HTHL Space Launch Integrated Systems: Flight Control Problems

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Abstract

Integrated launch systems that include aerospace plane (ASP) and another big winged vehicle (plane or better ekranoplane) as a booster are analyzed[1]. It is proved that ekranoplane with mass of 1500 ton or more is capable to launch ASP with initial mass of 500 ton and landing mass of 60-70 ton. Ekranoplane can give to ASP the primary speed of Mach 0.5-0.65 in required direction that allows to lower the requirements to ASP wing area and its engines. Some other advantages of the offered transport system are connected with possible using the ekranoplane at ASP landing. Heavy ekranoplane is the single vehicle for realization the progressive idea of docking to descending ASP the stage allowing to expand opportunities of its landing. The technology of ASP horizontal landing without undercarriage by docking with ekranoplane at the last stage of decent and the requirements to control systems is discussed. Some main problems of ekranoplanes motion automatic control and multipurpose use are described.

1. Introduction

The cost reduction of useful mass injection into near-Earth orbit, expansion of functionality of space transport systems and ecology safety requirements are among the major problems of space engineering. The fully reusable single-stage-to-orbit (SSTO) aerospace plane (ASP) with horizontal launch and landing might be ideally applied to meet such requirements. However, other demands and limitations, which bound with the state of the art of necessary technologies and forecasting of future technological level, force to consider a SSTO ASP only as a purpose which can be achieved stepwise. On the near-term steps of ASP improving it is necessary to consider them as a part of integrated space transport system.

Among two methods of ASP launching into orbit, vertical take-off (VT) and horizontal take-off (HT), presently VT prevails compared to HT. The decisions for the X-33 program by NASA, for HOTOL by British Aerospace, for MAKS by RSA also, seems to favor VT (but modern designs of Skylon, SpaceShipOne and SpaceShipTwo again give chances to HT). In retrospect, almost all of the launch vehicles in the past have been VT. However, broadening the range of requirements for space transportation systems seems to favor the need for HT.

The project of ekranoplane (or Wing-in-Ground effect vehicle or WIG-craft) use for horizontal launch and landing of ASP was offered by N.Tomita, Y.Ohkami and A.Nebylov in 1995 [1,2] and since that time it has been developed in a view of detailed reasoning and feasibility study [3-9]. The goal of investigation is the creation of space transportation system

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2. Concept of ASP-Ekranoplane launch system

What are the reasons to use the ekranoplane as an additional component in space transportation system that assists at ASP launch and landing? Four main reasons may be pointed.

1. The launch point and the landing point can be chosen at any area of ocean that gives wide possibilities for ASP landing trajectory selection.
2. Ekranoplane can carry more heavy ASP than plane, and give to it the necessary initial speed.
3. The cosmodrome with specially prepared runway is not required.
4. ASP 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 ASP one. 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, ekranoplane use can increase the payload of ASP on 30% and to decrease accordingly the specific cost of launch.

One of the important reasons forcing to use HT – their big freedom in a choice of time and a place of start. If it is necessary to launch the satellite or the spaceship from a stationary platform not on any, and into strictly set orbit, it can be done in the defined periods ("launch window"), sometimes the quite short. Besides some projects promise essential economy of fuel in comparison with the usual carrier rocket. In particular when flying in the atmosphere as an oxidizer it is possible to use simply oxygen from air.

The problem of ekranoplane’s type choice for ASP-Ekranoplane system is very relevant. The generally accepted classification of ekranoplanes involves three types. The ekranoplanes of a type A can move only in the zone of WIG-effect strong action at the altitude approximately equal to a half of the wing chord or less. Ekranoplanes of a type B have an elevator and flaps that allow to select an optimal altitude from a coverage of WIG-effect, and also to accomplish the transient increasing of the flight altitude in the mode «dynamic zoom». The ekranoplanes of a type C can fly not only at the altitudes of WIG-effect action, but also in an airplane mode. For this purpose they should mate aerodynamic and design qualities of ekranoplane and airplane, that as a matter of fact results in impairment of both capacities.

If it is necessary to cause an airplane to use sea surface as an aerodrome, for this purpose there is a well-known and very successful engineering solution called a seaplane. But a heavy ekranoplane with a wing of small length factor and special profile, with "under-blowing" engines, with a ship-type body of corrosion-resistant metal, with different means of longitudinal stability maintenance in a WIG mode of flight and good stiffness afloat, must not compete against airplane in the ocean of air, it would be not logically. Of course, it is possible to construct an ekranoplane of a type C, but at a large take-off mass such an ekranoplane will be too expensive and having restricted effectiveness. At the same time the heavy ekranoplanes of a type B with good seaworthiness are promising in several applications [8]. Therefore the ekranoplane of a type B has to be used in the project "ASP-Ekranoplane".

Nine variants of ASP landing with ekranoplane assist were analyzed [4]. The variant of ASP landing to the deck of moving ekranoplane by the use of docking and mechanical mating is the most interesting and produces the most harsh demands to motion control systems accuracy and reliability.

3. Requirements to ekranoplane

The demanded carrying capacity in 530-700 ton with a mass ratio about 35% determines ekranoplane take-off mass in 1600-2000 ton. By accepting specific loading on a wing of 5-6 kN/m^2, one can estimate the required area of ekranoplane wing S in (3-4)10^3 m^2. With conditional lengthening of the wing λ =3-4 the wing length should make $L = \sqrt{S\lambda}$ = 90-110 m.

With the normal thrust-to-weight ratio of ekranoplane in 25% the total trust of engines should be of the order (4-5)10^3 kN, which can be ensured by 6 engines with a single trust of 600-800 kN. As it is important to raise the speed of starting ASP to maximum, it is expedient to involve in this mode all engines, as well as at ekranoplane take off. The criterion of fuel saving is not paramount for ekranoplane-launcher. However, the stock of fuel should ensure an opportunity of ferry flight for a distance no less than 3000 km.

Seaworthiness of the ekranoplane with linear dimensions about 100 m and mass of 2000 ton can be defined from the experience of Russian ekranoplanes "Lun" and "KM" operation, which with the mass approximately 400 ton have confirmed seaworthiness in 5 numbers appropriate to allowable height of a wave with three-percentage providing in 3.5 m. The factor of recalculation can be determined under the Frude's formula as a cubic root of the relation of weights, that is (2000 / 400) 1/3 = 1.71. It gives allowable height of wave 3.5m *1.71 = 6.0 m that corresponds to seaworthiness in number 6 for the modes of take off and landing.

Similarly one can estimate achievable maximal speed of large ekranoplane-launcher in 600-650 km / hour, though basically the value of 550 km / hour can appear quite sufficient, and the optimal landing speed lies inside the interval 400-550 km / hour. At last, 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 moments arising basically at ASP start. The stiffness and correct centering of floating ekranoplane should be also supplied.

It is clear, that the given requirements cannot be executed in the framework of the well-explored plane configuration of ekranoplane "a carrying wing + tail assembly" even with essential increase of the dimensions in comparison with ekranoplane "Lun". It is also clear, that ekranoplane-launcher should be catamaran. The possible design of "combined wing type" ekranoplane with ASP is shown in Fig.1.

For ASP launch ekranoplane (1) carries it to the chosen point of start which may be several thousand kilometers apart, (2) refuels ASP with the components of liquid propellant directly before start having onboard powerful cryogenic equipment and tanks for liquidized gas and (3) gives to ASP the initial velocity M=0.5-0.65 at the altitude of 10-20 m. In this case ASP in compare with MAKS project obtains less mechanical energy, but in recalculation to the attainable final velocity this loss does not exceed a few percents [2-4]. A buster main goal is connected with jumping over the zone of small velocities which is unacceptable for hypersonic wing and engines, and ekranoplane masters this role well.

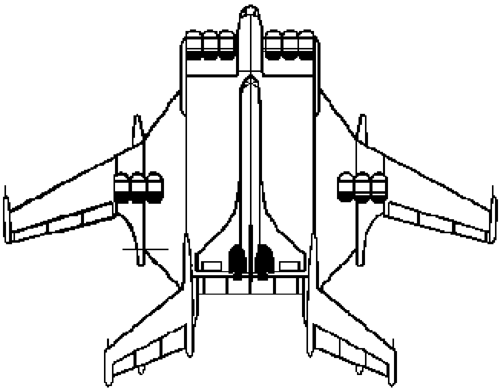


Fig.1. Ekranoplane of "Combined Wing" configuration with docked ASP.

4. Specific problems of large ekranoplanes automatic control

The technologies of creation small and large ekranoplanes are quite different. The fundamental difference consists in the following peculiarities.

1. The main material for big ekranoplanes is light metal and composite materials. Small cheap vehicles use mainly plastic. It requires other construction, other design methods (including adequate strength and aerodynamic performance providing) and other production equipment.

2. The number of control elements of large ekranoplanes is greater against small ones, and the control strategy (manual or automatic) is easier. The following five parameters of motion need to be automatically controlled: altitude of flight, pitch, roll and yaw angles and angle of attack, air speed. The control elements of large Ekranoplanes are: elevator, rudder, flaps, ailerons or flapperons, engine thrust controller. Most of the control elements are trimming tab.

3. For large ekranoplanes, as different from small ones, flexibility of the body must be taken into account for perfect motion control design. As a rule, three modes of oscillations are considered. The models of flexibility are described in [7]. Perfect models permits to develop recommendations for control laws optimization and sensitive and control elements installation on the vehicle body. If possible, control elements and accelerometers must be installed close to the nodes of oscillation modes, but gyroscopic sensors must be installed in the antinodes having undisturbed angular position. Including the notch filters in the control loops may be advisable.

4. The eigenfrequencies of large ekranoplanes as a plant are essentially smaller against the small ekranoplanes. It gives additional difficulties in providing the smart modes of flight control. As a rule, oscillating units in the vehicle model have smaller natural frequencies and smaller damping ratio. Oscillating or aperiodic instability is a usual practice, only perfect controller may provide the longitudinal stability in some modes.

5. For large ekranoplane the substantive roll angle is more undesirable than for small ones. That is why not ailerons but rudder is mainly used for turning. Really the coordinated control by practically all control elements has to be considered.

6. As the large ekranoplane must fly above the stormy sea, the sea waves of significant height (more than 3.5-6 m) and length can influence the flight control. The adequate models of waves disturbances were considered in [1]. At altitude control it may be advisable not to stabilize the absolute altitude regarding the average level of undisturbed sea and not to follow each significant wave. It would be reasonable to follow the sweeping curve of wave profile with the time constant, equal the integrated time constant of ekranoplane in the longitudinal plane. It this case the WIG-effect will be used more effectively and the flaps resource will not be spent too fast. It is a particular problem of the control law optimization [4].

7. For small ekranoplane the cost of autopilot often considered as the brake for going to market. For large ekranoplane the cost of autopilot is only a small part of vehicle total cost. The most perfect equipment and powerful reliable computers must be involved into the autopilot which has to be adaptive and provide the perfect flight control at all considered modes of flight.

5. Control laws optimization

Design of automatic control systems for ekranoplane may include the following stages.

1. Development of the vehicle draft model for WIG mode of flight on the basis of comprehensive analysis of aerodynamic features, mass distribution, control elements effectiveness and installation points, number of sensors and many other essential factors. The general set of equations may be similar to plane, but most of coefficients will depend on the altitude of flight.

2. Automatic linearization of the vehicle equations relatively to a rectilinear trajectory of flight at the fixed typical altitude.

3. Simplified separation of vehicle multidimensional control system into several independent linear control loops.

4. Estimation of controllability and observability for the simplified linear vehicle model.

5. Synthesis of rather simple control law for each separated control loop. PID-regulator may be used in the simplest case as it corresponds well to the available set of sensors. Investigation of these laws robustness to the parameters variation.

6. Initial investigation of the wave and wind disturbances influence on the vehicle (directly applied to the wing and body or corrupt the output signals of sensors and sensor systems). Perfection of the filters into the measuring channels, investigation of optimal filters advantages against the simplest filters taking into account the uncertainty in disturbances features.

7. Investigation of the vehicle body flexibility influence on the control loops. Perfection of the simplest control loops for providing damping of the most unacceptable oscillation modes. Application of optimal filtration methods.

8. Jointing of the separate control loops into the multidimensional linier control system with interaction between channels. Comprehensive investigation of this system on the basis of MATLAB tools and other available software packages use.

9. Input of the main nonlinear units in the control channels, composing the nonlinear differential equations for such channels for stationary case. Simulation and investigation of nonlinearities influence on the control quality indexes.

10. Simulation of control system with the full vehicle dynamical model taking into account complex dependence of parameters on altitude of flight. Investigation of control performance and stability in the range of altitudes. Study of control system sensitivity to vehicle model parameters change. Development of adaptive control laws.

11. Simulation and investigation of the vehicle take-off from the water, especially waved water. Development of control laws for take-off. Evaluation of the required thrust for take-off in different conditions.

12. Development of the special control laws for landing, coordinated turn and attitude change, including obstacles avoidance. Simulations of the wing end touch the wave crest at flight in WIG-mode.

13. Simulation of fails of engines or control elements. Development of control system reconfiguration algorithms.

14. Identification of inadmissible combinations of flight parameters values (first of all for altitude, air speed and attack angle), development of algorithms of such events exclusion, especially after the wrong actions of pilot.

15. Step by step implementation of automatic control options for test vehicle. Finely debugging and operational development of control laws and elements during the test flights.

Of course, some changes in the sequence of the named stages are possible for the certain cases of design.

Many peculiarities of design are essential. For example, it is possible to execute the altitude control under the change of wing lift force at:

a) Trailing-edge flap deflection;
b) Elevator deflection (thus a pitch varies);
c) Change of speed of flight at the expense of engines thrust control.

As at pitch angle variation the drag and, therefore, the flight speed changes, the version *b)* demands the presence of speed stabilization system. Thus all channels of the control complex substantially participate in maintenance of the ekranoplane demanded motion in the longitudinal plane. The synthesis of control laws can be fulfilled under the several criteria, but the main ones are certainly the admissible values of control errors in different modes and adequate margins of stability on amplitude and phase. The estimations of the vehicle control errors, linear and angular rates and also wave and wind disturbances, being filtered accurately, have to be used at the formation of control signals.

The automation of ekranoplane take-off and landing is a separate complex problem, it is connected with the coordinated control in several channels, including one of the swivel nozzles of engines.

Obtained current data of the field of wave disturbances can be used (1) for the adaptation of the main motion control loops and (2) for the realization of the principle of combined control. This lets arise the quality of motion control. However, main difficulty in construction of the channel of control on wave disturbances is the complexity of the calculation of disturbing forces and moments, attached to the vehicle, based on measured ordinates and the biases of wave field. At two-dimensional sea waves this task is solved enough successfully, but in general case of three-dimensional waves it is necessary to use approximations. But positive effect may be guaranteed in any case.

The developed measuring system allows to track the profiles of sea waves in three points, corresponding to the points of radioaltimeters installation at a nose and both sides of the wing, with the accuracy 10 cm at seaway number 5 [4]. The problem of automatic estimation of the general direction of sea waves propagation with the use of three radioaltimeters outputs is also solved, that is important for optimization of a mode of landing approach and splashdown.

Instead of phase radioaltimeter the laser devise drawing a figure at the water surface, and cameras, taking the pictures of these figures, may be used. Specially developed algorithms for such images processing permit to estimate accurately the altitude of flight and sea state [8]. This equipment can be cheaper against radioaltimeters, but the reliability at the full spectrum of possible conditions of operation is still under investigation.

6. Arrangement of mechanical docking Elements

The initial position of fueled ASP on the ekranoplane deck has to be practically horizontal and close to the deck to reduce the aerodynamical drag during ekranoplane take-off and cruising flight to the area of ASP launch. At the moment of ASP engine switching on the ASP must receive around 15º attack angle [3-4] and some space between the engine muzzle and the ekranoplane deck. That means that ASP center of gravity is elevated for approximately 10m and, probably, the whole ASP is shifted a bit back to locate the engine muzzle in the free space.

Such initial elevation of ASP could be provided by rather powerful mechanism, which applies lifting force at the area of ASP center of gravity. It may be the extensible hydraulic column that could produce the force in 5000 kN and to be rather stable against longitudinal aerodynamical force applied to ASP connected with ekranoplane motion. Practically this column has to carry the ASP weight minus aerodynamic lifting force of ASP wing.

Another important requirement to the undocking mechanism consists in minimal disturbed forces and moments applied to ASP at its disconnection with ekranoplane. The ASP weight must be balanced by its wing lifting force. Any turning moments in the longitudinal plane must be canceled out by the right deflection angles of the elevator and flaps. That is reason for the ASP attitude stabilization system to be switched on before the launch. ASP engine thrust has to approximately balance a drag force. So, ASP engine has to be switched on also before ASP disconnection with ekranoplane.

Taking into account the listing above requirements, the arrangement of mechanical mating elements for connection and disconnection of ASP with ekranoplane can be drawn out as it shown in Fig.2.

The central extensible column CC is the main facility at ASP launching procedure. It is buried deeply into ekranoplane body during ASP transportation to the launch area, but arises at maximal height of around 10m before ASP undocking. It is not necessary for CC column to manage the ASP pitch. Directly before undocking this function will belong to ASP flight control system. But for preset ASP the initial angular position and for partly help CC column in load carrying two or three another connecting elements will be used. For example, it could be a nose column NC and two tail columns TC1 and TC2. NC is located on the central line in a forward part of the Ekranoplane deck.

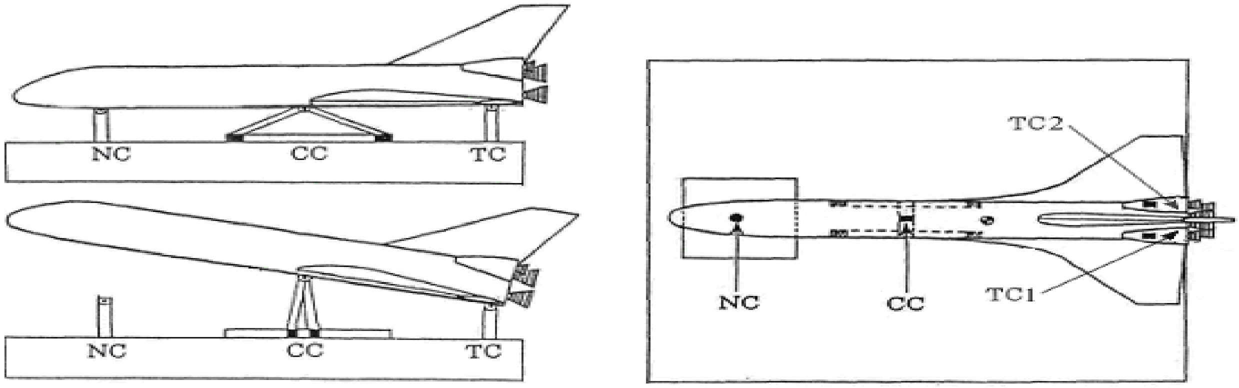
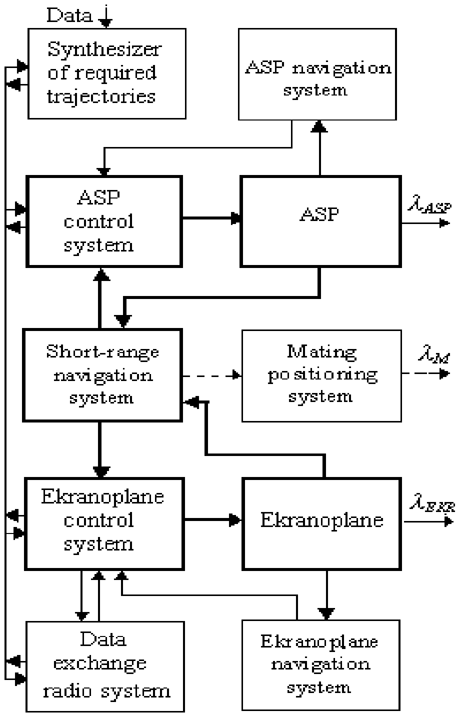


Fig. 2. Arrangement of mating elements



7. Motion control at docking

A generalized scheme of automatic control multi-dimension digital system for mutual motion control at docking is shown in Fig.3. As it follows from the diagram, the docking process of ASP and ekranoplane must be operated under motion control complex which involves closed control loops for ASP and ekranoplane absolute motion with controlled values matrices l_{ASP} and l_{EKR} consequently, relative motion closed control loop with the controlled value matrices l_{ASP} - l_{EKR} and an additional open loop channel for local shifting the docking element along and thwart landing deck with output coordinates matrix l_{M}.

The required landing trajectory of ASP is determined by synthesizer priory and described by given functional matrix l (t). The navigation system of ASP generates an estimation of an actual motion trajectory l_{ASP}(t). The residual l (t)-l_{ASP}(t) is used in control law. Optimization allows to reduce a norm of the matrix l (t)-l_{ASP} (t) and to provide the high accuracy in holding the required landing trajectory. At the final stage of approach the errors of relative positioning may be within 2-3m, and the local positioning of matting elements (especially, Fig.3. Motion control complex nose element) could reduce the errors to 30 cm.

The ekranoplane absolute motion control system has to ensure the required trajectory of its flight to the point of ASP landing, approach to this point from given direction at required time, and the capture of ASP by the shot-range optic navigation system.

8. Conclusion

1. ASP with ekranoplane assist at horizontal take-off could be competitive with vertical space launch system from aggregate functional, technological and life cycle cost viewpoint.

2. Ekranoplane with perfect control system can realize the idea of docking the stage that would allow ASP landing without gear.

3. The accurate and reliable control of relative motion at undocking and docking is the key problem of ASP-Ekranoplane integrated space system feasibility.

4. The demanded characteristics of large ekranoplane can be achieved only at use of the new capabilities of perfecting the systems of navigation and motion control on the basis of modern control theory and powerful onboard computers. The control algorithms and some hardware of automatic control systems for such vehicles differ from airborne ones and require the special

research and design. The essential difference exists also in principles of design of small and large ekranoplanes.

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