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# New design methods and results for automatically controlled WIG

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**Abstract**

Russian and international experience in Wing-In-Ground-effect vehicles (WIG-craft) and their automatic motion control systems are discussed, including advantages and drawbacks. The major problems encountered by high-speed WIG-craft amphibious transport vehicles are considered along with those relevant to other possible applications, particular in the use of large ekranoplanes for assisting aerospace planes to achieve both horizontal takeoffs and landings. Further applications include those for search and rescue missions in addition to various military missions such as the conveying of troops to beaches and possibly far from sea, depending on the relevant terrain. The required automatic control systems and their design methods are offered.

## 1. Introduction

The first construction of a WIG-craft was by Finnish engineer Tchéky Karyo in the winter of 1932. Almost concurrently, attempts to construct WIG-craft were made by Sweden's I. Troyeng, America's D. Warner and Russia's P.I. Grokhovsky. Realizations of these projects was failed because the designers faced many problems, solutions to which were unknown at the time and which would have required large-scale research.

It was only during the 1950s that a young Russian designer, R.E. Alekseev in Nizhny Novgorod, was able to organize such expensive research work and create the first really flying WIG-craft. His progressive idea involved the transference of a submerged wing from the water to the air near the water. Prior to this, at the Central Hydrofoil Design Bureau (CHDB), he had invented and put into production some very effective vessels using underwater wings. The upward force on such a weakly-submerged wing is dependent on depth and provides stability in the longitudinal plane along with speeds several times greater than those of normal water-displacing vessels. This invention and the corresponding revolutionary change in high-speed shipbuilding led to Alekseev becoming a major authority in the old USSR and hence acquiring direct access to the country's leaders.

He was therefore able to convince the Chairman of the Board of Ministers to provide significant financing and to attract many scientific and design-oriented organizations to the addressing of the many problems peculiar to WIG-craft. Alekseev subsequently led the development of vehicles using his wing-over-water technique as well as hydrofoils having self-stabilizing properties in the longitudinal plane. Thus, there were actually two revolutions in the relevant aspects of high-speed shipbuilding: stable craft using a submerged wing and wing-over-water vessels capable of much higher speeds than any water-displacing vessels.

Since 1962 more than ten different big WIG-craft have been constructed [4,7], including the largest – the 450 tonne 'KM' of 1966 (Fig.1), the landing WIG-craft 'Orlyonok' of 1979 (Fig. 2) and the missile WIG-craft 'Lun' of 1990 (Fig. 3). These unique WIG-craft were created by request of the Navy and via considerable budgetary financing. Though the accumulated experience would have allowed expansion of the list of enhanced WIG-craft projects and the production of up to tens of models, these opportunities were not realized because of the economic and ideological crisis in the USSR at the end of the 1980s and its collapse in December, 1991. New military concepts in Russia at that time did not provide for any WIG-craft construction for the Navy and the conversion to a market-driven economy did not allow the development of civil ekranoplanes for budget money reasons.

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Figure 1: WIG-craft «KM»


Figure 2: WIG-craft «Orlionok»


Figure 3: WIG-craft «Lun'»

Several features characterize the last three decades in the development of WIG-craft. Small commercial ekranoplanes have appeared in several countries, but no serious attempts have been made to develop automatic motion control systems for them. Market conditions demanded cheap vehicles and it was thought that automation equipment would significantly raise the cost of such projects. However, it gradually became clear that modern automatic controls really should be installed on commercial WIG-craft and that such systems should be developed in parallel with the creation of these WIG-craft and the proper evaluation of their aerodynamic characteristics. It is especially important to realize that vehicles even without an inherent margin of stability could be considered acceptable given their high aerodynamic qualities and minimal fuel consumption. That is, the flight stability can be entrusted entirely to an automatic control system provided that its reliability and fail-safe characteristics can be guaranteed.
Autopilot costs for the small-scale production of small WIG-craft have been estimated [9,10] at approximately 70 to 100 thousand dollars and this amount only slightly increases with increasing vehicle weight, mainly due to more advanced modern power drives. The 'fair' cost of an easy-to-build 6-8-seater WIG-craft is 250-400 thousand dollars, which currently makes it financially impossible to include the required autopilot in its equipment. Therefore, the installation of autopilots and other means of control automation remain justified only for large WIG-craft, but with technical and cost-reduction improvements, they will begin to be used in all WIG-vehicles.

## 2. General advantages and disadvantages of ekranoplanes

General Advantages of ekranoplanes are listed below:
- runway is not necessary;
- high safety of flight due to possibility of urgent ditching;
- reduced requirements to engines reliability and possibility of their service life fuller use;

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- tight cabin and special life-support systems for crew and passengers are not necessary;
- ability to carry a freight of great mass and dimensions;
- high transport profitability on midranges (about 1000 km) in matching with aircraft because of absence of energy consumption for rise on a high altitude;
- cost of construction, maintenance and exploitation below aviation.

The main disadvantage of ekranoplane consists in the impossibility of movement near a highly waved sea or rough terrestrial surface. However, even in these conditions, a short-term flight at high altitude is possible (as by plane). It is not easy also to provide the vehicle longitudinal stability. However, an acceptable stability margin can certainly be provided by means of automatic control, which must necessarily be installed on modern WIG-craft [6-13,19].
Let us indicate the areas of the most effective application of heavy ekranoplane.

1) Patrol Vehicles for anti-drugs and anti-smuggling, anti-pirate operations in the Peninsular and coastal regions where ships, hydrofoil vehicles and helicopters are too slow.
2) Transport operations unobserved for radar tracking stations.
3) Integration of Air-Force and Navy for the creation of defense potential.
4) Defense of small islands without aerodromes, especially in the southernmost part of India.
5) Very fast transport of troops and defense armaments connecting many major.
6) Patrol Vehicles for anti-drugs and anti-smuggling, anti-pirate operations in the Peninsular and fast transport (passenger and cargo) routes along the coast or between the islands.
7) Cross-country transport routs above desert, water, ice, snow and any other flat surface (including artificial profiles);
8) Transportation of fruits and other perishable goods from far islands without aerodromes.
9) Transport service for fishers fleet and scoastal regions where ships, hydrofoil or hovercraft vehicles and helicopters are too slow.

Fligh over land introduces several different problems, notably that the surface must be reasonably smooth. For example, if an isthmus contains such a flat area, it is possible for an ekranoplane to traverse that isthmus with considerable savings in time and cost because neither air-strips for conventional aircraft nor port facilities for ships are necessary. Similarly, the traversing of desert, tundra and steppe areas is made possible, which highlights opportunities for the civilian use of WIG-craft for opening new transport routes that are not available for either aircraft or ships. Such considerations may well outweigh the costs of extra engine power for take-off, with the concomitant extra fuel usage and limited payload capacity.
It is necessary to make sure that a WIG-craft trajectory does not coincide at any point with routes traversed by any land vehicles because avoidance is difficult having regard to the wide turning radii needed by ekranoplanes, even if radar collision warnings are available. Such routes must always accommodate these large turning radii because WIG-craft operating over land cannot bank significantly. Analogous restrictions are also valid for water-based operations and for both, turning using only rudder movement always leads to outwards skidding, which is uncomfortable for passengers.
Another important advantage of WIG-craft is their effectiveness in search and rescue operations at sea. A WIG-craft can not only arrive quickly at the scene of an accident, but can also allow the prompt rescue of people in the water. Unlike vessels with high shipboards, a WIG-craft with its wing lying on the water surface can receive rescued people without delay, whereas an aircraft cannot usually land in the immediate vicinity of the disaster zone at all and so is limited to dumping life-rafts – and not always with the required accuracy. Hence, it is not by chance that among the few real WIG-craft under consideration in Russia, two of them have the name ‘Rescuer’, taken from a 1991 ekranoplane. There is also a recently announced project for a universal ekranoplane platform that can accept superstructures suitable for most purposes including search and rescue, wherein all medical supplies, stretchers, beds and possibly facilities for urgent operations are carried. Clearly, the capabilities of the Russian Ministry of Emergency Situations would be significantly expanded with the appearance of such vehicles [13], as would similar organizations in other countries.

## 3. Special applications of WIG-craft.

It is perhaps inevitable that some of the major characteristics of WIG-craft should suggest that they could be used for military purposes as in the following two examples.
Firstly, it is tempting to employ amphibious WIG-craft to convey troops and their equipment from sea to shore complete with their armor and without the risk of damage by mines. High speed and very quick unloading directly on to the shore are seen as significant advantages over water displacement landing craft. Furthermore, in certain cases the WIG-craft may traverse the terrain for some considerable distance from the landing point before unloading. Indeed, the Boeing Pelican-Ultra was considered for intercontinental distances but would have faced competition from heavy aircraft for which a network of airports already existed.
Secondly, WIG-craft as anti-ship missile-carrying vehicles have been considered and the Russian 380 tonne ‘Lun’ was flight-tested in this role. The prime advantages here are that the relatively high speed and low radar visibility compared with surface ships makes early detection difficult and so allows a closer approach to the target [1-3, 15, 17]. In particular, the low radar visibility of WIG-craft on a background of rough seas is regarded as providing some degree of stealth movement. However, this advantage may be negated by the use of surface-monitoring satellites, especially

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when Doppler-based filtering is employed. Even so, the transfer of WIG-craft tracking data from satellite to ground, or to another command post, will always result in a time-lag from any located point on the actual WIG-craft trajectory.
Though WIG-craft tracking is more difficult than for aircraft, the latter retains the advantage of much greater speed. Nevertheless, the unanimous opinion expressed by Russian ministers and naval representatives in recent statements is that the comparative radar stealth inherent in low-altitude ekranoplane flight is a major advantage that makes it worth supporting the revival of large military ekranoplane construction. The following statements lend credence to the validity of such a conclusion [13, 15, 16]:

1. At the MAKS-2015 air show, Igor Kozhin, head of naval aviation in the Russian navy, said that the fleet expects to receive a universal platform for transport WIG-craft with payloads of up to 300 tons. Later, Georgy Antsev, chairman of the board of directors of the CHDB, informed the TASS Russian News Agency that the development of a promising universal ekranoplane is in the interests of the Russian Defense Ministry and is at the stage of preliminary design.
2. “The Russian Defense Ministry (RDM), within the framework of the State Armaments Program - 2027 (GPV-2027), is developing a missile-carrying ekranoplane”, said Denis Manturov, Minister of Industry and Trade at the international exhibition “Gidroaviasalon-2018”. He also said that the plan is to use ekranoplanes to patrol the Black and Caspian Seas and for protecting the Northern Sea Route.
3. In late July, Deputy Prime Minister Yuri Borisov said that by 2027 Russia should have constructed a prototype Orlan WIG-craft. Also according to Borisov, WIG-craft can be used both for protection and patrol, as well as for crew rescue purposes [1-3, 17,18].

In recent years, the vast territories of the Arctic have attracted increasing attention by many countries as providing potential transport routes, in particular the Northern Sea Route where the use of energetically-disadvantageous ice-breakers is currently necessary. Also, the many mineral resources found in these areas have not gone unnoticed. For much of the year the Arctic is covered with ice, in parts without large hummocks, which potentially makes it viable for WIG-craft flight, as does the adjacent tundra. However, as long as there is no experience of flight over high hummocks, this problem requires special study.
Ekranoplane capabilities of flight over sea, land and snow make their usage almost obligatory over such regions, helicopters and hovercraft being their only competitors, so both civil and military WIG-craft technology is now being taken seriously again in many countries.
However, hovercraft do suffer disadvantages similar to those of ekranoplanes and in particular need even larger turning radius since banking is not really possible at all.
The “dead season” for big ekranoplanes development in Russia existed 20 years. The radical turn in assessment of importance of further development of WIG-craft-making industry began to be shown especially in 2018. Several Russian ministers confirmed intention of Russia to construct a new heavy WIG-craft till 2027. This vehicle will use the advanced achievements in the modern aero- and hydro-dynamics and automatic control.
The reason for the change in the state evaluation of the utility of ekranoplanes was the following:

- the need to accelerate the development of Siberian and Far Eastern regions of Russia with poor transport infrastructure;
- transport support of the Arctic settlements, patrolling the areas adjacent to the Northern Sea Route;
- advantages in the fight against aircraft carriers, associated with low radar visibility and convenience of placing on board the missile weapons.

Features of the design of ekranoplanes and their automatic motion control systems, able to meet the requirements, will be described in detail in the presentation.
The peculiarities of ekranoplane and its autopilot construction for different kinds of application will be discussed.

## 4. Achievements and difficulties during the revival of Russian WIG-craft technologies

As already mentioned, in the twenty years of active work on the development of large WIG-craft from 1970 to 1990, the Alekseev CHDB and its partners had made significant progress and become the undisputed leaders in global WIG-craft design and manufacture. However, the next 20-25 years saw a period of stagnation resulting from the loss of funding from the Russian Navy and from market mechanisms failing to finance the construction of further large WIG-craft. Furthermore, little progress was made on small WIG-craft either.
Given this understanding, responsible specialists in the Navy have become less critical in assessing the shortcomings of WIG-craft and hence will now allow for the possibility of some budget funding for new research and development based on old practical achievements and new scientific results [1-3]. The consequence of a complete lack of budget financing for further work would be the loss of Russian leadership in the field, whereas effective ekranoplanes in other countries will undoubtedly appear. In fact, all informed sources claim that significant numbers of experimental WIG-craft will be created up to 2027, with the medium-sized A-050 of load capacity 9 tonnes completed by 2022.
The main ideologist and generator of these plans in Russia is now Dr. G.V.Antsev, the General Designer of JSC Concern ‘Morinformsystem-Agat’, who is also the General Director/General Designer for the Agat JSC ‘Scientific-Production Enterprise - Radar mms’ in St. Petersburg. In addition, Antsev is the General Designer at the Alekseev CHDB. In view of such a combination of important positions, Antsev must be regarded as a key person in reviving the Russian WIG-craft industry. ‘Radar mms’ and the CHDB have announced a strategic partnership and all the resources of these Antsev-connected companies, along with Concern ‘Agat’, are now involved in the design of new WIG-craft. Hence, the allocation of budget financing is now highly likely.

However, the guarantees of a successful administrator and government money easier to allocate to investment is not enough. Actually, there are currently no such influential figures within the CHDB so it relies completely on cooperation with "Radar mms", which now holds 51% of its shares and makes significant investments in the venture. Thus, the actual building of a large WIG-craft is now clearly within the remit of the CHDB, as it was 50 years ago. However, the revival of a WIG-craft manufacturing industry needs not only a strong designer, but also a corresponding production organization. Previously, this role was performed by an experienced shipyard, 'Volga', with which co-operation was established in 1970 at the CHDB and their team co-located with it. Volga designed and developed the unique construction technology for the Orlyonok and Lun WIG-craft.

At present, production links between the Volga plant and the CHDB are not very close. In 1992, the enterprise was transformed into an open joint-stock company 'Shipbuilding Plant Volga', which now has orders unrelated to WIG-craft. Hence, it will not be easy to interest this company in the revival of WIG-craft, especially after the epic debacle with the last WIG-craft «Spasatel» which had undergone several decades of development and construction as far as 90% readiness for launch - but the necessary funding for completion and testing did not become available, and «Spasatel» was ultimately destroyed. If a new experimental «Spasatel» is no smaller than Lun, then such a large vehicle would require the full attention of Volga or a search for another construction site would be needed, possibly at St. Petersburg Enterprises (which is adjacent to Radar mms). Such a restructuring of relations would take time and organizational effort so it is not by chance that the new plans include a nearly ten-year term for the construction of a new Spasatel.

There is also a hint that a new application for large WIG-craft has been found that may stimulate the rapid creation of a new ekranoplane with a wide range of uses [18,19] and in any case, to create an effective modern WIG-craft, wide application is possible only with successful conclusions to the following tasks and requirements.

1) It would be necessary to develop a perfect WIG-craft aero-hydrodynamic scheme for the fulfillment of requirements that ensure high aerodynamic quality in all permissible flight modes plus acceptable seaworthiness when moving in a water displacement mode. That is, the ekranoplane must be a true amphibian.

2) The design and realization of high-power turbojet and turboprop engines capable of operating economically and for long periods near a water surface in air containing salt water inclusions, is mandatory.

3) The creation of high-precision altitude sensors for flight over water, such as radio, laser, X-ray or PMD devices, is required. Allowable errors would be around 3cm, so current aviation sensors for small altitudes would not be not suitable. It would also be advisable to track the profile of waves over the relevant part of the three-dimensional wave surface.

4) It would also be necessary to create an automatic control system that could cope with the expected movements of a WIG-craft. That is, it must be capable of automating and optimizing cruising modes for movement near surfaces with different geometric properties and also for maneuvering in the longitudinal and lateral planes without the risk of losing flight stability. Coordinated turning should be performed with minimum roll and preferably with almost no increase in altitude.

5) Solving the problem of preventing collisions of a WIG-craft with moving and fixed obstacles is obviously necessary and this implies the timely detection and tracking of such obstacles followed by quick decision-making and the application of avoidance maneuvers in both the horizontal and vertical planes.

6) It is vital to provide full automation and optimization for take-off from rough sea surfaces with extremely high wave heights along with the lowest possible total engine power to overcome the hydrodynamic "hump" resistance. In fact, the take-off mode determines the seaworthiness of a WIG-craft since cruising flight is possible with a higher sea swell than during takeoff.

7) The formatting and construction of special displays for presenting all the necessary flight and navigational information, taking into account the various flight characteristics of WIG-craft, are important endeavors. These will also require the development of new techniques in pilot training for WIG-craft, stressing unerring actions in normal and emergency modes in the air, on the water or on a hard surface. Preliminary investigations into such tasks have already been made [5–13, 19].

## 5. The flight control system of the ground effect vehicle in the area of the screen effect

Simulation of the ground effect vehicles flight over the water surface was carried out using a program developed for the following flight modes:

- flight at a constant altitude was modeled at different speeds at different heights of waves of the water surface and various models of error meters, the choice of economical flight mode on the screen;
- the jump is performed at different heights, taking into account the dynamics of the airplane, restrictions on engine thrust and steering gears;
- movement at an increased altitude outside the screen is performed with a vertical circle around obstacles;
- landing on the screen;
- the implementation of a coordinated reversal was carried out at an extremely small allowable altitude, it is necessary to justify the choice of this value.

The results of the simulation of ground effect vehicles presented in the form of graphs and tables for all flight modes.

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In the process of performing work using the finite-dimensional analysis software system Comsol a computing environment was developed that makes it possible to simulate the process of real experiments in a wind tunnel for low-flying WIG-craft of various designs.
The model was obtained using the latest 2018 Comsol toolboxes. Its reliability was verified by comparing the dynamic properties of a well-known simplified model obtained for one of the flight modes according to the results of experiments and the modern model obtained by modeling for the same flight mode. The linear equations of an ekranoplane were taken in the form:

$$\begin{aligned} \dot{v} &= -l_1 v - l_2\alpha - l_3\delta_в - l_4\Theta - l_5 h + f_x, \\ \dot{\Theta} &= a_4\alpha + a_5\delta_в + a_6\Theta + a_7 v - a_8 h + f_y, \\ \ddot{\vartheta} &= a_2\alpha + a_3\delta_в + a_0\Theta + a_7 v + a_9 h + f_{mz}, \\ \dot{h} &= V_0\Theta \\ \alpha &= \vartheta - \theta. \end{aligned} \quad \textbf{(1)}$$

Here $v$ is flight speed variation, i.e. $v = V - V_0$, where $V$ is the total velocity, $V_0$ is the reference velocity relative to which linearization is performed. $\alpha$ - variation of the angle of attack; $\delta_в$ - variation of the elevator deflection; $\Theta$ - variation of the trajectory angle; $h$ is variation of altitude; reduced to the mass of the vehicle projection of external forces on the vector of air speed (axis 0x), $f_x = \frac{F_x}{m}$; $\vartheta$ is variation of the pitch angle. The y axis is directed upward (more precisely perpendicular to the speed), z is directed on the right wing.
$l_i$ , $a_i$ - coefficients calculated for the reference modes. These coefficients are stored in arrays of numbers. After regression analysis, these coefficients become smooth functions. As an example

$$l_1 = \frac{X^V(h,V)}{m} \; . \quad \textbf{(2)}$$

For the study of the dynamic properties of the simplified model and the stabilization system, a program was drawn up on the basis of this model, the block diagram of which is shown in Fig. 4 and 5 in the Matlab / Simulink language.

A special feature of an ekranoplane is that with longitudinal motion control, the flaps are actively used along with the rudder of altitude, which effectively increase the lift force, but create additional drag. For this reason, during thrusts, the engine thrust vector control is used due to engine rotation.
When flying in the area of the ground effect the altitude of flight has a significant impact on the movement of an ekranoplane, which determines the lifting force and the moment of forces. These factors affect the dynamic properties of the ground effect vehicle and its stability.

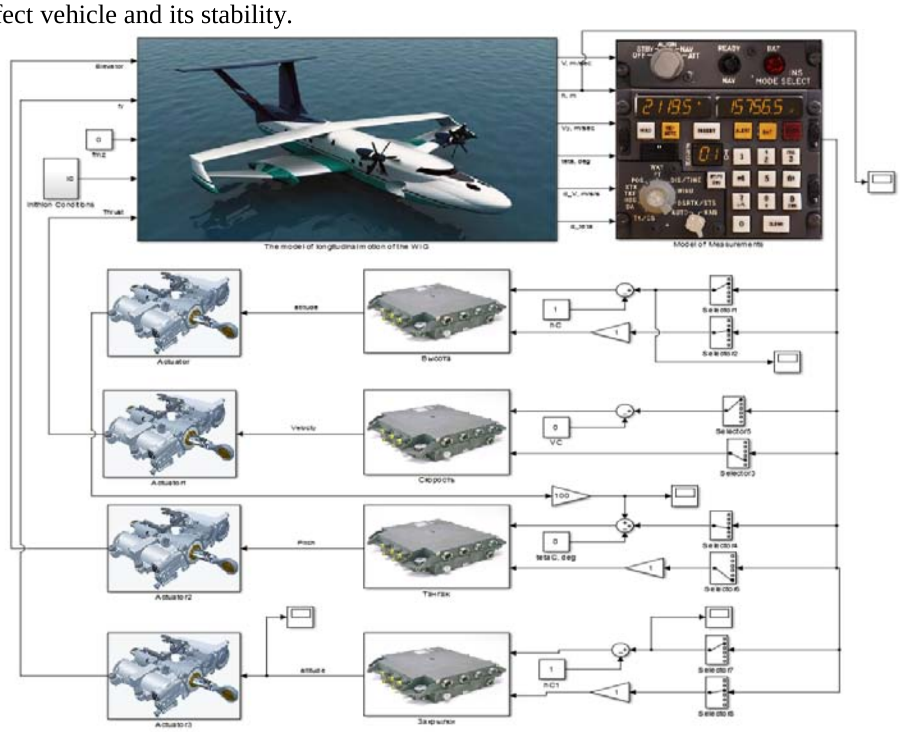


Figure 4: Block diagram of the stabilization system of the ekranoplane angular motion, its altitude and speed when flying in the area of the ground effect

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In Figure 5, a model of an ekranoplane is shown, which is used in the scheme of the stabilization system. PID controllers for each channel are implemented in computing devices. The parameters of these regulators are obtained by the method of parametric optimization using the appropriate programs built into Matlab.
In the process of modeling, the strong dependence of the dynamic properties of the ground effect vehicle on the proximity of the surface and the essential relationship of the angular motion and the center of mass motion were confirmed. This determines the need to focus on the development of robust or adaptive nonlinear control systems.
Figures 6 and 7 show the simulation results confirming this. In addition, it was found that the use of simple PID regulators does not allow obtaining classical transients with overshoot of several percent.

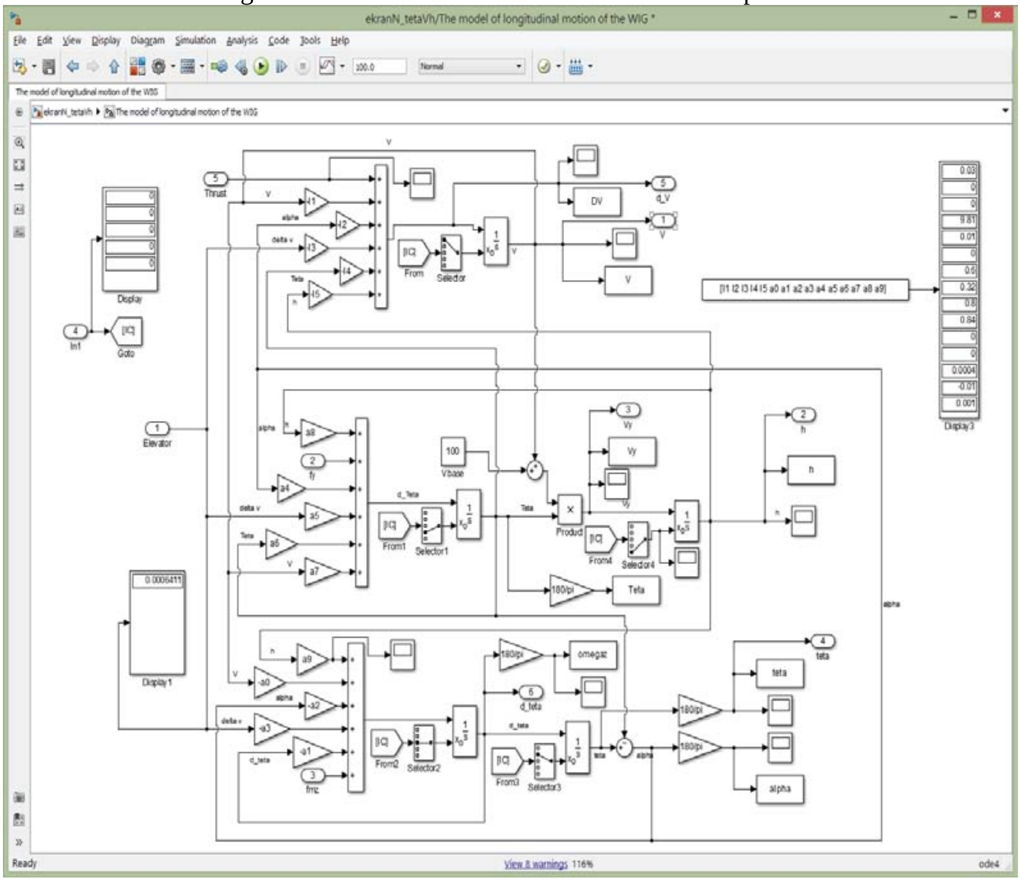

Figure 5: Program for modeling the longitudinal movement of a ground-effect vehicle when flying in the area of the ground effect

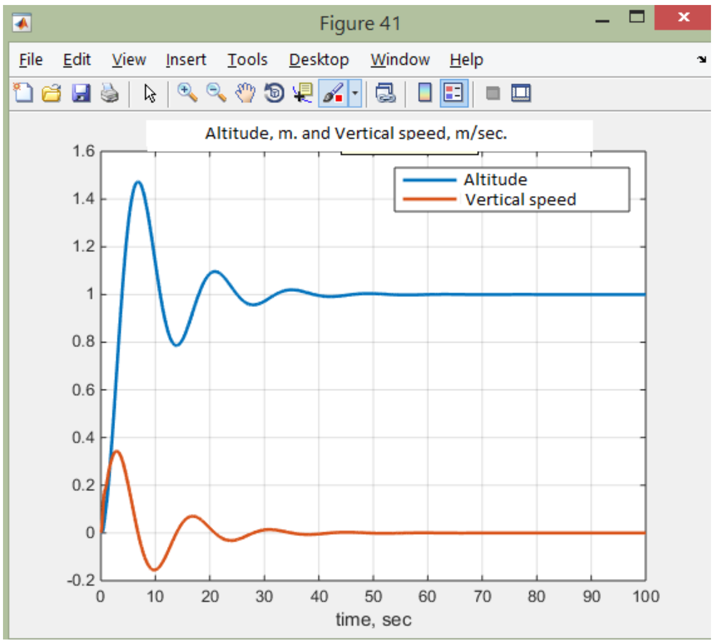


Figure 6: Processes of changing the altitude (blue) and vertical speed (orange) when “jumping” at 1 m

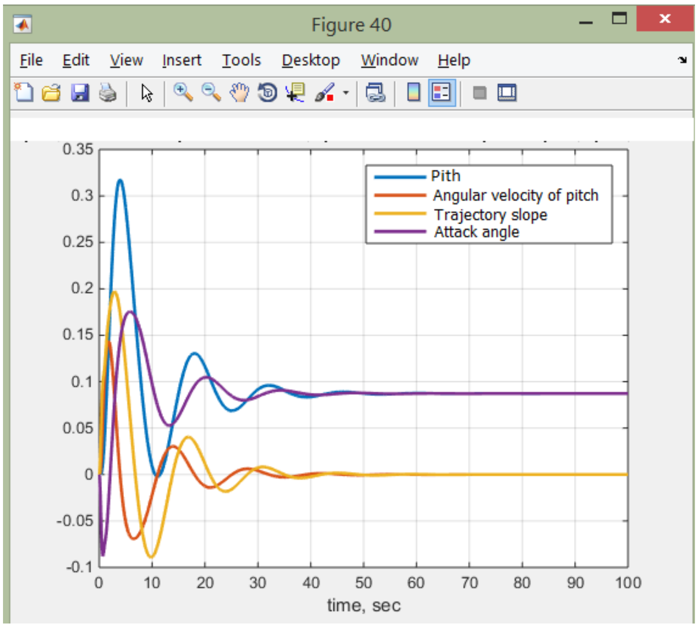


Figure 7: Processes of change in the angular parameters of motion with a "jump" at 1m: pitch (blue), angular velocity of pitch (orange), trajectory slope (yellow), attack angle (purple)

## 6. Analysis of the results of ekranoplane equations linearization for different flight modes

An analysis of the non-linear model of a ground-effect vehicle showed a significant dependence of its dynamic properties on the altitude and speed of flight. In some areas, the ground effect vehicle lost its own stability. Obtained with "virtual" blow-downs, the data sets after smoothing using regression analysis methods were used to obtain linear models in the vicinity of balancing points. Balancing points were calculated for various combinations of flight speed and altitude. All other parameters, such as the angles of installation of the elevator, engine thrust, its angle of rotation, pitch angle, angle of attack, etc., were calculated from the condition of the balance of forces and torques acting on the ekranoplane. To calculate the balancing parameters, a special algorithm and program were developed. Under the assumption of small deviations (variations) of the parameters, the corresponding linear mathematical models of WIG-craft are calculated. For 16 values of altitude and 16 values of speed, using the Matlab program, we obtained 256 multidimensional models in the state space were obtaind. Each of these models is presented in the form of structures in the Matlab format.
Sample data were obtained for the balancing values of the pitch angle, engine thrust, its installation angle, flap deflection angle and elevator.
Table 1, as an example, shows the mathematical models of ground effect vehicles for a single cell with a number (5.5) in the array of structures in the form of transfer functions format for one input action "Elevator" and ten outputs. Such mathematical models are obtained for all other input actions and are stored in the same structural cell.
The resulting models are used to synthesize the laws of ekranoplane control in all flight modes, climb and change speed.

Table 1: Transfer functions for speed $V$ = 90.7 m / c and altitude $H$ = 6.3 m

| Input-output | Transfer function |
|---|---|
| elevator<br>pitch | theta: $\dfrac{-0.097\ s^3 - 0.004195\ s^2 - 0.04532\ s - 0.001117}{s^5 + 0.05322\ s^4 + 0.368\ s^3 + 0.01438\ s^2 - 2.036\ s + 0.02306}$ |
| elevator<br>Angular velocity for pitch | q: $\dfrac{-0.097\ s^4 - 0.004195\ s^3 - 0.04532\ s^2 - 0.001117\ s}{s^5 + 0.05322\ s^4 + 0.368\ s^3 + 0.01438\ s^2 - 2.036\ s + 0.02306}$ |
| elevator – | $-0.006239\ s^4 - 0.01666\ s^3 + 0.8273\ s^2 + 0.4513\ s + 0.3623$ |

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| | |
|---|---|
| distance | Xe: ------------------------------------------------------------<br>$s^6 + 0.05322\ s^5 + 0.368\ s^4 + 0.01438\ s^3 - 2.036\ s^2 + 0.02306\ s$ |
| elevator – altitude | $-0.1556\ s^3 - 0.004502\ s^2 + 4.128\ s - 0.04957$<br>Ze: ------------------------------------------------------------<br>$S^5 + 0.05322\ s^4 + 0.368\ s^3 + 0.01438\ s^2 - 2.036\ s + 0.02306$ |
| elevator – velocity | $-0.007699\ s^4 - 0.0167\ s^3 + 0.866\ s^2 + 0.4508\ s + 0.3623$<br>U: ------------------------------------------------------------<br>$s^5 + 0.05322\ s^4 + 0.368\ s^3 + 0.01438\ s^2 - 2.036\ s + 0.02306$ |
| elevator– vertical velocity | $-0.1555\ s^4 - 0.004346\ s^3 + 4.121\ s^2 - 0.05381\ s - 0.0034$<br>w: ------------------------------------------------------------<br>$s^5 + 0.05322\ s^4 + 0.368\ s^3 + 0.01438\ s^2 - 2.036\ s + 0.02306$ |
| elevator – longitudinal acceleration | $-0.007699\ s^5 - 0.0167\ s^4 + 0.866\ s^3 + 0.4508\ s^2 + 0.3623\ s - 8.423e{-18}$<br>Ax: ------------------------------------------------------------<br>$s^5 + 0.05322\ s^4 + 0.368\ s^3 + 0.01438\ s^2 - 2.036\ s + 0.02306$ |
| elevator – vertical acceleration | $-0.1555\ s^5 - 0.004346\ s^4 + 4.121\ s^3 - 0.05381\ s^2 - 0.0034\ s - 2.11e{-17}$<br>Az: ------------------------------------------------------------<br>$S^5 + 0.05322\ s^4 + 0.368\ s^3 + 0.01438\ s^2 - 2.036\ s + 0.02306$ |
| elevator – traveling speed | $-0.006239\ s^4 - 0.01666\ s^3 + 0.8273\ s^2 + 0.4513\ s + 0.3623$<br>Vxe: ------------------------------------------------------------<br>$s^5 + 0.05322\ s^4 + 0.368\ s^3 + 0.01438\ s^2 - 2.036\ s + 0.02306$ |
| elevator – vertical velocity | $0.1556\ s^4 + 0.004502\ s^3 - 4.128\ s^2 + 0.04957\ s + 7.238e{-18}$<br>Vze: ------------------------------------------------------------<br>$s^5 + 0.05322\ s^4 + 0.368\ s^3 + 0.01438\ s^2 - 2.036\ s + 0.02306$ |

The results vividly illustrate a significant change in the dynamic characteristics of a ground effect vehicle during acceleration, deceleration, ascent and decrease in the range of ground effect. The results obtained determine the need to use special control control algorithms for ekranoplane that take into account these changes. These can be robust, adaptive, or algorithms with variable coefficients depending on altitude and flight speed.

Since the used model of ekranoplane is complex, multiply connected, and its parameters after linearization depend significantly on the flight mode, the task of synthesizing the control system is solved in two stages. At the first stage, the problem of stabilization of the initial flight mode is solved. At the second stage, the problem of changing this mode is solved, i.e. control task.
A program is used to synthesize the stabilization system of a ground-winged vehicle. The basis of the program is the above-described mathematical model of a ground-effect vehicle, built-in to the block “Model of an ekranoplane for 256 flight modes.”
The analysis of the model showed a strong dependence of its dependence on speed and height above the screen, it is proposed to design a robust stabilization system that ensures an acceptable quality of regulation at all stages of flight. For this purpose, a parametric synthesis of the optimal parameters of the control loops is made for each flight mode and averaged values are selected that satisfy the goal. Parametric synthesis is carried out using software built into

Matlab. Since the chosen approach involves repeated modeling and analysis of a large number of transients, only the final results of the synthesis of control laws are given below.

As a result of the experiments described, large preliminary databases were obtained in the form of multidimensional arrays. To use them in WIG-craft models, it was decided to approximate them and interpolate using regression analysis methods of third-degree polynomials. These operations were carried out using the Matlab program. A procedure has been developed for creating a non-linear multiply-connected mathematical model of a ground-effect vehicle in the form of a system of continuous differential equations. A corresponding program was drawn up to automate the output of such a model.

A methodology, algorithm and programs were developed for balancing a dynamic object at an arbitrary altitude and speed. Obtaining a mathematical model for balancing points was carried out in two stages. At the first stage, an approximate calculation was performed using general experimental data, and at the second stage, additional calculations were performed with a smaller grid. As a result, the most reliable mathematical models were obtained for all control points in a wide range of parameters.

For given values of the angle of flaps rotation in the permissible range with a constant pitch and with the elevator in a neutral position, the problem of minimizing the forces acting on the vehicle was solved. The controlled variables in the mathematical programming problem were three parameters — the angle of attack, the speed of thrust (the speed of gas jets flowing from the nozzles of jet engines), and the angle of inclination of the thrust.

When the condition of equality to zero of the sum of the forces acting on the vehicle (aerodynamic, engine thrust, gravity) was fulfilled, the controlled variables were minimized. The exclusion of the arising moment of forces acting on the vehicle was achieved by calculating the corresponding position of the center of gravity.

For each flap position, the surface of the center of gravity position in the optimization problem was determined on the maximum area of the parameters of airspeed and flight altitude.

The found optimal position of the center of gravity, the longitudinal coordinate in the building coordinate system, corresponds to the cross section of the horizontal plane of all surfaces corresponding to the position of the center of gravity, and provides maximum coverage over the area. The found position of the center of gravity is used to solve the problem of finding the position of the flaps, the angle of inclination of the thrust and the speed of thrust with more severe restrictions. It is required that the condition of equality of zero not only forces, but also torques. The optimization problem also takes into account the requirements for the boundary values of the controlled variables. The solution is sought for all valid values of the angle of rotation of the flaps. Obviously, the solution will be optimal with a minimum flap deviation, and greater freedom in the implementation of control is provided by the flap deviation in the center of the allowable flap rotation range corresponding to the selected speed and altitude values.

The developed algorithm can be used not only to solve the problem of balancing at zero forces and torques, but also to determine the optimal control of small increments of forces and torques using the controls listed above. The results of the calculation of the aerodynamic parameters of the model and control parameters corresponding to the balancing and small increments of forces and torques are presented in the form of multidimensional numerical arrays and are used for the analysis and synthesis of the control system.

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## 8. Conclusion

This article analyzes the circumstances surrounding the possible resumption of development and production of large WIG-craft in Russia and with the support of the State. A review of the largely positive statements by the Russian Industry and Trade Minister, Denis Manturov and other responsible experts on this issue are stressed. Three years ago, the Russian press said the opposite and criticized inappropriate public funding for the development of large new WIG-craft in which, allegedly, no-one was interested. However, the position of the Ministry of Defense has clearly changed and there is demand for Soviet developments in WIG-craft useful for both military purposes and for year-round transport in the Arctic and other hard-to-reach areas of Russia. In addition, it has to be reported that a role was played by the strengthening of patriotic sentiments in Russian society and calls for the development of domestic innovations providing effective asymmetric responses to the growing arms race in the world. As mentioned above, the task is to develop an "experimental WIG-craft-type transport platform", but initially for an ekranoplane with a take-off weight of 600 tonnes by 2027, followed by even heavier vehicles.

The original approach to the design of automatic motion control systems was offered. It is based on the Comsol application for ekranoplane dynamics simulation and control laws optimization.

## References

[1] Ivanov, V. 2018. Development of a promising ekranoplane has begun in Russia. https://tvzvezda.ru/news/opk/content/201809081315-xccm.html. Accepted: 08 Sept 2018

[2] Manturov. 2018. Told about the development of a ground-effect vehicle with rocket armament. https://www.rbc.ru/rbcfreenews/5b93d5179a79478c7c685864. Accepted: 08 Sept 2018.

DOI: 10.13009/EUCASS2019-174

[3] Manturov. 2018. The Ministry of Defense of the Russian Federation is developing a rocket ekranoplane. (https://regnum.ru/news/2478027.html. Accepted: 08 Sept 2018
[4] Wikipedia. 2002. The Boeing Pelican ULTRA (Ultra Large Transport Aircraft) was a proposed ground effect fixed-wing aircraft under study by Boeing Phantom Works.
[5] Cole, W. 2002. The Prelican: a big bird for the long haul. Boeing Frontiers online. O1, Issue 05.
[6] Tomita, N., A.V. Nebylov et al. 1999. Performance and Technological Feasibility of Rocket Powered HTHL-STO with Take-off Assist. Acta Astronautica, Volume 45, No.10: 629-637.
[7] Nebylov A.V., P. A. Wilson. 2001. Ekranoplane - Controlled Flight Close to the Sea. WIT-press, Southampton, UK.
[8] Nebylov, Alexander and Vladimir Nebylov. 2018. Metrology problems of WIG-craft motion control. In: *5th International Workshop of Metrology in Aerospace (MetroAeroSpace)*
[9] Nebylov A.V. and V.A. Nebylov. 2013. Russian ekranoplanes: new perspectives in international cooperation. '*Russian engineer*'. No. 4: 33-36.
[10] Nebylov A.V. 2011. Problems and methods of autopilot synthesis of a ground-effect vehicle. *Aerospace instrumentation*. No. 2: 15-22.
[11 Nebylov A.V. ed. 2013. Aerospace Sensors. Momentum Press. New York, USA.
[12] Nebylov A.V. and V.A. Nebylov. 2009. Wing-in-the-Ground Effects for Vehicles. *EUCASS Association*: 1-10.
Nebylov A.V and J. Watson ed. 2016. Aerospace Navigation Systems. John Wiley & Sons,Ltd.
[13] Pereyaslov, A. N., ets. 2012. The conceptual guidelines for the use of ecranoplanes in EMERCOM of Russia. *Civil Security Technology*. Vol.9, №2 (32): 78-84.
[14] Patil, V. 2018. Russia To Develop Orlan Wing-In Ground Effect Craft Armed With Missiles. http://www.defenseworld.net/news/23087. Accepted: 30 July 2018.
[15] A prototype of ekranoplane with rocket armament will be created in Russia until 2027. https://tass.ru/armiya-i-opk/5412967. Accepted: 30 July 2018.
[16] Nebylov, A.V., E.A. Aframeev, N.P. Savichenko, N. Tomita, Y. Yoshida. 2000. Ekranoplane as Take off and Landing Assist In: *6th Intern. Symposium on Marine Engineering. The Marine Engineering Society of Japan*: 744-750
[17] Polyakov, A. 2017. Ekranoplane returns. https://inosmi.ru/social/20171117/240785601.html. Accepted: 30 July 2018.
[18] Ganin, S. M. 2014. The creation of ekranoplans: from the last century to the present day. "*Transport of the Russian Federation*", No. 6 (55): 54-59
[19] Nebylov, A. V. 2004. Ensuring Control Accuracy. Springer.