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TECHNICAL AND ECONOMIC SUBSTANTIATION OF THE AIR LAUNCH AEROSPACE SYSTEM PARAMETERS

The substantiation of the technical and economic parameters of the air launch aerospace system, which consists of a reusable unmanned aerial vehicle and integrated launch vehicle, is given. A combination of a turbofan engine and a ramjet engine is used as the unmanned aerial vehicle propulsion system. The considered vehicle is capable of delivering a payload into low-Earth orbits without the use of a spaceport. We have developed the methodology of the technical and economic substantiation of the parameters of the air launch aerospace system. The results were obtained by searching for the minimum of the objective function, which established the relationship between the technical and economic parameters of the aerospace system. For the objective function solution, the design parameters of the integrated launch vehicle and unmanned aerial vehicle were determined, as well as the limitation of the total acceleration velocity of the aerospace system. The methods used allowed us to determine the velocity constraints provided by the operation of the turbofan engine, ramjet engine, and the three solid propellant motors of integrated launch vehicle stages, as well as maximum dynamic pressure and maximum permissible temperature on the unmanned aerial vehicle surface. We determined the scheme for estimating the cost of launching the spacecraft into Earth orbit by the air launch aerospace system. The result of the substantiation is the determination of the technical and economic parameters of the integrated launch vehicle, unmanned aerial vehicle, and the aerospace system as a whole. The influence of the maximum temperature on the surface of the unmanned aerial vehicle and the specific impulse of the ramjet engine on the parameters of the aerospace system was also evaluated. The substantiation is the first step towards the creation of the Ukrainian aerospace air launch system.

Keywords: *aerospace system, air launch, technical and economic parameters, unmanned aerial vehicle.*

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INTRODUCTION

Using space around the Earth is essential for human life. It is difficult to imagine a world without satellite communication, the Internet, television, positioning systems, space images, and weather forecasting. Many countries of the world use outer space. Active participation of Ukraine in this type of activity is difficult because the country does not have its own launch site and infrastructure required for launching vehicles from its own territory, which is due to the territorial features and geographical location of Ukraine since there is a question of ensuring the safety of integrated launch vehicle drop zones.

An alternative option for delivering satellites to near-Earth orbits is the use of an air-launched aerospace system (ALASS) consisting of a reusable unmanned aerial vehicle (UAV) and an expendable integrated launch vehicle (ILV). Such a system can be operated from existing airfields. For Ukraine, the implementation of such a project will allow launching of both its own satellites and commercial satellites independently of other countries.

It should be noted that the leading countries of the world are conducting studies aimed at determining the technical and economic parameters of the air-launched payload delivery system. Pursuant to Order #1581-r of the Cabinet of Ministers of Ukraine dated 16 December 2020, a list of priority investment projects has been determined for the state until 2023, which provides for investment into the air-launched system project.

METHODOLOGY

The methodology of the technical and economic substantiation of the parameters of the air launch aerospace system (ASS) consists of the following main phases:

1. Analysis of the current status of payload delivery systems and selection of the ASS basic configuration;
2. Selection of a range of ASS technical and economic parameters;
3. Selection of a criterion for ASS costs minimization;
4. Establishing dependencies between technical and economic parameters and the criterion of ASS costs minimization and determining the target function;
5. Definition of:

• ASS main design parameters of the first approximation;

• Limiting the ASS total acceleration velocity;

• Allowable dynamic pressure for the UAV;

• Maximum allowable UAV surface temperature;

• Cost of the ASS development;

• Speed and altitude at UAV and ILV separation

6. Technical and economic substantiation of the ASS parameters.

An analysis of the current status of payload delivery systems was carried out in [8], as a result of which a basic configuration of the ASS was determined, containing a high-altitude hypersonic unmanned aerial vehicle as the first stage and a three-stage integrated launch vehicle as the second stage. A combination of a turbofan engine and a ramjet engine (RJE) is used as the UAV propulsion system. Selecting the range of parameters and the minimization criterion and establishing the relationship between them was carried out in [9], where the target function (1) was formed, reflecting the main design parameters that affect the efficiency of the ASS.

$$E = \left\{ B_p + n\left[B_{sp}^{A} \frac{(M_{ASS} - M_{ILV})m_k}{n} + \right.\right.$$
$$\left.\left. + B_{sp}^{O} M_{ILV} + M_{ASS}\mu_P + B_{pp} \right]\right\} / (\mu_{pay} M_{ASS} n)\,, \quad (1)$$

where B_p are the costs for the development and development tests of the ASS components, i. e., one-time costs, B_{sp}^{A} is the averaged specific depreciation expenses of the design of reusable ASS components, M_{ASS} is the ASS launch mass, M_{ILV} is the ILV mass, m_k is the UAV structure relative mass, n is the number of ASS launches, B_{sp}^{O} is the average unit cost of fabrication of the structure of expendable ASS components, μ_P is the relative propellant mass, B_{pp} is the cost of routine maintenance and services of the aerodrome, μ_{pay} is the relative payload mass.

For a feasibility study of the ASS parameters, it is necessary to find the minimum of the dependence (1). Relationship (2) was used to determine the mass of the entire ASS. At the same time, the relative masses of propellant consumed for acceleration using the turbofan and ramjet engines are functions that depend on the specific impulses and velocities to which the turbofan and ramjet engines operate, respectively, and are determined as a result of searching for the minimum of the target function (1). The ILV and ASS masses are found from expressions (2) and (3), respectively.

$$M_{ILV} f(V3, V4, V5) = M_{pay} \frac{1-\varepsilon_{k1}}{1-\mu_P f(V3, I_S)-\varepsilon_{k1}} \times$$
$$\times \frac{1-\varepsilon_{k2}}{1-\mu_P f(V4, I_S)-\varepsilon_{k2}} \cdot \frac{1-\varepsilon_{k3}}{1-\mu_P f(V5, I_S)-\varepsilon_{k3}}, \quad (2)$$

where $V3$, $V4$, $V5$ are the velocities provided by the operation of the ILV first, second, and third stages, M_{pay} is the payload mass, ε_{k1}, ε_{k2}, ε_{k3} is the relative mass of the ILV stage (booster) structure, I_S is the specific impulse of solid propellant.

$$M_{ASS} f(V1, V2, V3, V4, V5) =$$
$$= M_{ILV} f(V3, V4, V5) / \{1 - [m_k + m_c + m_e +$$
$$+ \mu_{PP} + \mu_P f(V1, I_{Turbofan}) + \mu_P f(V2, I_{RJE})]\}, \quad (3)$$

where $V1$, $V2$ are the velocities provided by the operation of the turbofan and RJE, m_c is the relative mass of the UAV equipment, m_e is the relative mass of the UAV engines, μ_{PP} is the relative mass of propellant for the UAV return, $I_{Turbofan}$ is the turbofan specific impulse, I_{RJE} is the RJE specific impulse.

To find the minimum of the target function (1), it is necessary to determine the following:

- Design parameters ILV and UAV used in expressions 2 and 3;
- Limiting the ASS total acceleration velocity;
- Allowable dynamic pressure;
- Maximum allowable UAV surface temperature;
- Plan for estimating the ASS development cost.

PROBLEM SOLUTION

First of all, the design parameters of the ILV and UAV were determined. The relative mass of the ILV stages structure was determined from the dependencies given in [4] for solid-propellant ILV. The following relative masses of the ILV stages structure were obtained: $\varepsilon_{k1} = 0.173$, $\varepsilon_{k2} = 0.206$, $\varepsilon_{k3} = 0.296$. The function of the relative mass of the propellant was determined by expression (4), where g is the free fall acceleration.

$$\mu_P f(V, I) = 1 - \exp\left(-\frac{V}{gI}\right). \quad (4)$$

The vacuum specific impulse for HTPB fuel for air-launched ILV solid-propellant motors, taking into account the research [10], was taken equal to ~290 s.

The relative mass of the UAV structure, the relative mass of the UAV equipment, and the relative mass of the UAV engines were determined taking into account the relative masses of aerospace vehicle components [1, 6]. The following relative masses were adopted: $m_k = 0.362$, $m_c = 0.09$, $m_e = 0.145$. The specific impulse of the turbofan engine in the afterburner mode was determined from the results of an analysis of the characteristics of similar modern engines for the afterburner mode of the engine, which amounted to 1800 s. Determining the specific impulse RJE is hampered by the lack of close analogues and the complexity of the technique for determining the parameters of the air intake device [11]. Therefore, to determine the design parameters of the first approximation, we use the RJE specific impulse ranging from 500 to 1000 s.

The limitation of the total acceleration velocity of the ASS was determined, which is equation (5), in which the velocity provided by the turbofan, RJE, and ILV stages is equated to the required circular velocity, taking into account the losses.

$$V_{cir} + \Delta V = \Sigma V f\left(V1, V2, V3, V4, V5\right) \quad (5)$$

where ΣV is the total acceleration velocity of the ASS, V_{cir} is the circular velocity in orbit, ΔV is the losses of velocity.

The ASS total acceleration velocity was determined by expression (6).

$$\Sigma V f(V1, V2, V3, V4, V5) =$$
$$= I_{Turbofan}\, g \ln\left(\frac{1}{1-[\mu_P f(V1, I_{Turbofan})]}\right) +$$
$$+ I_{RJE}\, g \ln\left(\frac{1}{1-[\mu_P f(V2, I_{RJE})]}\right) +$$
$$+ I_S\, g \ln\left(\frac{1}{1-[\mu_P f(V3, I_S)]}\right) +$$
$$+ I_S\, g \ln\left(\frac{1}{1-[\mu_P f(V4, I_S)]}\right) +$$
$$+ I_S\, g \ln\left(\frac{1}{1-[\mu_P f(V5, I_S)]}\right). \quad (6)$$

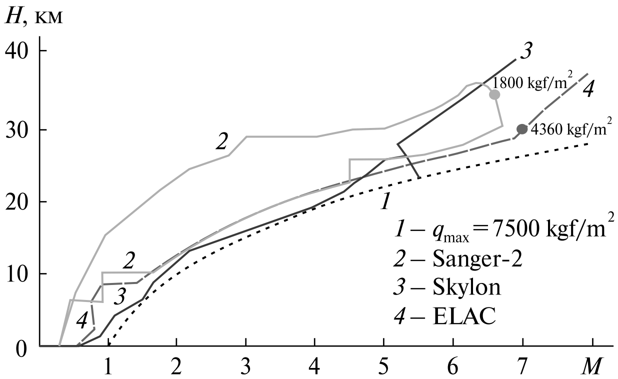

Figure 1. Limitation of the dynamic pressure in analogous systems

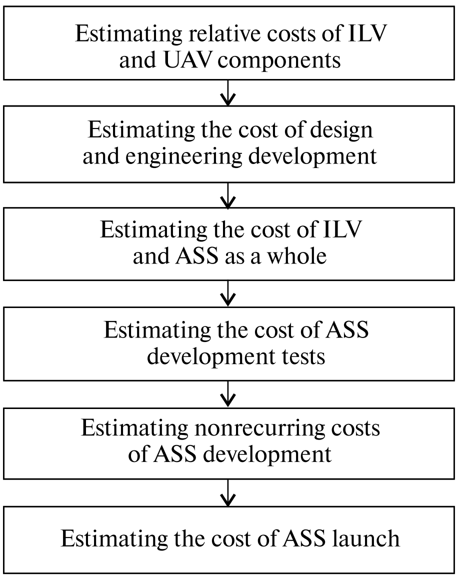

Figure 2. ASS cost estimation plan

The following constraints were also set to solve equation (5):

• The velocity provided by the operation of the turbofan engine $0 \le V1 \le 600$ m/s;

• The velocity provided by the operation of RJE $V2 < 2065$ m/s $- V1$;

• The velocities provided by the ILV stages are assumed equal $V3 = V4 = V5$.

The value of the maximum dynamic pressure affects the UAV strength: the greater the dynamic pressure, the stronger the structure must be and the heavier. The magnitude of the dynamic pressure at UAV and ILV separation also affects the ability to achieve shock-free separation, and therefore, to reduce loads, the ILV must separate at lower dynamic pressure. Based on the results of the analysis of similar projects, shown in Fig. 1, and scientific articles [2, 3], the maximum dynamic pressure of 3500 kgf/cm^2 was adopted.

The maximum permissible temperature on the UAV surface was determined by expression (7) depending on the ILV / UAV separation velocity. At the same time, when searching for the minimum of the target function, it was limited by the maximum operating temperature of the available structural materials, namely, a BH-2AE heat-resistant niobium-based alloy, which has sufficient strength at the maximum operating temperature of 1400... 1500 °C without special coatings.

$$Tof(V2+V1) = T_H\left(1 + r_t\frac{k-1}{2}Mf(V2+V1)^2\right), \quad (7)$$

where To is the UAV skin surface temperature, T_H is the temperature of the approach flow, which depends on the UAV/ILV separation altitude, r_t is

Table 1. **ASS basic technical and economic parameters**

Parameter	Value					
RJE specific impulse, s	500	600	700	800	900	1000
Velocity at stages separation, M	6.03	6.4	6.4	6.4	6.4	6.4
Altitude at stages separation, km	29.1	29.8	29.8	29.8	29.8	29.8
Payload mass, kg	30	30	30	30	30	30
ILV mass, kg	3438	3140	3140	3140	3140	3140
ASS mass, kg	27234	21881	18577	16640	15367	14468
UAV skin surface temperature, °C	1329	1500	1500	1500	1500	1500
ASS launch cost, USD million	2.81	2.55	2.46	2.41	2.37	2.34
1-kg payload delivery cost, USD thousand/kg	94	85	82	80	79	78

the boundary layer recovery coefficient, which is 0.89 for the turbulent boundary layer, k is the adiabatic coefficient, which is 1.4 for air, M is the Mach number of the approach flow.

The cost calculations were based on the recommendations and methods given in [5, 7, 12]. The cost estimation plan is shown in Fig. 2.

The following expressions were used to determine the cost (8)—(13).

$$B_{ILV} f(V3, V4, V5) = M_{3st}\varepsilon_{k3} b_k + M_{3st}\mu_P f(V5, I_S) b_P + M_{2st}\varepsilon_{k2} b_k + M_{2st}\mu_P f(V4, I_S) b_P + M_{1st}\varepsilon_{k1} b_k + M_{1st}\mu_P f(V3, I_S) b_P \,, \quad (8)$$

$$B_{ASS} f(V1, V2, V3, V4, V5) = B_{ILV} f(V3, V4, V5) + M_{ASS} m_k b_k + M_{ASS} m_c b_c + M_{ASS} m_e b_e + M_{ASS}\mu_P f(V1, I_{Turbofan}) b_P + M_{ASS}\mu_P f(V2, I_{RJE}) b_P \,, \quad (9)$$

$$B_{test} f(V1, V2, V3, V4, V5) = B_{ILV} f(V3, V4, V5) n_{ILV} + B_{UAV} f(V3, V4, V5) n_{UAV} + B_{org} \,, \quad (10)$$

$$B_p f(V1, V2, V3, V4, V5) = [B_{design} + B_{test} f(V1, V2, V3, V4, V5)]\cdot 1.1 \,, \quad (11)$$

$$B_A f(V1, V2, V3, V4, V5) = \frac{M_{ASS} m_k b_k + M_{ASS} m_c b_c + M_{ASS} m_e b_e}{n}\cdot 1.1 \,, \quad (12)$$

$$B_{launch} f(V1, V2, V3, V4, V5) = B_A f(V1, V2, V3, V4, V5) + B_{ILV} f(V3, V4, V5) + M_{ASS}\mu_P f(V1, I_{Turbofan}) b_P + M_{ASS}\mu_P f(V2, I_{RJE}) b_P + B_{pp}. \quad (13)$$

In the expressions (8)—(13), b is the relative mass of the corresponding component.

Having determined all the initial data and limitations, a search was made for the minimum of the target function (1) for delivery of a payload mass of 30 kg to an altitude of 500 km. The calculation results are shown in Table 1.

The effect of the reduction of the UAV maximum surface temperature to 1200 °C (for ХН70Ю alloy) and 1000 °C (for Inconel 718 alloy) on the velocity at separation was analyzed. The results are shown in Fig. 3. The effect of the RJE maximum operating velocity on the ASS mass and the cost of 1 kg payload delivery was analyzed. The results are shown in Fig. 4.

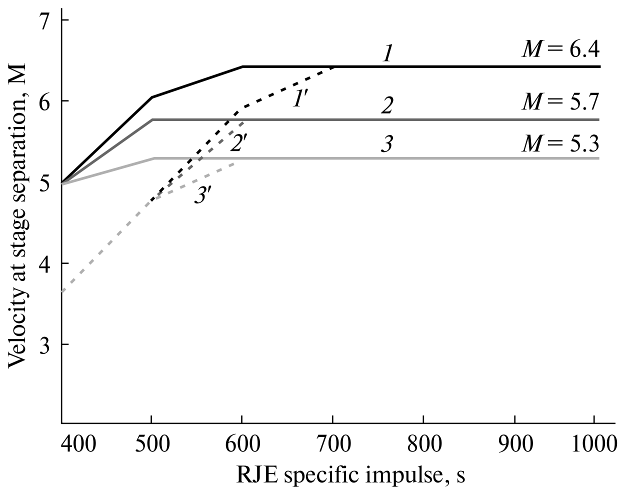

Figure 3. Effect of UAV maximum surface temperature on velocity at UAV/ILV separation: *1, 1'* — at T_{max} = 1500 °C (ВН-2АЕ); *2, 2'* — at T_{max} = 1200 °C (ХН70Ю); *3, 3'* — at T_{max} = 1000 °C (Inconel 718). Line *1, 2, 3* — for E_{min}, *1', 2', 3'* — for M_{0min}

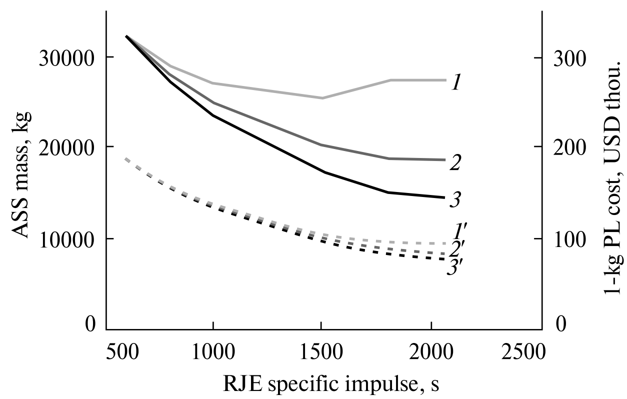

Figure 4. Effect of RJE maximum operating velocity on ASS mass and 1 kg payload launch cost: *1, 2, 3* — ASS mass, *1', 2', 3'* — 1-kg PL cost (*1, 1'* — at I = 500 s; *2, 2'* — at I = 700 s; *3, 3'* — at I = 1000 s)

CONCLUSIONS

The technical and economic substantiation of the parameters of the air launch system capable of launching payloads into Earth orbit without a launch site has been carried out. The substantiation is the first step towards the creation of the Ukrainian aerospace air launch system.

REFERENCES

1. Badyagin A. A., Eger S. M., Mishin V. F., Sklyansky F. I., Fimin N. A. (1972). *Aircraft design*. M.: Mashinostroenie, 516 p. [In Russian].
2. Balakin V. L., Bebyakov A. A., Kochyan A. G. (2008). Optimization of the motion of a hypersonic aircraft-accelerator of a two-stage aerospace system. *Bull. Samara State Aerospace Univ.,* № 1, 23—32 [In Russian].
3. Bebyakov A. A. (2013). Optimal control of the angle of attack of a hypersonic aircraft at the stage of acceleration-climb in the atmosphere. *Bull. Samara State Aerospace Univ*., № 1 (39), 26—38 [In Russian].
4. Blyznychenko V. V., Jur E. O., Krasnikova R. D., Kuchma L. D., Linnyk A. K., et al. (2007). *Design and construction of launch vehicles:* Textbook. Ed. of Acad. S. M. Konyukhov. D.: DNU Publ. House, 504 p. [In Ukrainian].
5. Dietrich E. (2007). *Koelle Handbook of cost engineering for space transportation systems: Statistical-analytical model for cost estimation and economical optimization of launch vehicles*. Revision 2. Report No TCS-TR-184, 283 p.
6. Eger S. M., Mishin V. F., Liseytsev N. K., et al. (1983). *Aircraft design: Textbook for universities*. Ed. by S. M. Eger. 3rd ed., revised and supplemented. M.: Mashinostroenie, 616 p. [In Russian].
7. Gstattenbauer G. J. (2006). *Cost comparison of expendable, hybrid and reusable launch vehicles*. AFIT/GSS/ENY/06-M06, 118 p.
8. Kalynychenko D. (2013). *A technical approach to select design parameters of the air-launched space systems*. 64th International Astronautical Congress, 7792—7799.
9. Kalynychenko D. S., Baranov E. Yu., Poluyan N. V. (2016). Formation of the efficiency criterion for the selection of design parameters of the aerospace system. *Space Science and Technology*, **22**, № 2 (99), 48—51 [In Ukrainian].
10. Khorolskyi M. S., Lavrynenko S. P., Potapov O. M., Kozys K. V. (2017). Prospects of creating the reliable thermal barrier coating systems from elastomeric materials for solid propellant rocket engines. *Space Science and Technology*, **23**, № 6 (109), 46—50 [In Russian].
11. Kornev A., Stetsenko S., Yatsenko V., Smolyakov A., Kalinichenko D. (2021). Integrated approach to gas-dynamic designing of supersonic air intakes of aircraft. *Aviation*., **25,** № 1, 1—9.
12. Valerdi R. (2005). *The constructive systems engineering cost model (COSYSMO)*: Dissertation doctor of philosophy. California, 152 p.

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ТЕХНІКО-ЕКОНОМІЧНЕ ОБГРУНТУВАННЯ ПАРАМЕТРІВ АВІАЦІЙНО-КОСМІЧНОЇ СИСТЕМИ ПОВІТРЯНОГО СТАРТУ

Проведено обґрунтування параметрів авіаційно-космічної системи повітряного старту у складі багаторазового гіперзвукового безпілотного літального апарата та одноразової ракети космічного призначення за технічними та економічними характеристиками. В якості силової установки безпілотного літального апарата застосовується поєднання турбореактивного двоконтурного двигуна та прямоточного повітряно-реактивного двигуна. Розглянутий