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Research paper

Analysis of Suitability of Fixed-wing Aircraft for Launching Satellites into Low Earth Orbit

Zbigniew KORUBA[*1] (ksmzko@tu.kielce.pl)
Nikolay KULESHOV[2] (kuleshov0552@gmail.com)
Sergey KRAVCHENKO[2] (sergiey@cvsys.eu)
Vladimirs SHESTAKOV[2] (sestakovs@rtu.lv)

[*]Corresponding author
ORCID: https://orcid.org/0000-0003-0715-593X

Kielce University of Technology,
7 Tysiąclecia Państwa Polskiego Av., 25-314 Kielce, Poland
Cryogenic and Vacuum Systems,
7/9 Andreja Str., Ventspils, LV-3601, Latvia

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Abstract. The use of near-Earth space for scientific and commercial purposes has skyrocketed in recent years. However, progress continues to be hampered by the cost and availability of vehicles relied upon for delivering payloads to the Earth's orbit. The Riga Technical University (Latvia), with the assistance of the Technological University in Kielce (Poland), is developing a concept of a novel payload launch system. The implications of such a system for launching payloads into low Earth orbit (LEO) are presented in the article. The system, intended for launching small spacecraft, comprises the A319 MPA transport airplane used as a platform aircraft and a three-stage payload carrier, codenamed LatLaunch. The first and second stages of the three-stage launch vehicle are unmanned winged aircraft. The third stage is a classic rocket which, once dropped from the launch platform, takes the payload to a specific height, at a given rate of speed and at a predetermined trajectory angle. The article presents the results of a study focusing on designing this system.
Keywords: aircraft platform, satellite launch system, launch stage, launch system, waverider

1. INTRODUCTION

Small spacecraft (SSC) as well as pico- and nanosatellites (PNS) are currently commonly used to solve scientific and applied problems in low Earth orbit (LEO) [1, 3, 4, 5]. The methods and means of their delivery to LEO play a crucial role in their application. Practice shows that the cost of the launch system is estimated to account for one third or more of the cost of the entire project. Thus, the average cost of launching a satellite weighing up to 100 kg can reach 70,000 euros/kg or more [2, 6, 7]. Therefore, the developers of such projects in many cases create their own versions of specific launch systems. The project pursued by the Riga Technical University (RTU, Latvia), called LatLaunch [8], is one of them. The overall goal of the LatLaunch project is to develop an innovative concept of an aerospace system relied upon for launching and deploying PNS into LEO.

A comparative analysis of various systems used for launching PNS into LEO, carried out by the authors within the framework of the Latlaunch project, has shown that in the dense layers of the atmosphere, fixed-wing carriers have a significant advantage over traditional carrier rockets [9]. Similar conclusions have been drawn previously by other groups of researchers conducting other projects, and some of them have been put into practice, with a particular emphasis placed on the successful Pegasus project [10]. However, these projects suffered from a number of disadvantages, such as significant environmental pollution, for instance, as all carrier stages were, as a rule, disposable (see the Pegasus project, for example). Under the LatLaunch project, the concept of launching PNS into LEO using a subsonic platform aircraft as well as supersonic and hypersonic reusable unmanned winged carriers operating in less dense layers of the atmosphere has been proposed.

The concept was formalized in the form of two patent applications [11, 12] and the potential of using such reusable winged carriers in missions aiming to insert PNS into LEO was evaluated.

The results of the study were published in several articles, with an emphasis on different aspects of the study, i.e. determining the type of aircraft capable of acting as the air platform [13], determining the weight and size parameters of the primitive of the first unmanned winged carrier stage and assessing its flight characteristics using an aerodynamic prototype, determining the weight and size parameters of the primitive of the unmanned second winged carrier stage and evaluating its flight characteristics using estimated aerodynamic characteristics of such an aircraft [14]. As part of the LatLaunch project, the use of all elements of the PNS system in different sections of the trajectory was also evaluated and the effectiveness of the proposed system for launching PNS into LEO was shown.

The proposed article discusses some aspects of the concept developed by the authors of the LatLaunch project. It also presents the results of 3D models and calculations confirming the possibility of launching a satellite or a set of satellites weighing from 65 to 175 kg into LEO (an intermediate circular orbit with a height of 300 km), with the mass of payload depending on the configuration of the third stage.

It should be emphasized that the article presents the results of the first stage of the LatLaunch project, exploring the fundamental ability to launch pico- and nano satellites into low Earth orbit using the proposed carrier scheme (with its innovative nature confirmed by patents [11, 12]). Some technical solutions related to the separation of the satellite carrier's stages are innovative and it is the intention of the authors to protect them with patents. Therefore, for the time being, they cannot be disclosed in publicly available articles.

More detailed results can be found in the referenced articles published earlier.

2. SUBSTANTIATION OF THE METHOD SELECTED FOR LAUNCHING SSC AND PNS INTO LEO

Currently, numerous new methods for launching PNS into LEO are being developed, competing with the means of delivering these into space using traditional launch vehicles. Over the past 50 years, various countries used or attempted to use different missile designs for this specific purpose, including all types of combat missiles withdrawn from combat duty [15, 3], as well as other launch vehicles relying on various launch platforms. Three factors determine the choice of a specific PNS launch system: launch cost, reliability, and technical capabilities of the system. To determine the most efficient launch method, functional dependencies between the individual parameters are analyzed to determine the speed of the carrier's orbital maneuver achieved during the launch of the PNS into orbit while relying on various launch methods, denoted as ΔV.

This velocity may be used to determine, in a generalized manner, the cost of fuel, energy, and the mass of the entire PNS launch system. To estimate those parameters, specific increments in carrier velocity are relied upon.

A carrier inserting PNS into LEO must reach a specific orbital maneuver velocity ΔV which significantly exceeds the calculated target (orbital) velocity of PNS, V_{PNS} [16]:

$$\Delta V > V_{PNS} \tag{1}$$

The specific orbital maneuver velocity ΔV is the sum of the orbital velocity V_{sat} of PNS and the virtual velocity increments that are necessary to compensate for various losses during the launch. In general terms, this condition can be written as [16]:

$$\Delta V = V_{sat} + \sum_{k=1}^{5} \Delta V_k \tag{2}$$

where: ΔV is the specific orbital maneuver velocity of the carrier (the required speed of the launcher); V_{PNS} is the estimated speed of PNS.

This velocity remains the same for all launch methods, is determined based on the target orbit and payload (PNS) and its value is between the first space velocity of 7.8 km/s and the second space velocity of 11.2 km/s. ΔV_k is the virtual speed increment required to compensate for various losses encountered while launching the satellites. ΔV_1 is the increase in speed needed to keep the carrier in the gravitational field. ΔV_2 is the compensation for the loss of speed due to aerodynamic drag. ΔV_3 is the loss of speed due to a change in the direction of the initial speed vector towards the required direction. ΔV_4 is the compensation for speed lost due to a decrease in engine thrust, coinciding with increasing atmospheric altitude. ΔV_5 is the projection of the Earth's rotation velocity vector.

The analysis performed shows that the most acceptable system for launching loads into LEO, assessed within the framework of the LatLaunch project, is an aircraft-based platform:

- it allows to take off from an area that maximizes the use of the Earth's rotation speed,
- the initial speed of the launch system will be equal to the speed of the platform aircraft, i.e., approx. 230 - 250 m/s. The initial launch altitude is approx. 12,000 m. The total cost of resources (fuel, etc.) used during the launch will be reduced by 20–35%, and the characteristic maneuver speed of the first stage of the launch vehicle will be reduced by 15–25%,
- The main problems in such a launch system are related to the technical implementation of the connections between the launch aircraft platform and PNS carrier, ensuring aerodynamic stability of the aircraft platform and PNS carrier, their orientation in space, and safe separation of the entire set-up.

3. SELECTION OF LAUNCH PLATFORM AND DETERMINATION OF PERMISSIBLE OVERALL DIMENSIONS OF LatLaunch SYSTEM

Based on the research carried out, it was decided that the LatLaunch concept system would comprise an aircraft platform and a three- or four-stage carrier [14]. A military transport plane of the A319MPA type with an external payload suspension point was selected as the aircraft platform, in accordance with the project's objectives [14]. The A319MPA aircraft has significant advantages over all other transport planes manufactured in the EU (as well as in other countries), as it is equipped with an external suspension point of sufficient capacity under its fuselage, and its cabin is designed to accommodate the flight control and command center for the dropped cargo. The suitability of this particular aircraft type was confirmed by the results of 3D modeling performed in the SolidWorks environment to determine the size of the space available for lifting LatLaunch, taking into account aircraft configuration changes associated with the use of its various systems during the flight, as well as considering the various operating modes of the aircraft platform itself. A schematic view of the platform aircraft and the carrier system, as well as the appearance of the first stage of the carrier, are shown in Figure 1.

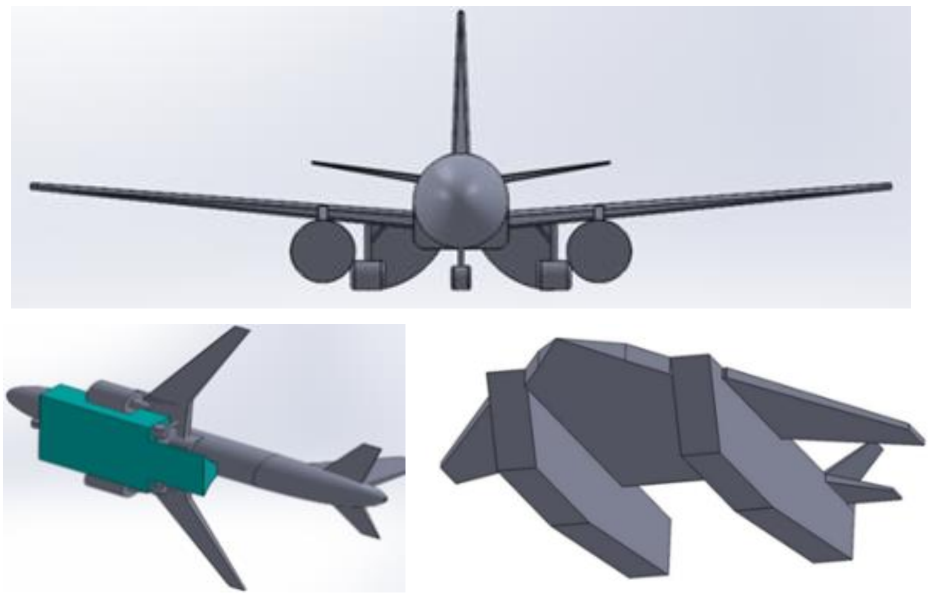

Fig. 1. Diagrams of the primitives studied: A319MPA aircraft platform with space for retracting its landing gear and placing the carrier under the fuselage, and the first stage of the LatLaunch carrier

The first stage of LatLaunch carrier is a twin-boom, high-wing aircraft suspended in the space available under the fuselage and wings of the aircraft platform. The presence, in this space, of the plane's engines, retractable landing gear and other moving aerodynamic surfaces (slats and flaps) of the aircraft carrier's wing has been accounted for as well. The twin-boom winged aircraft is accommodated under the fuselage of the aircraft platform and its underwing space in such a way that the second and subsequent stages of the satellite carrier fit in the space between the beams of the first stage of the LatLaunch structure, i.e. the twin-boom winged aircraft.

The use of primitives is justified by the fact that at this stage of the LatLaunch development process, it is mainly necessary to determine the interactions between various elements of the launch system. A more detailed study of specific components of the launch system will only be essential at subsequent stages of the process, while preparing for modeling various aerodynamic and design features. It is necessary to take into account the fact that a detailed study of the external appearance of the aircraft is a rather laborious process and is carried out while modeling aerodynamic parameters (for instance in the ANSYS program) or while detailing the design of an aircraft.

4. ELECTION OF AERODYNAMIC PROTOTYPE OF LatLaunch FIRST STAGE

After analyzing the practical experience related to various PNS launch methods gathered by the leading space exploring countries (USA, USSR-Russia), the decision was made that a fixed-wing aircraft used as the first stage of the LatLaunch system would be the most effective solution for the project in question. Winged aircraft enjoy serious advantages over classical rocket launchers in dense layers of the atmosphere, as they use the aerodynamic forces created by the wing, rely on atmospheric oxygen as an oxidizer in their engines, and use the mass of airflow passing through the engine as a working fluid. Based on a practical analysis of using modern supersonic fighter jets at high altitudes, an interceptor fighter jet was chosen as an aerodynamic prototype for LatLaunch due to the peculiar technical characteristics of this type of aircraft (ceiling record, airspeed record, and the availability of information the aerodynamic characteristics of some aircraft). The jet's specific aerodynamic and weight-related characteristics observed in all speed ranges, as well as some design features allowing it to fly at high speeds and altitudes [17] were used for calculations and for 3D modeling processes performed with the use of SolidWorks and SciLab software. Using the graph showing the derivative of the lift coefficient and its relation to the angle of attack, depending on the prototype's airspeed expressed in Mach number M (Figure 2), the duration of its flight has been divided into three stages:

- Subsonic mode, $M < 0.5$,
- Transonic mode $0.5 \leq M < 1.5$,
- Supersonic mode, $M \geq 1.5$.

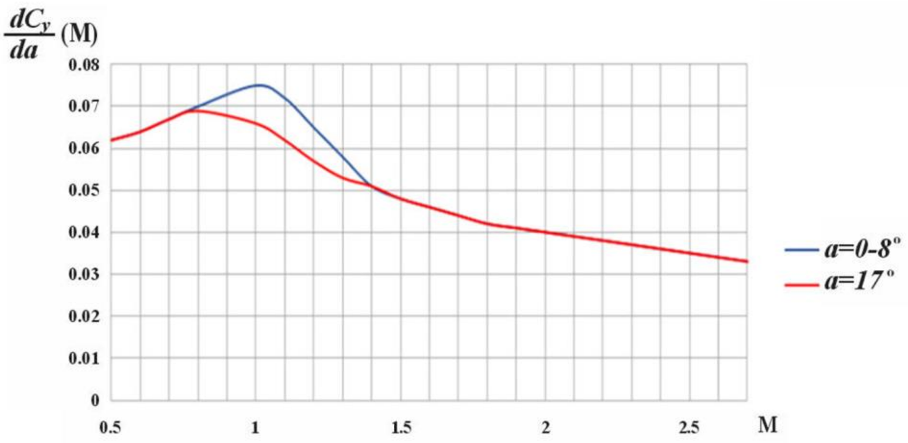

Fig. 2. Changes in the derivative of the lift coefficient *Cy* with respect to the angle of attack α depending on the prototype's airspeed expressed in Mach number *M* [17]

The next step was to model the drag polar for all three flight modes (Figure 3). The following relationship was adopted as a mathematical model of the drag polar, describing the dependence of the drag coefficient *Cx* of the aircraft *Cx*(*M*, *Cy*) on the lift coefficient *Cy* and the airspeed, which was expressed using Mach number *M*:

$$\mathrm{Cx}_\mathrm{r}(\mathrm{M},\mathrm{Cy}_\mathrm{r}) = a_\mathrm{r}(\mathrm{M}) \cdot \mathrm{Cy}_\mathrm{r}^{\mathrm{b}_\mathrm{r}(\mathrm{M})} + \mathrm{c}_\mathrm{r}(\mathrm{M}) \qquad (3)$$

where: α_r, b_r and c_r are the coefficients characterizing the aircraft's flight mode; *M* – airspeed, expressed in Mach number; *r* – mode parameter (sub – subsonic, t – transonic, sup – supersonic).

Additionally, coefficients α_r, b_r and c_r are power polynomials of the aircraft's airspeed expressed in Mach number *M*, the degree of which depends on the flight mode *r*:

$$a_r(M) = \sum_{i=0}^{nar} ka_i \cdot M^i \,,\; b_r(M) = \sum_{i=0}^{nbr} kb_i \cdot M^i \,,\; c_r(M) = \sum_{i=0}^{ncr} kc_i \cdot M^i \qquad (4)$$

where: $k\alpha_i$ are the coefficients of the polynomial of parameter $\alpha_r(M)$, i=0, $n\alpha_r$; kb_i are the coefficients of the polynomial of parameter $b_r(M)$, i=0, nb_r; kc_i are the coefficients of the polynomial of parameter $c_r(M)$, i=0, nc_r; $n\alpha_r$, nb_r, and $n\mathbf{c}_r$ are the degrees of the polynomials of parameters $\alpha_r(M)$, $b_r(M)$, and $c_r(M)$, respectively, depending on the *r* mode.

After processing the prototype vehicle's aerodynamic data using regression analysis software (Scilad), parameters of the mathematical model were obtained.

Lift coefficients were denoted by *Cy*0i, ..., *Cy*3i at different flight speeds (from subsonic speeds lower than 1 M, with an index of 0, to the speed of 3.0 M, with an index of 3), with their arrays denoted by *MCy*0, …, *MCy*3, and with the i^{th} element of the array denoted by *MCy*3i. *MCx*0i, ..., *MCx*3i were used to denote the drag coefficient of the ith element of the array. f*Cx*0(*Cy*) denotes the values of the *Cx*(*M*, *Cy*) function at *M* <0.50, f*Cx*1(*Cy*) denotes the values of the *Cx* (1, *Cy*) function, while f*Cx*2(*Cy*) and f*Cx*3(*Cy*) are the graph functions modeling the values of *Cx*(2, *Cy*) and *Cx*(3, *Cy*), respectively. The graphs of these dependencies are shown in Figure 3.

The correlation coefficients of the aerodynamic prototype's drag polar data and the data obtained through mathematical modeling, determined for each of the aerodynamic prototype's drag polars [17], range from 0.956 to 0.999, which evidences a good agreement between the simulation data and the aerodynamic prototype's data.

The mathematical drag polar model (3) allows to obtain a drag polar for any Mach number in the range from 0 M to 6 M.

The actions performed while dropping the LatLaunch satellite carrier from the A310MPA platform, before the satellite carrier transitions to horizontal flight, are divided into several stages:

- Separation of LatLaunch and its transition to the stationary gliding mode,
- Stable gliding of LatLaunch prior to starting its own engines,
- Transition of LatLaunch to level flight.

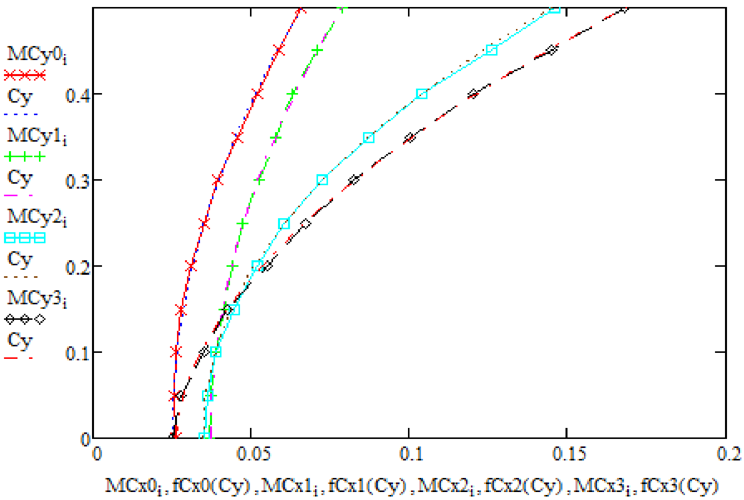

Fig. 3. LatLaunch drag polars depending on flight modes, expressed in Mach numbers *M* (red line - *M* <0.50; green - *M* = 1; blue - *M* = 2, and burgundy - *M* = 3)

The second stage is decisive. It is proposed to perform the flight in the maximum aerodynamic efficiency mode (with the maximum lift/drag coefficient ratio. This ensures that altitude losses will be minimized. Gliding occurs at a minimum trajectory inclination angle, with a constant indicated airspeed maintained. Gliding takes place at the most favorable velocity which depends on the altitude. It equals 239.4 m/s at an altitude of 11,000 meters (the calculated LatLaunch drop altitude) and 224.4 m/s at an altitude of 9,950 meters which will be reached by LatLaunch 35 seconds after being released from the platform aircraft. This time is necessary for starting LatLaunch's own engines and entering the phase of its powered flight. At the same time, LatLaunch loses 1,000 meters of altitude and 12 m/s of horizontal speed, reaching a vertical rate of descent of 30 m/s. These calculations show that the aerodynamic design of the prototype aircraft is capable of gliding at such altitudes and speeds and, accordingly, LatLaunch has sufficient time to start its engines when in the controlled glide phase.

Based on the analysis carried out, the AL-55G engine used to power the first stage of the LatLaunch system has a maximum thrust of 30,000 N, weighs 425 kg and offers a specific fuel consumption of 0.168 kg/(N·h) and use 29.5 kg/s of air. The thrust of the engine and its operating altitude can be increased by deploying a Mass Injection Pre-Compressor Cooling technology (MIPCC), with injection of water (or a mixture of water and methanol) into the engine’s inlet and the simultaneous use of hydrogen as fuel in a two-stage afterburner [18] being one of the viable options.

5. SECOND WINGED SUPERSONIC STAGE

The appearance of the 2nd stage of the LatLaunch system will be based on the waverider aerodynamic concept taking advantage of the overpressure cushion effect which is limited by oblique shock waves and creates additional lift due to the positive interference of shock waves formed by various parts of the waverider. This effect was already used in the middle of the 20th century in the USA [19, 20].

The second stage of the three-stage satellite carrier system is a twin-boom winged aircraft relying on the low-wing waverider aerodynamic concept. Its aerodynamic characteristics were estimated based on the data presented in [19], see Figure 4 and Figure 5.

A dual-mode rocket-ramjet engine is proposed to power the second stage of LatLaunch. It is a rocket engine that consists of two stages. The first stage of the rocket-ramjet engine used solid fuel and is capable of independently bringing the third stage to a specific altitude at a specific speed, using the aerodynamic characteristics LatLaunch’s second stage.

The first stage of LatLaunch releases the second stage at an altitude of 45,000 meters, at a speed of 5.85 M, and at close-to-critical angles of attack, with the trajectory inclination angle equaling 20 degrees.

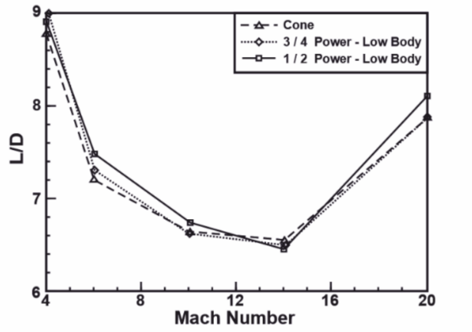

Fig. 4. Lift-to-drag ratio vs. velocity in Mach numbers *M*, for optimum waveriders [19]

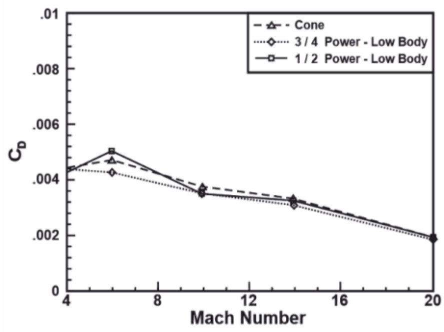

Fig. 5. Drag coefficient vs. velocity in Mach numbers *M*, for optimum waveriders [19]

This mode is not optimal and requires the use of the second stage's propulsion system to increase velocity until the optimal angle of attack is reached (i.e. until the maximum lift-to-drag ratio is reached), at which the use of engine thrust is optimized. The solid fuel booster, using the aerodynamic characteristics of the second stage of LatLaunch, accelerates the second stage of LatLaunch to a velocity of 10 M and a flight altitude of 100,000 meters (such flight parameters were achieved during tests [19]) and then separates from the third stage of LatLaunch (solid propellant rocket) and jettisons the solid propellant booster.

The third stage is a normal aerodynamic rocket stage. It is located in a compartment between the engine nacelles of the second stage (the second stage vehicle is a twin-boom design, with the boom doubling up as an engine nacelle). Such a solution allows to maintain a compact design of the multi-stage system used for launching and inserting payloads into LEO.

6. CONCLUSIONS

As a result of calculations and three-dimensional modeling, the layout of the LatLaunch system was created [11-14], making it possible to integrate it into the platform aircraft – see Figure 6 and Figure 7 (the third rocket stage is moved backwards from the internal compartment of the second stage, so that is can be seen).

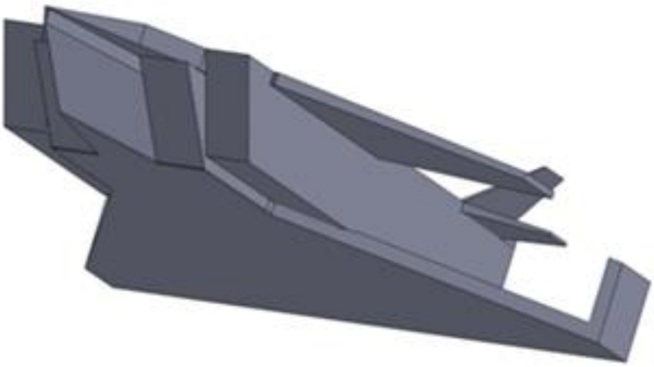

Fig. 6. Appearance of the primitives of the LatLaunch's 1st, 2nd, and 3rd stages used for launching PNS – shown as an assembly

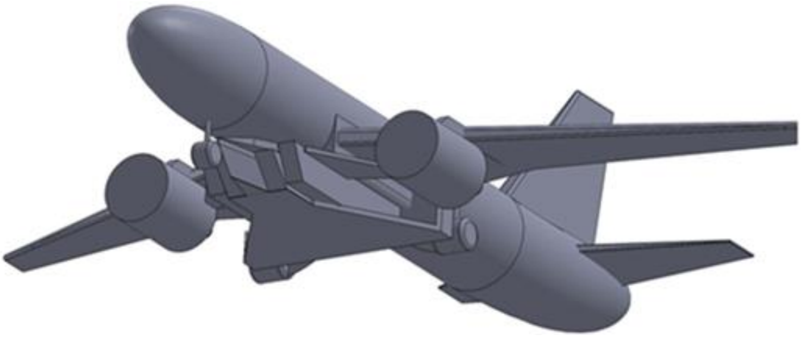

Fig. 7. 1st, 2nd, and 3rd stage of the LatLaunch satellite launching system under the A319MPA platform aircraft

The discussion of the results:

1. On the basis of the research conducted, a concept of a PNS launch system was created within the framework of the LatLaunch project, comprising an aircraft platform and a three-stage carrier. The A319MPA military transport aircraft was chosen as the aircraft platform. The first and second stages of the three-stage satellite carrier system are winged aircraft equipped with airbreathing engines with afterburners, as such a solution allows to benefit from the aerodynamic advantages of winged aircraft and peculiar characteristics of the dense layers of the atmosphere. The third stage of the LatLaunch system is a normal aerodynamic rocket stage. It is located in the opening between the engine nacelles of the second stage, which makes it possible to assemble all three stages of the LatLaunch carrier as a compact package. Thus, a multi-stage system used for launching and inserting payloads into LEO is created.

2. The concept developed based on 3D modeling and detailed calculations confirms the feasibility of launching, into LEO (an intermediate circular orbit with an altitude of 300 km), a PNS weighing from 65 to 175 kilograms, depending on the configuration of the third stage. At the same time, the first and, partially, the second stage of the LatLaunch system are fully recoverable and reusable. They are aviation-grade products that do not require so much inter-flight maintenance.
3. The LatLaunch concept will significantly reduce the cost of launching payloads, simultaneously increasing accessibility of PNS LEO launches and reducing environmental pollution.

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Analiza przydatności pojazdów powietrznych, wyposażonych w skrzydła, do wystrzeliwania satelitów na niską orbitę okołoziemską

Zbigniew KORUBA[1], Nikolay KULESHOV[2], Sergey KRAVCHENKO[2]
Vladimirs SHESTAKOV[2]

Politechnika Świetokrzyska,
Al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce
Cryogenic and Vacuum Systems,
ul. Andreja 7/9, Ventspils, LV-3601, Łotwa

Streszczenie. Przedstawiono wyniki prac nad koncepcją systemu wynoszenia małych statków kosmicznych na niskie orbity okołoziemskie (LEO). Ten system startowy małych statków kosmicznych obejmuje samolot transportowy A319MPA jako samolot platformowy oraz trzystopniowy mały nośnik pojazdów latających o nazwie LatLaunch. Pierwszy i drugi stopień trzystopniowego nośnika małego statku kosmicznego to uskrzydlone statki powietrzne. Trzeci stopień to klasyczna rakieta, która po zrzuceniu przenosi ładunek na określoną wysokość z zadaną prędkością i kątem trajektorii. W artykule przedstawiono wyniki badań nad tworzeniem tego systemu. Zastosowano metody aerodynamiki naddźwiękowej i trójwymiarowego modelowania. W wyniku obliczeń i trójwymiarowego modelowania powstał schemat LatLaunch, który umożliwia zintegrowanie go z platformą powietrzną – trzeci stopień rakiety jest warunkowo przesunięty z wewnętrznego przedziału drugiego stopnia.

Słowa kluczowe: platforma samolotu; system startowy satelity; etap startu; system startowy.