Review Article

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Performance and Technological Feasibility of Aerospace Plane Horizontal Launch and Landing with Ekranoplane Assistance

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Introduction

Numerous attempts to reduce the cost of launching a satellite into low Earth orbit (LEO) were undertaken in many countries and characterize the current trend to make space projects economically viable and less costly. This is necessary for the progress of the development of our earthly civilization, its evolution according to the plans of the outstanding Russian thinker, the founder of cosmonautics Konstantin E. Tsiolkovsky. Mastering of the Moon and Mars are the necessary steps in the cosmic evolution of earthlings. Unfortunately, this process has not led presently to a sharp decrease in the specific launch cost. The concepts of such task solving are considered in this paper.

Can the rocket launches become cheaper?

First, let us analyze the current situation in rocket and space technology. To reduce the cost of launching, several ideas for improving space vehicles may be involved, but the main one presently is the attempts to ensure the reusability of at least some of the construction elements of the launcher.

The most significant event in the development of this astronautics activity was the successful launches of the Falcon 9 rocket, the first stage of which, with nine engines, had previously been used in another launch. After that it softly landed on a special platform in the Atlantic Ocean [1]. The preparation of the returned launch vehicle for a new launch took four months. Savings of funds and re-use of the first stage amounted to 30%. In the future SpaceX led by Elon Musk plans to shorten this period of preparation of the rescued first stage to several days, and then this would be an even more significant step in reducing the cost of space launches.

In parallel, SpaceX is working out another innovative solution - saving the used head fairing of the Falcon 9 rocket with a parachute and a stretched network. Of course, both improvements require the development of additional terrestrial and maritime infrastructure for launch, but undoubtedly testify the effectiveness of the technical and organizational solutions of the private capital in comparison with state structures in space projects.

SpaceX achievements have already significantly influenced the market of space launches, pushing the Russian "Proton-M" and "Angara" in the group of cheap cargo (unmanned) variants. With an increase in the number of trouble-free launches of Falcon 9, an increasing number of customers will give it the preference.

It should be noted that the Russian Space Agency is currently experiencing serious difficulties with cargo launches. "Angara" rocket developed by Khrunichev State Space Research and Production Center, which was to fully satisfy the Russian launch market in four of its modifications, was delayed due to the transfer of production from Moscow to Omsk (at "Polet" production center), and the first samples are planned to be assembled in Omsk only in 2020. In the meantime, the "Proton-M" rocket carrier, produced since 2001, is a modernized variant of the "Proton-K" booster rocket, which has improved energy-mass, operational and environmental characteristics - recently experienced several failed starts. The causes of these accidents are established and are not related to fundamental design flaws, but with inattentiveness of personnel and lack of rigorous quality control of the assembly. The situation is now being corrected, and the completion of the economic and ideological crisis experienced by Russia in the early 2000s also contributes to this. However, the production cycle lasts several years and it is impossible to raise the reliability of equipment instantly. Due to problems with "Proton" engines, insurers raised the prices for insurance of the satellites they launch, which complicates competition with "Falcon 9". However, such competition is quite real both in weight and cost of launch.

Despite the fact that "Proton" will fly until 2025, it was decided to create by 2020 the cheaper versions of "Proton Medium" and "Proton Light". It was decided to extend the tanks of the first and third stages and completely get rid of the second stage. As a result, the payload will be comparable to "Falcon 9". The leadership of the Khrunichev Center believes that the cost of the missile will be reduced by 25% compared to the "Proton-M" rocket, which will bring the cost of launching to $ 50-55 million.

Now the minimum cost of launching Falcon 9 with payload (output to 5.5 tons per geo-transfer orbit) is $ 62 million. The launch using the returned first stage will cost 30% cheaper, or about $ 40 million, as E.Musk previously said. The current specific costs for some launchers are shown in Table 1.

Table 1: Launch cost for some launchers

Name	Weight to LEO, kg	Cost, mll $	Specific cost for kg, $	Country
Falcon 9	22800	62	2700	USA
Proton-M	23000	65	2900	Russia
Angara	3800-25800	100	3900	Russia
Soyuz	9000	48	5300	Russia
Arian 5	9800-18810	165-220	10300	Europe
Arian 6	20000	90	4500	Europe

Another direction to reduce the cost of launch is associated with the "Sea Launch" project, the implementation of which is now linked to "S7" Group of Companies (head and co-owner - Vladislav F. Filev, who recently purchased this project). While the project involves the use of the Russian-Ukrainian missile "Zenith", but in the future Roskosmos intends to produce a similar but fully assembled in Russia rocket. Registration of the "Sea Launch" project in the United States will make it possible to circumvent the existing political problems of cooperation between Russia and Ukraine in the space sector, since the US company will be the buyer for Russian and Ukrainian enterprises. At the same time, the peculiarity of the "Sea Launch" project (the launch of the "Zenit" rocket is made from a floating platform at the equator in the Pacific Ocean) makes it possible to discharge into the orbit a similar mass load, like "Proton" from Baikonur. Thus, if all plans are implemented, in the near future two similar rockets will compete in the market of commercial launches: "Proton-M" / "Proton Medium" from Baikonur and "Zenit" from the "Sea Launch", trying to intercept orders from "SpaceX" and each other.

India and China are also trying to reduce the cost of their launches. Such a tough competition in the market for space launches certainly contributes to the technical progress in this area. However, in rocket technology with vertical launching, there are fewer and fewer unused possibilities for providing reusability, which does not allow expecting any sharp jumps in the reduction of specific cost of launch. Fortunately, there is an alternative direction for the development of launch vehicles, associated with the use of an Aerospace plane ASP. It is under intense pressure and competition from the military, which are faced with the necessity, in one way or another, to get rid of the huge arsenal of strategic missiles and, of course, choose the option of their destruction by launching into space. At the same time, horizontal launch systems have significantly greater opportunities for quickly launching loads on the trajectory required by the customer, and this is becoming an increasingly convincing argument in favor of using the ASP.

Advantages of horizontal launch and landing

The promising direction to make the launch cheaper is the transition from the vertical to the horizontal launch, which uses an air breathing engine. A simple method of expansion the velocity range for the vehicle flight consists in the use of booster, able to give to (ASP) the aviation speed at which the main air breathing jet engine begins to operate effectively.

The ASP has a hypersonic wing that gives it the ability to fly and increase the altitude and speed of flight with engine thrust lower than the weight of the vehicle. Unlike a vertically accelerating rocket, this allows the use of relatively low thrust engines, but with a longer cycle of operation for spacewalk. Such engines have, of course, less self-weight, which, at other things being equal, can increase the payload. An essential advantage of ASP during the flight in the atmosphere is the possibility to use atmospheric oxygen as an oxidizing agent in the combustion of fuel, which is 21% of the air volume. This requires an air-jet engine (AJE), consuming only fuel from the tank, and an oxidizer taking from the atmosphere.

Unfortunately, to ensure the effective operation of the AJE is possible only in a limited range of speeds and altitudes, and beyond the dense atmosphere and at speeds approaching space, a ram jet is needed. NASA uses a 122-kilometer (400,000-ft) mark as the boundary of the atmosphere, where the shuttles switched from maneuvering with engines to aerodynamic maneuvering. For AJE, the maximum altitude is less, but still the use of atmospheric oxygen reduces the specific cost of launch. Significant results in the creation of Synergetic Air-Breathing Rocket Engine (SABRE) were achieved by the British company Reaction Engines Ltd. [2].

Recently, this firm announced they had received money from the ESA to develop three key parts for an air-breathing rocket engine. The firm hopes those components could one day help fulfill a decades-old plan to build a space plane called Skylon, which could take off and land horizontally. This task could be solved by 2024.

Skylon is not a unique project. Similar experience exists in Russia. The flying laboratory "Igla" ("Research Hypersonic Aircraft Vehicle") was designed and tested many times in hypersonic flight, intended for the fundamental study of the problems of creating ASP.

Interesting experimental results were obtained in the project "Spiral" of Mikoyan's Design Bureau, in which the returned aerospace hypersonic aircraft was brought to a low near-earth orbit by a hypersonic airplane-accelerator, and after completing the tasks in orbit returned to the atmosphere. The main goal of the program, led by G.E. Lozino-Lozinsky, was the creation of a manned spacecraft for carrying out applied tasks in space and providing regular transportation along the route Earth-orbit-Earth. It also carried out maneuvers at hypersonic speeds. The results of the project "Spiral" were used in the projects of BOR and Russian space shuttle "Buran" with automatic horizontal landing.

The project of the multi-purpose aerospace system MAKS is the highest Russian achievement in the development of space systems for horizontal launching. This two-stage complex, consisting of a carrier aircraft (An-225 Mriya - more precisely, based on the An-225, it was planned to develop a new carrier aircraft An-325), on which the orbital plane was installed. The development was carried out from the beginning of the 1980s under the leadership of G.E. Lozino-Lozinsky at NPO Molniya. Due to repeated use of the carrier aircraft (up to 100 times), the cost of bringing cargo to a low Earth orbit was planned at about $ 1000 / kg, i.e. an order of magnitude lower than the current prices for vertical launch systems.

Instead of the first stage of the rocket, a heavy aircraft was used; and the second stage could be performed, for example, with an orbital plane and a disposable tank (Fig. 1). The system was based on conventional airfields of the 1st class, equipped with the necessary fuel repositories for the MAKS fuel components, ground technical and landing complex, and fits basically into the existing means of the ground complex for operating of space systems.

Figure1: MAKS launch system with heavy plane, disposable tank and orbital plane

MAKS had undeniable advantages over the existing carrier rockets:
- the ability to launch in any direction;
- the possibility of launching into orbit with the necessary phasing and parallax relative to the departure aerodrome;
- the possibility of wide maneuvering in the longitudinal and lateral planes when returning from orbit;
- efficiency of application;
- possibility of return of MAKS when launch is canceled;
- ecological cleanliness, reduction of fields of falling of stages, non-toxic components of fuel.

Both stages of MAKS were winged and hence completely reusable. The project was unique and was able to reduce the specific cost of launching essentially. Unfortunately, after the collapse of the USSR, the project had to be stopped for the following three reasons:

- A drastic reduction in the budget for financing space programs in the early 1990s.
- Affiliation of the Antonov Design Bureau for Ukraine and the inability to implement joint projects with Ukraine.
- Attempts of raider capture of NPO Molniya, its bankruptcy, alienation of production facilities, transport corridors, undertaken with the participation of foreign organizations, and other acts of unfair competition.

All the marked projects on the projects “Igla”, “Spiral”, “MAKS” help to develop other concepts of horizontal launch, one of which involves the use of a heavy ekranoplane during the launch and landing of ASP.

The project “ASP + Ekranoplane”

Researches in the field of satellites horizontal launch and landing (HTHL) were carried out in different countries and with different boosters [2,3]. We will consider the project of launch system with Ekranoplane as a booster for ASP and a mobile landing strip. This project was offered by N.Tomita, Y.Ohkami and A.Nebylov in 1995 [4-6] and since that time it has been developed in a view of detailed reasoning and various feasibility studies.

Ekranoplane can give to ASP the primary speed of Mach 0.6 in needed direction which allows to lower the requirements to ASP wing area and its engines. Some other advantages are connected with possible use of ekranoplane for ASP landing. Heavy ekranoplane is the single vehicle for implementation the innovative idea of docking of the descending ASP with the specific stage allowing to expand the opportunities of its landing. The technology of ASP horizontal landing without undercarriage by docking with ekranoplane at the last stage of descent and the requirements of control systems are discussed.

Ekranoplane is a large marine winged vehicle capable to fly with the application of wing-in-ground (WIG) effect at a small altitude above sea or another rather flat surface [7,8].

WIG-effect is an interesting physical phenomenon gives the essential increasing of lift force and reduction of wing drag. For WIG-effect appearance the flight altitude has to be approximately one tenth of the wing chord. Several heavy ekranoplanes were built and successfully tested at Russia [7]. Application of heavy ekranoplane for spaceplane assist at launch and landing permits to create an integrated transport system with a number of advantages. Another option consists in using ekranoplane for spaceplane landing only, supposing its launch by means of any other facilities. In such case the mass of ekranoplane may be decreased several times and resulted from its required seaworthiness. The “landing” concept sets the most difficult demands to control systems of both vehicles.

Three main reasons may be pointed for considering of ekranoplane use as an important additional component in space transportation system:
1. Spaceplane can be supplied with simplified and lighted landing gear or has not gear at all when landing on ekranoplane moving with the velocity equal to spaceplane velocity. Extremely large saving of mass will be provided if all equipment for docking is an accessory of ekranoplane. The mass of gear for landing on runway may be approximately 3% of empty mass or 25-30% of payload. So, the using of ekranoplane can permit to increase the payload of spaceplane on 30% and to decrease correspondingly the specific cost of launch.
2. The specially prepared runway is not required that decreases essentially the cost of space transportation system and infrastructure.
3. The landing point can be chosen at any area of ocean that gives wide possibilities for spaceplane landing trajectory selection. Studying of feasibility and main principles of motion control at spaceplane launch with ekranoplane assist and landing on the deck of moving ekranoplane was performed and published in many papers. It is obviously that absolute and relative motion control facilities will be the key factor for such flight modes actualization.

Spaceplane Horizontal Landing Variants Analysis

Several variants of spaceplane landing with ekranoplane assistence could be analyzed [5]. All such variants are applicable for any spaceplane irrespectively to the variant of its launch (the variant of Space Shuttle may be considered too). Generally, there are nine, as minimum, possible variants of spaceplane horizontal landing.
1. Landing on a special runway by the use of a wheel undercarriage similarly to airplane landing.
2. Landing directly on water surface which has to be desirably rather smooth (similarly to seaplane landing).
3. Landing to the deck of moving ekranoplane by the use of undercarriage and the technology worked out for aircraft carriers.
4. Landing to the deck of moving ekranoplane by the use of docking and mechanical mating.
5. Landing on soft wide platform of type of inflatable boat (plastic or fiber-glass) being drawn by ekranoplane as a trailer. If a

material of such moving platform is not heatstable it is necessary to cool the spaceplane in advance by using subsonic flight under the variants 7, 8 or 9.
6. Like variant 4, but a soft inflatable platform is placed directly on ekranoplane deck.
7. Taking descending spaceplane in tow by means of rather long rope to ekranoplane or subsonic airplane with an opportunity of its transportation in a similar connection at the expense of plane engines to a required point of landing fulfilled by variant 1-6.
8. Hooking of descending spaceplane by using special “flying kite” or small glider being drawn by ekranoplane. Such controlled light flying craft without own engine is capable to raise the tow high and to join spaceplane to ekranoplane through a long cable.
9. Aerial refueling of descending spaceplane from subsonic plane with the subsequent independent flight in a required point of landing fulfilled by variant 1- 6.

The basic lacks of variant 1 are:
- fixed point of landing and direction of approach to landing;
- complexity of spaceplane transportation from a place of landing to a place of ekranoplane preparation for the next flight;
- mass of an undercarriage can be about 3% of spaceplane landing mass or about 20% of its payload.

The advantages of the variant 1 are it’s rather good acquiring and minimum number of the factors determining the reliability of trouble-free landing fulfillment.

Feasibility of the variant 2 is hindered by three adverse factors:
- in the presence of sea disturbance, the landing on the sea surface is associated with increased mechanical loads on the frame of spaceplane;
- fast cooling in water the spaceplane frame, heated during descending in atmosphere, will create a thermal impact which may destroy heat-shield of this space vehicle and make repeated use of spaceplane impossible (for this reason the landing of spaceplane onto water after a long duration of subsonic flight in the atmosphere is favorable by the reason that enough time would be available for cooling the frame);
- the preservation of spaceplane after landing on the water may be possible only at its buoyancy, with correct alignment and determined stability of movement at water surface.

These circumstances may require essential correction of the generally accepted conception of spaceplane design that is not desirable. Apparently, variant 2 should be considered as a possible variant of emergency landing of spaceplane when it is impossible to finish the flight by any other variant of landing. Just before landing by variant 2 in an emergency, the expediency of ejection of the crew with its independent landing on water may be considered.

The advantages of variant 3 and 4 in comparison with variant 1 are:
- significant expansion of opportunities of a choice of final point, trajectory of approaching, and consequently a final moment of landing;
- enhanced opportunity of increasing of spaceplane useful payload due to possible elimination of mass of undercarriage;
- simplification of spaceplane maintenance to prepare for the subsequent launch.

These variants can become rather reliable only after solving a number of technical problems in creating a high quality control systems and new types of docking assembly.

The variant 3, as compared with the variant 4, is closer to the classical variant 1 and in this sense is easier in implementation. However, it demands a landing gear that is the reason for the weakness of variant 1 compared to other variants due to decrease in useful payload. The possibility of equaling the spaceplane landing speed and the speed of ekranoplane makes landing easier compared to the case of landing onto low-speed aircraft-carrier and may decrease the length of landing deck to the minimum. Chassis may be easy and has basically another construction as compared to the classic one for aircraft. The required accuracy of motion control in the variant 3 will be higher than in the variant 1, but lower than in the variant 4. The variant 3 is positively perspective, but upon examination of motion control system it is superseded by variant 4, which is more complex.

The variants 5 and 6 occupy an intermediate position between variants 1 and 4 on complexity of practicability and advantages. The variant 5 is rather simple in feasibility and reliable. Ekranoplane can form (to blow up with air) the platform before spaceplane landing moment. The landing on rather soft platform moving with equal velocity to spaceplane velocity seems to be quite foolproof. Unnecessity of spaceplane close approach to ekranoplane at landing helps to provide absolute safety, too. The platform may be placed at a distance 100-200m behind moving ekranoplane. However, the variant 5 requires preliminary cooling of spaceplane in rather long subsonic flight. It may be better to combine the variant 5 with the variants 7, 8 or 9 (the variant 8 seems to be the best). The necessity of special means for overloading spaceplane from the floating platform to ekranoplane produces an additional problem in the variant 5.

The last problem disappears in the variant 6. But in this variant difficulties with required thickness of shockabsorber blown cushion and with aerodynamic properties are appeared.

In the variants 7 and 9 a heavy subsonic plane may be used for spaceplane assist at landing. In variant 7 the subsonic plane approaching in flight to descending spaceplane and occupying the position ahead of spaceplane can catch it with a tether by a hook which is specially put forward from nose of spaceplane. Further the plane can carry out transportation of spaceplane as a glider to a rather removed point which is convenient for landing and to carry out an approach on landing from a demanded direction. Just before spaceplane landing the tether is released. During such transportation in connection with plane the spaceplane, blown by air flow, will give back a significant part of accumulated heat, that also promotes successful accomplishment of landing when used in parallel with variants 5 or 6.

The variant 8 is a perspective one as preliminary operation for variant 5 or 6. The “flying kite” or glider can rise from ekranoplane to an altitude of about 300m high to meet spaceplane. It can be controlled in altitude and angles from ekranoplane. Its task is to carry the end of a tow for hooking spaceplane to ekranoplane. After that the variants 5 or 6 can be realized.

In the variant 9 it is possible to realize the idea of refueling in flight which is well-fulfilled in aviation. After refueling, the spaceplane carries out its flight independently to required point of landing performing the necessary maneuvering. In such a flight spaceplane will dissipate accumulated heat quickly into the air that is also favorably for fulfilling a successful landing. The basic problem of the variant 9 practicability is the maintenance of fire safety at refueling especially taking into account the high temperature of spaceplane frame.

All nine variants of horizontal landing may be considered, but the variants 3 and 4 at which landing is fulfilled with the use of ekranoplane, have an additional advantage. They allow realizing completely the available opportunities of integrated transportation system "Spaceplane + Ekranoplane" in which the basic function of ekranoplane is to assist spaceplane at takeoff. Hereafter the peculiarities of the realization only of variant 4 which produces the harshest demands to motion control systems are analyzed.

Stages of spaceplane landing by means of docking with ekranoplane

The landing of spaceplane may include six stages, each of which should be supplied with the appropriate opportunities and characteristics of navigation and motion control systems of both vehicles.

1. Choice of a point and time of landing in view of an opportunity of ekranoplane to arrive in the specified point in time, and the calculation of the trajectory of spaceplane descanting.
2. Fulfillment of standard operations of spaceplane entrance in atmosphere and braking up to subsonic speed.
3. Coordinated control of spaceplane absolute motion and ekranoplane absolute motion with the purpose of maintenance of their mutual close parallel motion with a difference of altitudes about 200 m and mutual mismatch in horizontal plane no more than 100 m.
4. Relative motion control system loops closure, and reduction of mutual mismatch of two vehicles in horizontal plane up to several meters and further - up to 1m, reduction of difference in their flight altitudes up to 3-5 m at the expense of spaceplane descending.
5. Engaging of the mechanism of docking, exact positioning of mating elements by quick-response automatic system, the mating (partial or complete), the attracting of spaceplane to ekranoplane.
6. Completion of spaceplane docking with ekranoplane, centering of spaceplane on the landing deck of ekranoplane, blocking of mating elements, ekranoplane returning to the port.

Recognizing that in a mode of spaceplane take off the loads on mating elements are much greater than ones in a mode of landing it is expediently to have no less than 4 mating elements from which only 3 are used in a mode of landing, and fourth (most powerful) should support completely filled spaceplane near to its center of gravity and cannot have any freedom of motion [8].

Requirements to automatic systems at different stages of space plane landing

At a stage of space plane leaving the orbit, space plane exact angular orientation with errors of no more than several angular seconds is important for correct formation of a brake pulse that shows the appropriate requirements to gyro systems and astrotrackers.

At a stage of aerodynamic braking the inertial system should keep the correct information on angular orientation and supervise a trajectory of motion, not admitting accumulation of too large errors in definition of position to the moment of the beginning of GPS receiver functioning. After finishing of this stage the trajectories of rapprochement of spaceplane and ekranoplane should be synthesized in view of estimations of their actual positions. It is necessary for it the switching on and further continuous work of the noiseproof radiochannel for data exchange between spaceplane and ekranoplane, joining their control system in an integrated complex. At a stage of spaceplane and ekranoplane approach the high accuracy of coordinates definition (at a level 50-100 m) of both vehicles in Earth frame and body-related frame is necessary. The main contribution to its maintenance should give GPS.

At a final stage of spaceplane and ekranoplane docking the high accuracy of holding of a difference of linear coordinates in all three axes is required within the limits of shares of meter and difference of speeds - within the limits of shares of m/sec. It is required also a precision (within the limits of 20") stabilization in pitch, roll and yaw of both flying vehicles. On the stage of direct approach (before contact) movement of both vehicles should be close to synchronous flat - parallel. At low power of the landing engine, it is possible to ensure only within a short time interval, in this connection the mating system should has a quick response.

According to preliminary researches, the most suitable method of getting the data about the parameters of linear and angular relative motion of spaceplane and ekranoplane is application of opto-electronic system on the base of video cameras [1,6,9,]. It requires to place at the deck of ekranoplane as minimum three video cameras of an infra-red range with special filters from solar radiation allowing to enter continuously in the processing system a sequence of the input images with the resolution of the order 640x480 and higher, depth of color of 8 bits (265 colors) and frequency of the frames more than 20 frames/sec. In this case at a final stage of approach the errors of relative motion parameters measuring will be no more than 10cm in horizontal plane, 10cm in altitude and 20' in angles.

The control system of ekranoplane motion should ensure its required trajectory and improve dynamic properties of ekranoplane as control plant, especially concerning the longitudinal stability. Nonlinear character of interrelations between separate channels of this system, intensive wind and wave disturbances, necessity of a special mode of turning away from surface obstacles and many other features give specificity to a task of system optimization and raise a role of computer simulation in its decision, though in statement of a task are used categories usual for the theory of automatic control. Great inertia of heavy ekranoplane-catamaran in course maneuvering forces to put it on the given line of a rectilinear motion in advance and actively operate only by the velocity. Ekranoplane flight altitude at spaceplane landing should be rigidly stabilized. Then the leveling of spaceplane and ekranoplane in altitude and decreasing of lateral displacement will occur with an active role of spaceplane, and their approach in the longitudinal plane can be performed by maneuvering in ekranoplane velocity. At approach it is necessary to combine control on errors with control on disturbances.

Peculiarities of ekranoplane and spaceplane motion control

It is known that the longitudinal stability of ekranoplane in flight requires the special solutions in aerodynamic scheme design for creation the necessary control forces and angular momentums [6]. A special multi-channel automatic control system for stabilization and damping of heavy ekranoplane motion is necessary to consider for each definite aerodynamic configuration at the initial stage of design. The problem of high accuracy and reliability of flight parameters measurement close to the rough sea surface also has to be solved [10].

Specific conditions of ekranoplane and spaceplane mutual motion at docking make it impossible to use in this transport system ekranoplane of the most known configuration "Wing + Tail Assembly" due to high tail which forbids the way for approach.

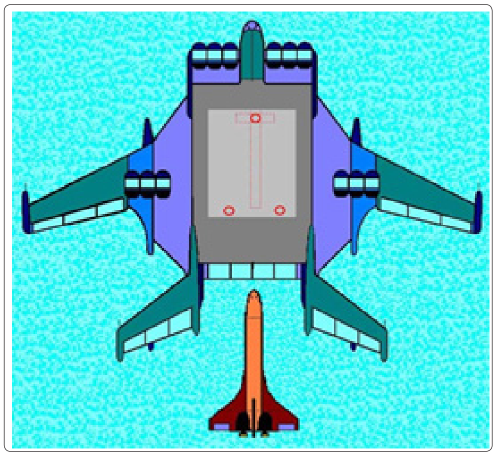

Figure 2: Ekranoplane of "Combined Wing" configuration with a spaceplane in approach

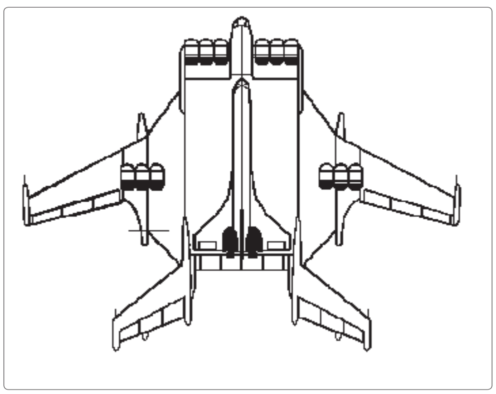

Figure 3: Ekranoplane-catamaran with spaceplane at its deck

Therefore the tail assembly of any form located near to a longitudinal axis of ekranoplane is inadmissible, and any consoles are possible only at sufficient displacement from this axis in a cross direction. The central part of ekranoplane deck should be practically flat for normal accommodation and motion of the spaceplane. So, the configurations of ekranoplane-catamaran of «combined wing» is preferable [8]. The ekranoplane of such configuration with spaceplane in approach is shown in Fig.2. The ekranoplane with spaceplane displaced at its deck is shown in Fig.3.

The control system of ekranoplane should ensure its required trajectory and improve dynamic properties. Nonlinear character of interrelations between separate channels of altitude, pitch, velocity, roll and yaw of this system, intensive wind and wave disturbances and many other features give specificity to the problem of system design [1].

Essential inertia of ekranoplane-catamaran in course maneuvering forces to put it on the given line of a linear motion in advance and actively operate only by absolute velocity at approach and docking with spaceplane.

The achievable maximal speed of large ekranoplane can be estimated in 600-650 km/hour, and the optimal landing speed of spaceplane lies inside the interval 400-550 km/hour. It is more than the landing velocity of «Shuttle» and «Buran» and permits to expect an extra high effectual steering of spaceplane at approach and docking with ekranoplane. Ekranoplane as the control plant should have a good margin of stability and react poorly to any variations of loading and other disturbing forces and momentums.

Important problem is the necessity of ensuring a very high reliability of all technologies engaged at spaceplane landing. The probability minimizing is requires of any failings of Ekranoplane that could prevent to participate in spaceplane landing. Special investigations must give an answer to the question, whether it is necessary to have a spare Ekranoplane for such cases or to use the alternative variant of landing.

The special integrated system of navigation and motion control is necessary, the main position gauges of which at both vehicles should be GPS receivers at the stage of approach and precise microwave or optic systems of local navigation at the stage of docking directly. The experience of the development of modern landing systems for deck aircraft seems to be very useful. In a part of other components (means of inertial navigation, Air Data System, altimeters) basically the requirements at a level «Space Shuttle» and «Buran», extrapolated in view of modern achievement in the appropriate technologies, are generally kept.

The system of a mutual motion control at docking has to be a multi-dimension digital automatic control system. It is clear that for arising the quality and reliability of control it is expedient to consider both vehicles as the elements of closed loops of such a dynamic system.

The docking process of spaceplane and ekranoplane must be operated under motion control complex which involves: closed control loops for spaceplane and ekranoplane absolute motion control, closed loop for relative motion control and an additional open loop channel for local shifting the docking element along and across the landing deck. The correct interaction of these four interconnected multidimensional loops and control algorithms optimization in each controlled linear and angular coordinate is a complicated problem of analysis and modeling.

Notice, that the most unfavorable external disturbance for a loop of lateral deflections depression would be a pulse rush of wind in a cross head direction. But even in this case the error could be acceptable due to the following reasons:

- high landing velocity of spaceplane will make this impulse short and its influence will be decreased;
- high landing velocity of spaceplane will increase essentially the effectiveness of its aerodynamic control elements;
- a pulse of wind will influence both spaceplane and ekranoplane that decrease their relative shift.

Objectively, the accuracy of spaceplane relative motion control at landing velocity of Mach 0.4-0.5 may be higher than one of ordinary plane motion control at landing on runway at half as much velocity.

At the final stage of docking the additional control loop of mating element will be switched on. It is the open loop channel for control of local shift of the mating element. Operating simultaneously with control mechanisms mentioned above, it must process only high-frequency components of control signals increasing operating speed of entire system to significantly decrease control errors.

Optimization of all control loops engaged at docking has to be fulfilled on criteria of minimization of maximum control errors. The theory of ensuring control accuracy deals with the nonparametric models of disturbances, particularly limitation of numerical characteristics of disturbance derivatives, is suitable for this aim [9].

The algorithms of navigation sensors integration

The methods of algorithms synthesis for processing of readings of several precise altimeters, inertial sensors, GPS receivers and many other different types of sensors in the interests of estimation of the current meanings of the parameters of low altitude flight above sea as well as of the characteristics of wave disturbances were developed [7]. Authors use approach to synthesis teaming up Kalman filtration and robust filtration that ensures the eligible quality of estimation in the circumstances of incomplete a priori information on the errors of primary sensors with allowance for all diversity of the modes of ekranoplane motion [10]. The dependence of the estimation accuracy on flight parameters and sea conditions are presented in by the array of graphs [7].

Separately the problem of automatic estimation the general direction of sea waves spread may be illuminated, that important for the optimization of the mode of approach and landing on water.

The algorithms of combined control on errors and wave disturbances

Obtained current data on the field of wave disturbances can be used firstly for the adaptation of the main motion control loops and secondly for the realization of the principle of combined control. This permits to arise the quality of motion control. However, main difficulty in the building of the channel of control on wave disturbances is the complexity of the calculation of disturbing forces and momentums, attached to the vehicle, based on measured ordinates and the biases of wave field. At two-dimensional sea waves this task is decided enough successfully, but in general case of three-dimensional waves it is necessary to use approximations. But positive effect may be guaranteed in any event.

Conclusion

The article analyzes possible directions of improving the technologies of space launches, allowing reducing the specific cost of launching payloads into near-earth orbit. Such a decline in cost is necessary for the successful further development of outer space, preparations for building settlements on Moon, Mars and other planets, which was predicted by the founder of astronautics K. Tsiolkovsky. Modern trends in the cheapening of rocket launches, their limitations and the possibility of solutions in private companies are described. As an alternative to vertical launch, the advantages of horizontal launch of ASP are analyzed. Details of the use of ekranoplane for horizontal launch and landing of ASP, requirements for automatic control systems for this of these two winged vehicles absolute and relative movement within the integrated space transportation system are described in details. There are serious experimental and theoretical developments on both the ASP and ekranoplane, but nevertheless for the project implementation it is required to create two absolutely new flying vehicles, that of course can delay the project implementation period. However, if in a short time there are no new positive ideas for improving the vertical launch, the construction of a space transportation system of horizontal launch and landing will certainly be topical.
It is shown at this paper, that:

- ekranoplane with perfect control system can realize the idea of docking the stage that would allow spaceplane landing without gear;
- the problem of accurate and reliable control of relative motion is the key problem of spaceplane docking with ekranoplane at the final stage of descent;
- the laws of motion control should be optimized under the criterion of ensuring the necessary accuracy of control;
- analysis of the requirements to control systems and their comparison with the existing nowadays prototypes allow to predict a technical opportunity of creation of all necessary components of onboard control systems in the near future.

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