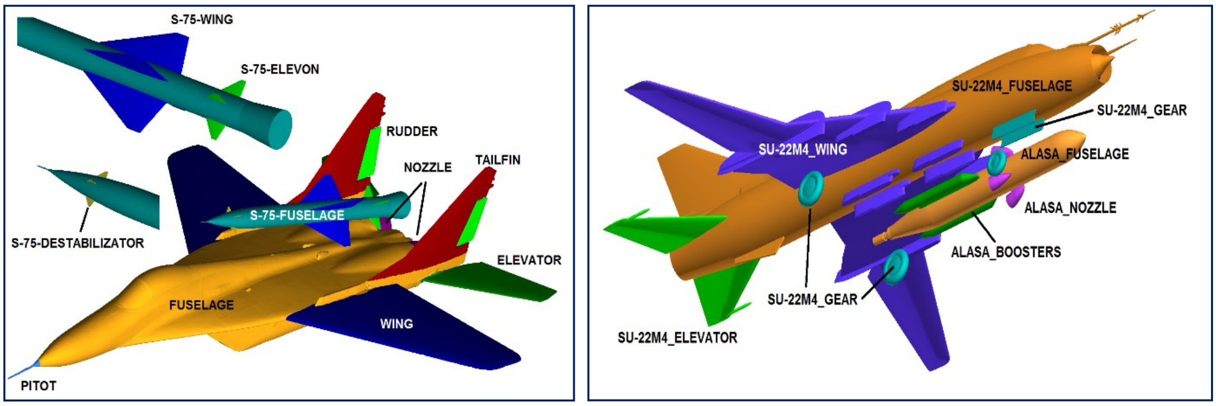
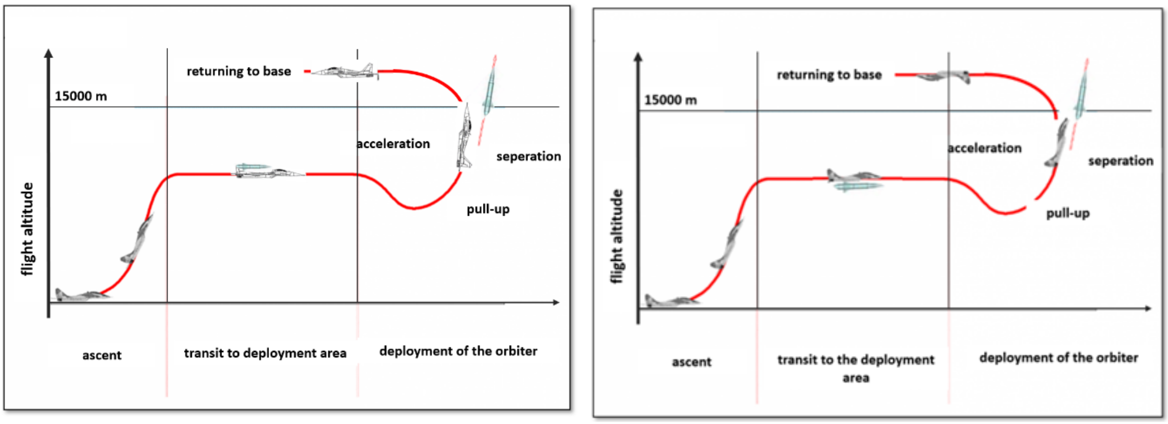


Figure 2 - Model variants of combat aircraft with carrier rockets attached to an airframe

The key parameters determining the effectiveness of an air-launch-to-orbit system are the speed of the carrier aircraft during deployment of the carrier rocket, which is its (approximate) initial velocity, the carrier aircraft altitude, and the flight path angle - trajectory angle of the aircraft during deployment, which is the launch angle of the carrier rocket. Two flight profiles were proposed for the mission task (Figure 3) where, to increase the altitude and flight velocity, the so-called dynamic ceiling must be achieved. It takes place after steady accelerating to the maximum possible velocity achieved in the height of about 9000 m and transition to the flight stage called "zoom climb" [8]-[10].



a) b)

Figure 3 - Mission profiles considered for carrier rocket launching, a) rocket mounted dorsally to the MiG-29, b) rocket mounted ventrally to the MiG-29 or Su-22.

3.2 Concept with the rocket plane

The second concept assuming adaptation of the vehicles for suborbital tourist space flights [11] and [12] into cargo version that is capable to reach an orbit. The first stage of the system is a mother plane which is designed in a tailless configuration with a high aspect ratio wing to ensure efficient climb flight performance (Figure 4). The second stage is a rocket plane that is going to be converted into cargo version. The first modification including engine change, the second modification is associated with adding an additional stage that is going to be carry inside of the rocket plane. This third stage is going to be responsible for putting the satellite into orbit. The rocket plane is going to fly on the suborbital trajectory so the return flight is not going to need adding heavy thermal shield. The third stage is going to accelerate the satellite to necessary speed. The mission profile can be found in Figure 5

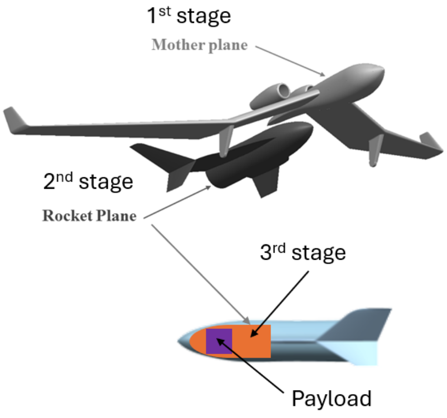


Figure 4 – concept of three stages system based on the rocket plane concept

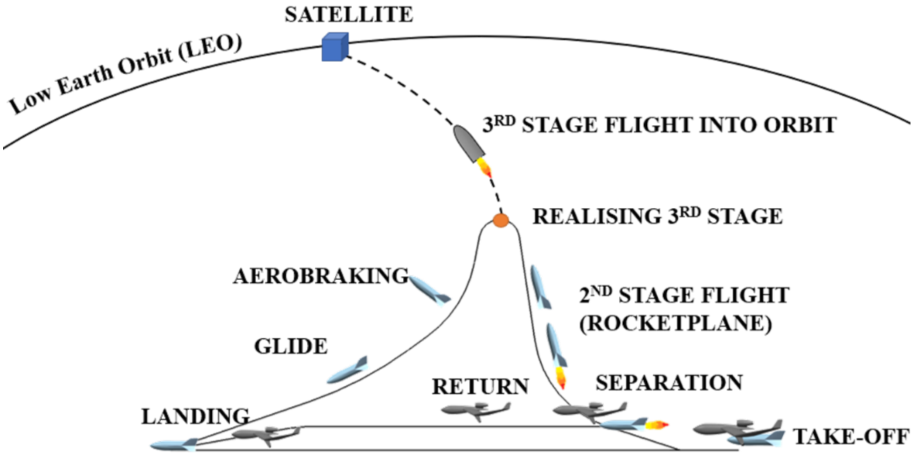


Figure 5 – Mission profile in case of rocket plane concept

4. Methodology

To address the research question, the flight simulation was built with use of the MATLAB Simulink. The simulations begins when the vehicle (either rocket plane or rocket) separate from its carrier. The manoeuvre of the separation is not modelled, as an initial simulation condition the separation speed and altitude are assumed. The simulation is composed of the following subsystems: aerodynamics, engine, mass, and gravity. Implementation of this system is explained below in this section.

In case of the descent flight, the simulation were performed by the SDSA software [12] and [14]. The detailed mathematical model is descried in [15] and [16].

4.1 Equations of motion ascent flight

The mathematical model of ascent flight was derived under the following assumptions:

- The vehicle is model as a point mass with 2 DoF.
- The drag coefficient depends on Mach number
- The gravity depends on the altitude
- The engine thrust characteristics is described by the trapezoidal shape and described by two parameters A and B that are annotated in Figure 6. The mass of the propellant was assumed as input data, so the operation time vary when A and B change. It was assumed that only solid motors are considered. In general, shape of thrust characteristics could be obtained by a proper propellant arrangement in the engine casing. But it was assumed that on this stage of the analysis the simplified model of the engine is sufficient and propellant arrangement is out of the scope of this paper.

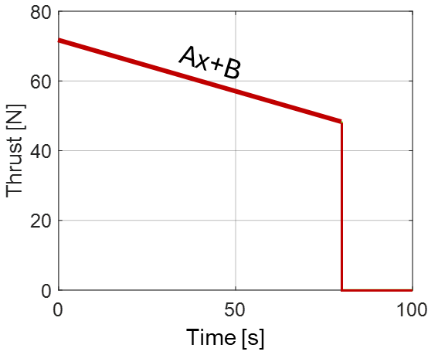


Figure 6 – Definition of the thrust curve

The simulation was built with use of switch case block that was implemented in the mass, engine and aerodynamic subsystem this allowed to define individual characteristics for each stage.

4.2 Rocket mass model

The designed rocket was developed on the basis of experience with known designs of rocket sets used in the armed forces of the Republic of Poland. As a result of the analysis, the project assumed a design with 3 stages, the first of which is the largest with the longest duration of operation. This results from the mission profile of space rockets. The first stage, works in the densest layers of the atmosphere, which translates into the presence of the greatest drag and the greatest impact of the gravitational field. Therefore, the initial stages of the rocket must generate a high flow. The thrust of the first stage is about three times the weight of the rocket. In a vacuum, however, a smaller value of thrust is sufficient to further accelerate the rocket. Analysis of the rocket's geometry and mass was carried out based on a simplified construction (Figure 7). It was assumed that the rocket consists of three stages, placed one on top of the other [17].

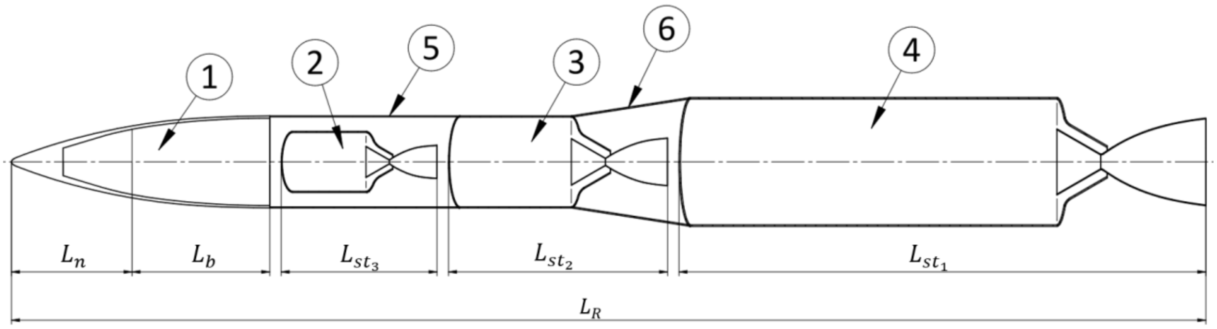


Figure 7 - Three stage rocket: 1 – nose; 2, 3, 4 – rocket stages; 5, 6 – interstage construction

Taking into account the change in the mass of the rocket during flight, the calculations of the main moments were performed at the time of launch and after the engine fuel of the given stage of the rocket was burned out. It was also assumed that the nose portion of the rocket is ejected at the same time as the second stage. At high altitudes, the thin air does not threaten to destroy the transferred payload, hence further securing it through the nose portion of the rocket is not necessary, and the weight reduction results in increased performance.

5. Aerodynamic Model

5.1 Rocket

A series of numerical aerodynamic analyses using Computational Fluid Dynamics (CFD) methods were carried out to determine the aerodynamic loads and to analyse the rocket influence on the change of the aircraft aerodynamic characteristics. The calculations of entire system were performed using ANSYS Fluent software based on the solution of partial differential equations by the Finite Volume Methods (FVM) [18]-[20]. The software used allows the analysis of incompressible and compressible flows, with optional consideration of flow viscosity [21]- [23]. For rocket itself ProdasV3 software were used. The software is an environment used to calculate axially symmetrical aerodynamic characteristics of flying objects. The results of the obtained aerodynamic characteristics of the space rocket are presented in the following graphs (Figure 8 and Figure 9).

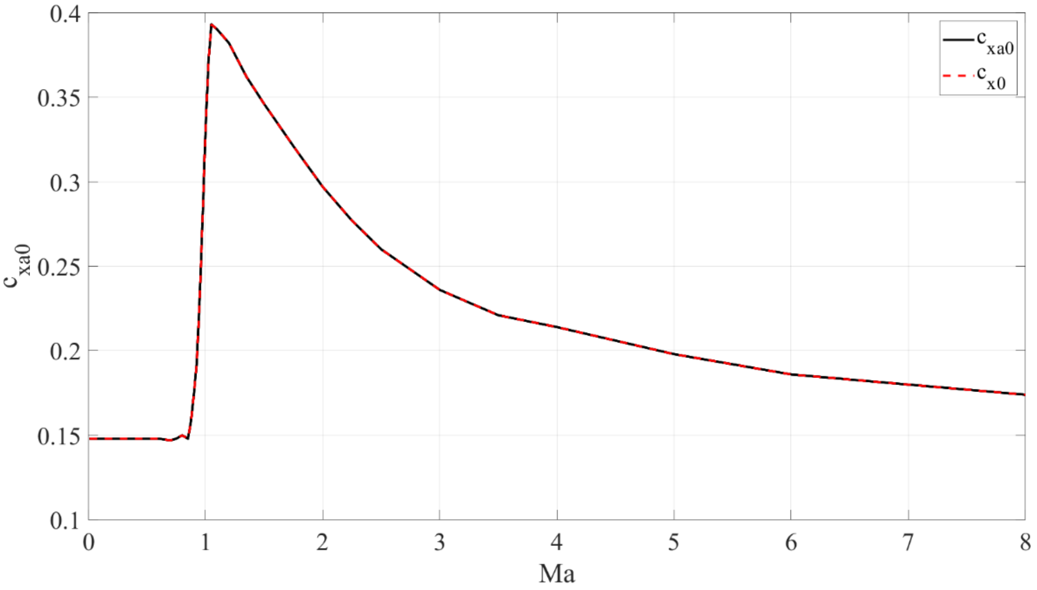


Figure 8 - Drag Coefficient c_{xa0} and coaxcial c_{x0} for 0 angle of attack

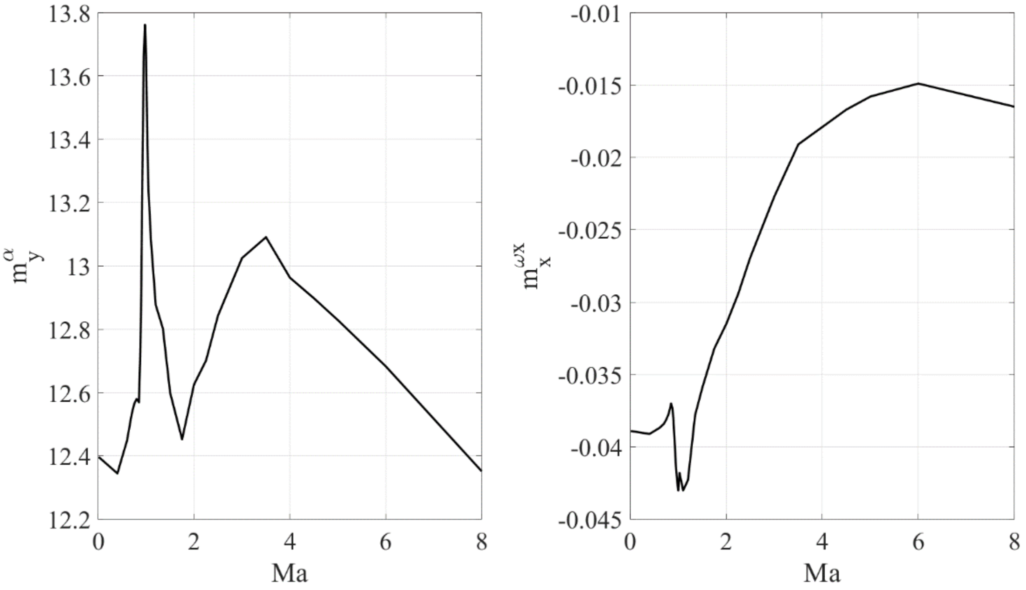


Figure 9 - Pitching moment m_y^α and bank moment $m_x^{\omega x}$

5.2 Rocket plane

Aerodynamic characteristics of the rocket plane were computed by MGAERO software. This is a commercial tool dedicated to aircraft CFD computations. Due to Euler's equations it well predict the flow for high Mach numbers with reasonable cost of computations. The software based on the Multigrid scheme, which require mesh on the object as well as blocks around that are composed in multilevel arrangement. The rocket plane model is composed of 20 158 on-body panels and 7 level of multigrid blocks which results in 3 768 788 off-body panels. Figure 10 shows the rocket plane drag characteristics. In case of the Simulink ascent flight, the drag coefficient change only with Mach number and it was assumed that drag coefficient correspond to value of angle of attack equal to zero. In case of descent flight, simulated in the SDSA, the drag coefficient vary with both Mach number and angle of attack.

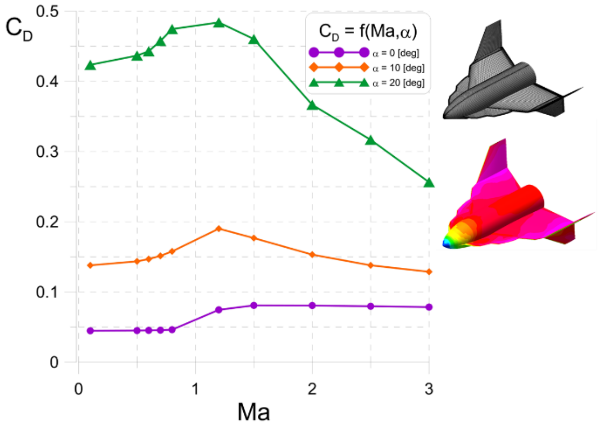


Figure 10 – Rocket plane drag coefficient versus Mach number for selected angle of attack

6. Simulations results

6.1 Concept with fighter aircraft

Results of the rocket simulation in case of the separation from the fighter aircraft are presented in Figure 11.

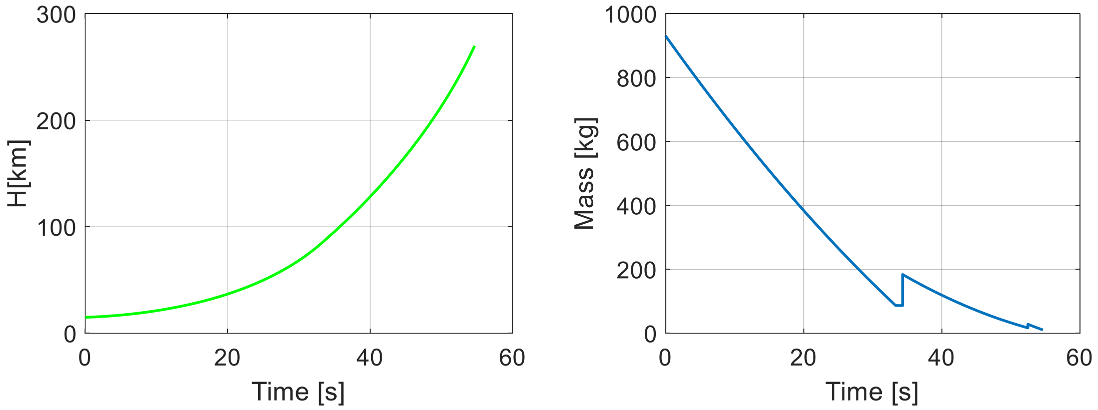


Figure 11 – Altitude and mass change with time for case of the

6.2 Concept with rocket plane

For the presented set of results, the masses of the payload and propellant are the same but the engine characteristics of the rocket differ, the slope (parameter A) varies. The flight parameters before the rocket separation are the same (Figure 12 left), but the impact of the second stage engine thrust on final parameters of the flight can be observed (Figure 12 right). The comparison of speed and altitude change during the flight for two different engine parameters are presented in Figure 13. The masses of the propellant are the same but the engine operation times vary this can be observed in Figure 14. The second set of results comparing the case when the slope (parameter A) is the same, comparison of the flight parameters is presented in Figure 15. In case of variation of the payload but the same amount of the propellant the following flight parameters were obtained, see Figure 16.

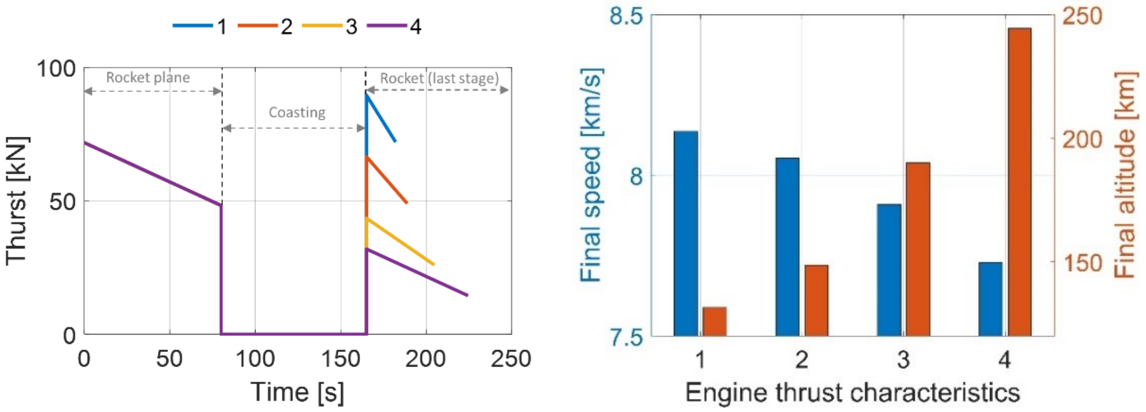


Figure 12 - Results of engine characteristics impact on flight parameters in case of payload mass of 30kg carry by the rocket released by the rocket plane. Plot on the left shows different engines characteristics while the plot on the right shows corresponding final flight parameters.

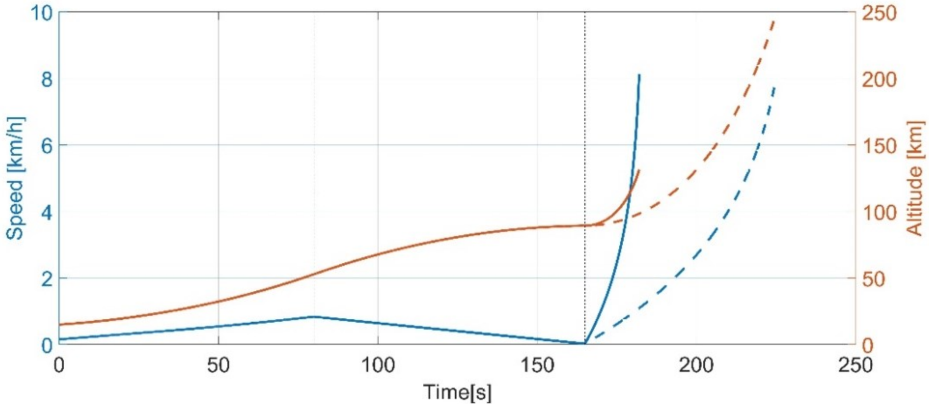


Figure 13 - The comparison of the speed and altitude versus time in case of different engine characteristics implemented in the rocket. The solid line represents case 1 where dash line represents case 4.

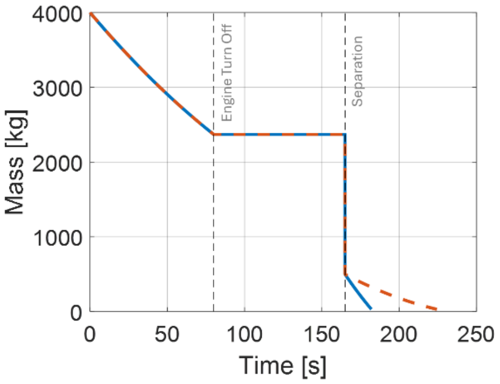


Figure 14 - The comparison of the mass change in case of different engine characteristics implemented in the rocket (third stage). The solid line represents case 1 where dash line represents case 4.

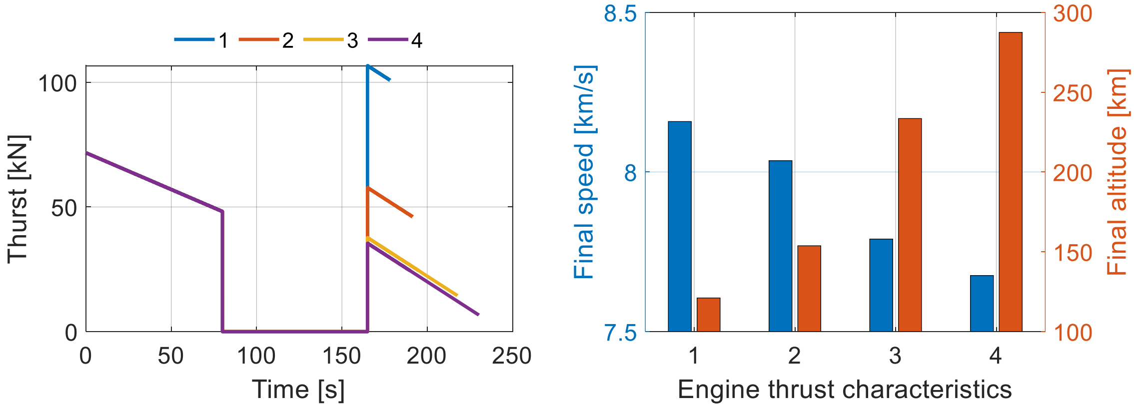


Figure 15 - Results of engine characteristics (the same slope) impact on flight parameters in case of payload mass of 30kg carry by the rocket released by the rocket plane. Plot on the left shows different engines characteristics while the plot on the right shows corresponding final flight parameters.

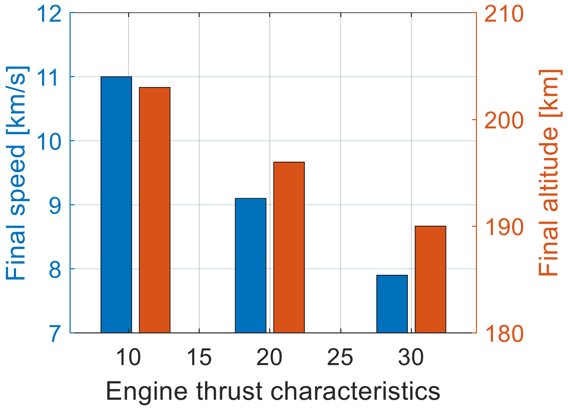


Figure 16 – payload impact on flight data

7. Conclusions

In the paper two concepts of airborne launch system were considered. This paper outlines sensitivity analysis for different mission profiles as well as payloads mass. Using a simple mathematical model allowed for robust analysis of many scenarios.

The system proposed may be deemed as the so-called Responsive Space Assets for the Armed Forces. Implementation of such a system not only offers independence from countries or commercial companies providing space services, but also allows to develop and master new capabilities in the context of deploying satellite systems for safety and defence purposes.

In this paper only part of the system was simulated, to fully assess the concept efficiency the carrier aircraft must be included in the analysis.

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