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D. S. KALYNYCHENKO[1]**,** Head of the Launch System, the Laureate of the Boris Paton National Reward of Ukraine
ORCID: https://orcid.org/0000-0002-8687-0255
E-mail: Kalynychenkodmytro@gmail.com
T. A. MANKO[2], Prof., Doctor of Technical Sciences, the Laureate of the Boris Paton National Reward of Ukraine
E-mail: tamaramanko1607@gmail.com

[1] M. K. Yangel Yuzhnoye State Design Office
3, Kryvorizka Str., Dnipro, 49008 Ukraine
[2] Dnipro National University named after Oles Honchar
72, Gagarin Ave., Dnipro, 49010 Ukraine

ANALYSIS OF PERFORMANCE CHARACTERISTICS OF AEROSPACE SYSTEMS

The paper discusses the solution to the crucial problem of analyzing the performance characteristics of an air-launched aerospace system (ASS) made in Ukraine as compared with similar foreign ASS. A feasibility study of the parameters of the air-launched aerospace system for the Ukrainian ASS, consisting of a reusable hypersonic unmanned aerial vehicle and an expendable launch vehicle, has been carried out. At the same time, two different types of air engines are used as part of a hypersonic unmanned aerial vehicle: a turbojet engine for takeoff from the runway and a ramjet engine for reaching the required height of hypersonic speed. The integrated launch vehicle consists of three solid propellant stages connecting to the side. An integrated launch vehicle is placed under the unmanned aerial vehicle and separates when it reaches a required height and speed. The technical and economic substantiation of the parameters was carried out according to the criterion of minimizing the costs of the aerospace system, which combines the costs of the development and operation of the aerospace system and shows the number of launches to achieve a reduction in the cost of removing the payload to a given indicator. The results obtained made it possible to determine the performance characteristics of the Ukrainian air-launched aerospace system. The paper presents a comparative analysis of the obtained characteristics. The comparisons were made in terms of overall performance, aerodynamic performance, flight performance, and cost performance. The comparison was made with the main analogs: the projects Spiral (USSR), Molot (Russia), GT RASCAL (United States), Sänger-2, and ELAC (Germany). Based on the comparison of the obtained ASS with existing systems, a rationale was provided for the parameters of the air-launched aerospace system.

Keywords: *Aerospace system, air launch, performance characteristics, unmanned aerial vehicle.*

INTRODUCTION

There is no aerospace system (ASS) currently in operation anywhere in the world. However, the leading countries of the world are working on projects such as ASS. As noted in [4], the main counterparts are the following projects: Spiral (USSR), Molot (Russia), GT RASCAL (United States), Sänger-2 and ELAC (Germany). There are other analogues, but there is not enough information about their parameters in open sources. These projects have not been realized and are currently not operational for physical and financial reasons. The main reason is the complexity of the proposed solutions and the use of a large percentage of new technologies that require time-consuming and expensive development. The ASS proposed in [5, 6] uses simpler solutions such as an

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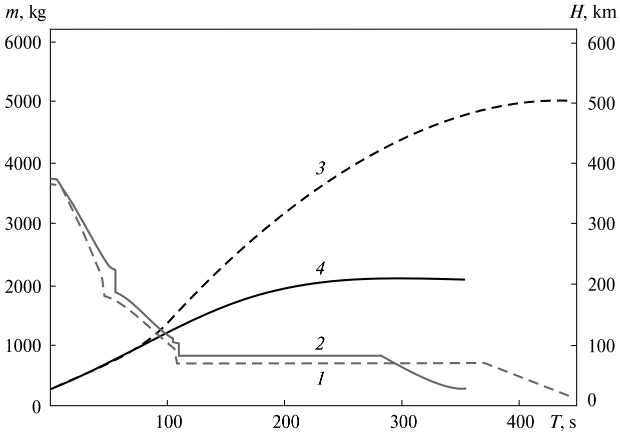

Figure 1. Comparison of LV flight trajectories to LEO and SSO (*1* — mass for 500-km SSO, *2* — mass for 200-km LEO, *3* — altitude for 500-km SSO, *4* — altitude for 200-km LEO)

expendable launch vehicle, developed based on well-known and successfully applied technologies, and two types of engines with separate air intake devices, which significantly simplifies the ASS development and operation. It should be noted that priority testing of the air intake device for the ramjet engine has already been completed [7].

METHODOLOGY

The methodology of the comparative analysis consists in searching for detailed information on similar projects and comparing it with the obtained characteristics of the Ukrainian ASS. To complete the comparative analysis and include information available on similar ASS, we will conduct a comparative analysis in the following areas:

1. Basic parameters of the ASS;
2. Design parameters of the UAV (unmanned aerial vehicle);
3. UAV aerodynamic performance;
4. UAV flight parameters;
5. ASS cost performance.

The main objective of the comparative analysis is to draw conclusions about the positive or negative differences between the substantiated characteristics of the Ukrainian ASS and analogous ASS.

SOLVING THE PROBLEM

To compare the basic parameters of the ASS, we will recalculate the launch vehicle (LV) flight trajectory to

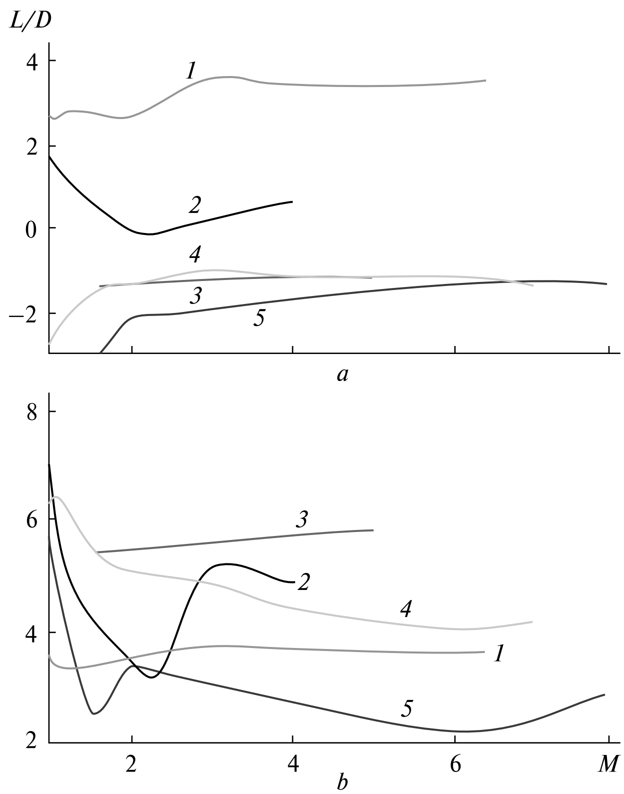

Figure 2. Comparison of lift-to-drag *L/D*: *a* — at an angle of attack of $\alpha = 0°$, *b* — at $\alpha = 6°$ (*1* — ASS, *2* — RASCAL, *3* — Molot, *4* — Sänger-2, *5* — ELAC)

a 200-km high low Earth orbit (LEO), since there is no information about analogues for a flight to a sun-synchronous orbit at an altitude of 500 km, and the payload parameters shown in [6] apply to the SSO with an altitude of 500 km.

Figure 1 compares the LV flight trajectories to 200-km high LEO and 500-km high SSO. According to the results of the calculation, the payload mass is $m = 88$ kg, the LV launch mass — 3710 kg, and the ASS launch mass — 22 560 kg.

Table 1 shows a comparison of the basic parameters of the ASS. The comparison results show that the altitude and velocity at separation closely match the analogues that have a similar application profile and range from 30 to 35 km and from 6 to 7 Mach. The launch thrust-to-weight ratio is sufficiently high and corresponds to the upper limit of the range of similar values, i. e. 0.81 within the range from 0.49 to 0.9. The payload mass and the ASS initial mass, respec-

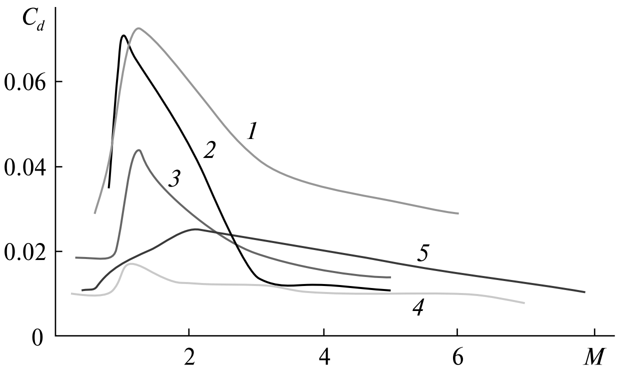

Figure 3. Comparison of drag coefficient C_d at an angle of attack of 0 deg (*1* — ASS, *2* — RASCAL, *3* — Molot, *4* — Sänger-2, *5* — ELAC)

tively, differ significantly, which can be explained by the miniaturization of the control systems and, consequently, the reduction in the payload requirements.

Table 2 shows a comparison of the UAV design parameters. According to the Table, the UAV design parameters are on a par with the analogues, which proves the correctness of the selected engineering solutions.

A comparison of the UAV aerodynamic characteristics is shown in Figures 2 and 3. According to the Figures, the lift-to-drag ratio at an angle of attack of 0° is the highest for the ASS. At an angle of attack of 6°, the lift-to-drag ratio is on a par with the analogues. The drag coefficient value is the lowest for the

Table 1. **Comparison of ASS basic parameters**

Parameter	ASS	GT RASCAL [12]	Spiral [8]	Molot [9]	Sänger-2 [11]	ELAC [3]
Velocity at stage separation, M	6.4	3.0	6.0	2.0	6.6	7.0
Altitude at stage separation, km	30	67.4	28...30	44	35	30
Launch thrust-to-weight ratio	0.81	1.37	0.61	0.49	0.62	0.90
Payload mass, kg	88	113.4	500	767	3000	7000
Relative payload mass, %	0.390	0.296	0.435	1.002	0.820	1.833
Orbit type	circular	transfer. elliptical	circular	circular	circular	—
Orbit height, km	200	148×500	130...150	200	—	—
Mass (upper stage), kg	3710	6473	63000	6174	112000	107400
ASS launch mass, kg	22560	38350	115000	76516	366000	381800

Table 2. **Comparison of UAV design parameters**

Parameter	ASS	GT RASCAL [12]	Spiral [8]	Molot [9]	Sänger-2 [11]	ELAC [3]
Upper stage relative mass	0.164	0.169	0.548	0.248	0.306	0.281
Propellant relative mass	0.321	0.294	0.139	0.344	0.268	0.233
Structure relative mass	0.242	0.296	—	0.275	—	0.266
Equipment relative mass	0.042	0.041	—	—	—	0.018
Engine relative mass	0.230	0.201	—	0.134	—	0.202
Specific loading on the UAV wing, kgf/m^2	453.0	152.9	479.2	661.9	225.5	293.7

Table 3. **Comparison of ASS cost performance**

Parameter	ASS	GT RASCAL (2004) [12]	Pegasus XL (1990) [2]	Pegasus XL (2015) [2]	LauncherOne (2021) [10]
ASS launch cost, million US dollars	2.41	1.25	21	56	12
Payload capability to 200 km LEO, kg	88	113.4	443	443	500
The cost of launching a 1 kg payload into 200 km LEO, thousand US dollars	27.3	11	47	126	24

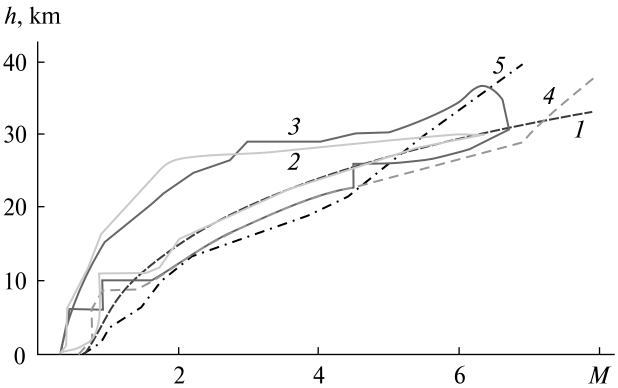

Figure 4. Comparison of UAV flight trajectories (*1* — q_{max} = 3500 kgf/m^2, *2* — ASS, *3* — Sänger-2, *4* — ELAC, *5* — Skylon)

ASS due to additional resistance created by the lower placement of the LV and the fastening elements and by the LV itself. However, this provides a significant advantage from the point of view of guaranteed safe separation of the UAV and the LV.

Figure 4 shows a comparison of the UAV flight trajectories. The flight trajectory of the SKYLON aerospace system [1] is also shown here for comparison. The data presented show that the ASS flight trajectory occurs at lower dynamic pressures, which means that thermal and aerodynamic loads and, consequently, mass are also lower.

Since data from other projects are not available, the cost performances can be compared using the cost parameters of the GT RASCAL project and existing subsonic ASS. Table 3 shows the cost performance comparison. Based on the comparison results, it can be seen that the specific cost of launching 1 kg of payload by ASS into LEO is low. The cost of the GT RASCAL project is lower because this project took into account the possibility of a third party paying for some of the services.

CONCLUSIONS

The paper compares the obtained ASS performance characteristics with those of existing analogues.

The comparison of the ASS basic parameters showed the following:

• The obtained altitude and velocity at separation are close to the analogues that have a similar application profile and range from 30 to 35 km and from 6 to 7 Mach;

• The launch thrust-to-weight ratio is sufficiently high and corresponds to the upper limit of the range of similar values, i.e., 0.81 within the range from 0.49 to 0.9;

• The payload mass and the ASS initial mass, respectively, differ significantly, which can be explained by the miniaturization of the control systems and, consequently, the reduction in the payload requirements.

The comparison of the UAV design parameters showed that the UAV design parameters were on a par with the analogues. The comparison of the aerodynamic performance of the UAV showed a high lift-to-drag ratio and a low drag coefficient. The comparison of the UAV flight trajectories showed that the ASS flight trajectory occurs at lower dynamic pressures. The comparison of the cost performance showed a competitive cost of launching 1 kg of payload by the ASS into LEO. Based on the comparison of the obtained ASS with existing systems, a rationale was provided for the parameters of the air-launched aerospace system.

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Д. С. Калиниченко[1]**,** нач. комплексу з проєктування ракетних систем.
Лауреат національної премії України імені Бориса Патона
ORCID: https://orcid.org/0000-0002-8687-0255
E-mail: info@yuzhnoye.com, Kalynychenkodmytro@gmail.com
Т. А. Манько[2]**,** проф. кафедри, д-р техн. наук. Лауреат національної премії України імені Бориса Патона
E-mail: tamaramanko1607@gmail.com
[1]Державне підприємство «Конструкторське бюро «Південне» ім. М. К. Янгеля»
вул. Криворізька 3, Дніпро, Україна, 49008
[2] Дніпровський національний університету імені Олеся Гончара
проспект Гагаріна 72, Дніпро, Україна, 49010

АНАЛІЗ ТЕХНІКО-ЕКОНОМІЧНИХ ПАРАМЕТРІВ АВІАЦІЙНО-КОСМІЧНИХ СИСТЕМ

Роботу присвячено важливій та актуальній задачі порівняльного аналізу характеристик авіаційно-космічної системи (АКС) повітряного старту України та аналогічних закордонних АКС. Для української АКС у складі багаторазового гіперзвукового безпілотного літального апарата та одноразової ракети космічного призначення було виконано техніко-економічне обґрунтування параметрів авіаційно-космічної системи повітряного старту. При цьому у складі гіперзвукового безпілотного літального апарата застосовуються два різні типи двигунів: турбореактивний двигун для зльоту зі злітно-посадкової смуги та прямоточний повітряно-реактивний двигун для досягнення необхідної висоти та гіперзвукової швидкості. Ракета космічного призначення складається із трьох твердопаливних ступенів, з'єднаних послідовно. Ракета космічного призначення розміщується під безпілотним літальним апаратом і відокремлюється при досягненні визначеної висоти та швидкості. Техніко-економічне обґрунтування параметрів проводилось за критерієм мінімізації витрат на авіаційно-космічну систему, що поєднує витрати на розробку та експлуатацію авіаційно-космічної системи та показує кількість запусків, необхідних для зниження вартості виведення корисного вантажу до заданого показника. Отримані результати дозволили визначити технічні та економічні параметри української авіаційно-космічної системи повітряного старту. Наведено порівняльний аналіз отриманих характеристик із характеристиками відомих аналогів: «Спіраль» (СРСР), «Молот» (рф), GT RASCAL (США), Sänger-2 та ELAC (Німеччина). Порівняння проводилось за загальними, аеродинамічними, льотно-технічними та економічними характеристиками. За результатами порівнянь обґрунтовано набір параметрів авіаційно-космічної системи повітряного старту.

Ключові слова: Авіаційно-космічна система, повітряний старт, техніко-економічні параметри, безпілотний літальний апарат.