WIG-Craft Flight Control Systems Development

Alexander Nebylov
State University of Aerospace Instrumentation,
67, Bolshaya Morskaya str., Saint-Petersburg, 190000, Russia
E-mail: nebylov@aanet.ru, Fax.+7 812 4947018

Abstract
The modern means of motion control automation has become applicable for Wing-in-Ground effect vehicles (WIG-craft) presently. The aim of such technologies development is to improve the operational performance of the vehicles of advanced design. The primary sensors and measuring systems for operation at low altitudes were designed to increase the accuracy of control and to provide the fault-tolerance properties. Methods of stability provision and solving other problems of WIG flight by means of automatic control are analyzed in this paper[1]. The experience and achievements in this field of high technology are described.

1. Introduction

Aviation, as well as maritime transport, do not use pre-built roads and allows for an infinite number of trajectories. This circumstance brings together aviation and marine transport modes. But the difference between them is very significant: aviation is the fastest kind of transport, and marine vessels - most low-speed, but have a number of other benefits. In the development of both modes of transport had the idea to pool their strengths by construction of WIG-craft capable to achieve an aircraft speed when moving in the vicinity of the sea surface. WIG-craft or Ekranoplane as it is called in Russia could take the significant part of the projected air traffic growth.

The first generation of heavy Ekranoplanes was created under the order of Russian Navy. The numerous changes appeared presently in the concepts of WIG-craft design and application.

WIG-craft or ekranoplane or ground effect vehicle may be considered as a flying vehicle with special structural features providing low altitude flight possibility when using wing-in-ground effect (WIG-effect). This effect consists in substantial wing lift force increase and air drag decrease when moving close to the supporting surface. In this case air compaction action in the space between wing and supporting surface is added to normal mechanism of lift force formation due to different speeds of air flow about upper and lower wing surfaces.

In order to make the full use of the WIG-effect and to provide high functional characteristics of ekranoplanes as transport vehicles they usually have the following features that distinguish them from aeroplanes:

- wide wing with small aspect ratio that is relatively low attached to the body, or flying wing configuration (Fig.1,2);
- boundary plates on wings that enhance wing aerodynamics when moving close to the supporting surface, often - float plates;
- developed tail assembly, high fin (or several fins) with rudder, horizontal stabilizer with elevator attached to the fin at the utmost height;
- hydrodynamically clean body with the bottom of increased strength;
- special equipment to expedite taking off from the water and water landing; etc.

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Figure.1 Ekranoplane Orlyonok

Figure.2. Korean WiG-craft WSH-1500 [11]

The important advantages of ekranoplanes are [2,3,6-8,10-12]:
- potentially higher safety of flight due to possibility of urgent ditching;
- reduced requirements to engines operation reliability and, therefore, possibility of their service life fuller use;
- absence of necessity for runway and possibility to perform special transport operations using amphibian property (ekranoplanes can fly, float on water and creep out to the shore);
- absence of necessity for tight cabin and special life-support systems for crew and passengers;
- possibility to achieve higher level of comfort for passengers.

WIG-effect vehicles occupy the specific place among the winged means of transportation. Flight straight above or in close vicinity to the underlying surface gives a lot of specific features to these machines, most of which are valuable for effective transportation. But flight control in WIG mode is more complex and difficult against control of free flight due to dependence of all aerodynamic indexes on the flight altitude. Methods of stability provision and solving other problems of WIG flight by means of automatic control are analyzed in [1,2,10,11].

Trouble-free motion close to disturbed sea surface may be guaranteed by the application of special methods and means of navigation and control, which have capability to solve such specific problems as:
- ensuring of the vehicle stability in the circumstances of action of flake non-linear aerodynamic effects attributed to nearness of surface;
- precise control of the altitude of motion with the error not above 3-10 cm;
- restriction the angles of airframe inclination for the preventing of undesirable tangency of water by the extreme points of body or wing;
- non-contact measurement, tracking and prediction of ordinates and biases of sea waves for rising of motion control effectiveness.

2. The criteria of WIG-craft control quality

It is advisable to consider the following criteria: of control quality of motion above disturbed sea surface:

- guaranteed stability of the vehicle motion at any permissible mode;
- rise of seagoing ability of a vehicle, i.e. its capability to move in required direction at the largest height of sea waves;
- reduction of fuel consumption;
- depression of vehicle rocking for creating the favorable conditions for crew and passengers or for functioning of on-board equipment.

Naturally, it is impossible to reach the extremum of all these criteria simultaneously and each case of design requires appointing the only main criterion of control effectiveness, transforming other ones to the rank of limitations. It is necessary also to provide economical expenditure of control elements resource. The possible effectiveness of development and application of ekranoplanes with automatic control facilities is stated in [2,8,10]. The aim of investigation is to define the way for operational performance improvement of the vehicles of advanced design by application of modern control systems. The experience and achievements in this field of high technology are described. It is shown that automatic systems are unexpendable for comparatively big ekranoplanes. Unfortunately, all attempts to construct the automatic control system for small commercial ekranoplanes were unsuccessful because the market requested the cheapest vehicles and automation means were not corresponding to this concept.

Step by step it became clear that this concept cannot permit to solve the problem of perfect ekranoplane creation and the modern means of automatic control must be the essential part of the vehicle. Automatic control system has to be designed in parallel with the vehicle design and influence on the acceptable class of vehicle's aerodynamic characteristics. It is especially important that vehicles without good own stability can be considered as admissible or even optimal if the lift-to drag ratio is good and fuel consumption is least. The control algorithms and some hardware of automatic control systems of ekranoplanes differ essentially from airborne ones and require the special research and design. Some new results in this field are described. When improved, cheapening and lightening of the on-board automatic control equipment the small ekranoplanes would also become automatically controlled and increase their marketability.

3. Stability problem

When flying far from the supporting surface an ekranoplane, like an airplane, can have longitudinal stability if its center of gravity is ahead of aerodynamic center. The correct center of gravity positioning, aerodynamic center in airplane flight mode depending slightly on angle of attack provides fulfillment of this condition with a certain margin. A small decrease of pitch angle and, hence, angle of attack takes place because of some disturbance, then the aerodynamic force negative increment applied to the center will give force moment relative to the center of gravity striving to increase pitch angle that exhibits its own longitudinal stability of vehicle.

In the supporting surface action zone the longitudinal stability can be disturbed because of aerodynamic force dependence not only on the attack angle but also on motion altitude. Besides, aerodynamic center position may vary depending upon several factors under supporting surface influence. When the altitude decreases focus moves backwards due to pressure increase at the wing back edge area under positive angles of attack and moves forward - under zero and negative angles of attack.

Undoubtedly, the effective mean of stable motion area extension and even of formation of such an area for structurally unstable craft is the use of special autopilots and other means of ekranoplane control automation.

For the essential action of WIG-effect the altitude of ekranoplane flight has to be less than a half of the wing chord. At the certain size of ekranoplane it is possible at the limited height of sea waves. Anyway it is necessary to choose the extremely low flight altitude, permissible as to criterion of flying safety at the definite height of sea waves. Even if the vehicle has the natural properties of self-positioning as to the altitude and the inclination angles, only the facilities of automatic control can ensure the required functional characteristics under the circumstances of rough sea.

The adoption of WIG has been slow due to the complicated technology issues surrounding the vessel; it is a hybrid vehicle that combines marine and aviation theory, wing theory and air cushion theory, aerodynamic and hydrodynamic theory [3,7,10].

4. Analysis of WIG-craft seagoing ability

It is necessary to note the particular importance of the criterion of maximization of seagoing ability not only for undisplacement ships but also for marine aircraft. Though it is administered to believe that for hydro-airplane and partially ekranoplane in the mode of cruise motion the sea conditions may be not taken into account, the seaworthiness of such vehicles must be appreciated as a complex index allowing for possibility of planned or crash landing in the arbitrary point of route. Explicitly, that seagoing ability is defined by the size and mass of vehicle and by the peculiarities of its construction, however even insignificant rise of seaworthiness and the level of the safety of motion accounted for the optimization of motion control with allowance for definite characteristics of sea disturbances is very advisable, since can noticeably heighten the effectiveness of vehicle application by comparatively simple means. These facilities let, in particular, to ensure the acceptable seagoing ability of the fast marine transport vehicles of comparatively small size that is very importantly for the widening of their application on transport lines with limited freight traffic, but with high frequency of sailing.

In any event it is important that the seaworthiness of vehicle would depend in the least on its dimension and tonnage which must be defined at first by the required payload capacity. If for displacement ships this dependence practically impossible to correct by the facilities of control, the undisplacement vehicles have considerably larger possibilities to parry the disturbances from sea waves at expense of the creation powerful controlling forces, including vertical. This is appertains not only to hydro-airplane and to ekranoplanes but also to hovercraft, controlled hydrofoils and others. Along with that it is explicitly, that rise of seaworthiness by the facilities of the automation of motion control can be achieved only at the very high level of intellectuality of control complex.

5. The models of wave disturbances

The effect of wave disturbances on the vehicle moving at small altitude or directly along the bound of water surface is complex and can have the following consequences:

- appearance of periodical forces and moments exciting trajectory of motion (rocking, the reduction of speed, the deterioration of the indexes of fuel saving);
- likelihood of the appearance of abnormal situation or catastrophe due to the impulsive exposures of too large value (the hazard of destruction or overturning of a vehicle);
- creation of significant interference for sensors (radar, sonar and others) of the parameters of low altitude motion of vehicle due to tracking by them of the profile of large sea waves.

It is necessary to allow for all these factors at the optimization of motion control laws and the ensuring of the potential characteristics of the seagoing ability of each vehicle [6,9,10]. Indeed, is necessary not only optimization of laws of control in classic mean, but also the composition of controlled (measured) parameters of motion and the parameters of wave disturbances, the composition and the placing of the diverse transducers of these parameters, the algorithms of their integration, the structures of the control channels, the laws of control, the tactics of the application of all accessible piloting-navigational information and the criteria of the choice of phase trajectory of motion.

The models of sea wave disturbances have a principal significance at the examination of the similar algorithms of estimation and control. The methods of calculation of spectral and correlation characteristics of wave disturbances on the base of the three-dimensional irregular model of sea waves are described in detail in monograph [10] and presented by the typical results for the various modes of vehicle motion. It is shown that the most lowest frequency spectral component of wave surface in moving coordinate system have a maximum at the definite speed of motion reckoned as the function of the course of vehicle and the parameters of the intensity of disturbances. It is also shown, that at the enough large speed of motion the recalculation of the characteristics of wave disturbances in moving coordinate system can be lawfully fulfilled with the application of the spatial spectra of “frozen” surface with simplified elements motions. This enables the speedy calculation of the characteristics of disturbances in real time on on-board computers and expands the possibilities of increasing the intelligence of control complex. The results received in this field are arranged in [5-8,10].

6. Development of high precision instrument for measurement of extra small altitudes

The non-contact measurement of the characteristics of sea wave disturbance may be produced on the base of processing of indications of several (really - two, three or more) sensors of sea waves profile each of which includes precise positioning altimeter and inertial means [8]. Presence aboard several sensors, actually measuring the geometrical altitude of flight with reference to disturbed sea surface, ensures also (and first of all) the measurement of the principal parameters of flight - altitude, the roll and pitch angles (as to the difference of altitudes). The problem of development of high-precise, light, reliable and cheap sensors of altitude in the range up to 10m is actual.

The advantages of application of specially designed phase radioaltimeters in compare with ordinary ultrasonic, radioisotopic or even laser altimeters are substantiated in [4,8].

Created under the leadership of the author the experimental specimens of such radar sensors (in integral execution, flat aerial, mass of 3.5 kg, digital and analog output) have already confirmed the required accuracy at trials in tank, and debugging as to abbreviation the effects of secondary reflection of radio signal are directed on the further rise of the quality of operation.

The following technical characteristics of phase radioaltimeter have already achieved:
altitude (or distance) measured - 0-10m (at necessity - up to 100m);
measurement error - not greater than 5 cm under sea conditions of number 0-5;
is possible to measure the vertical speed - with the error not greater than 0.1 cm/sec;
measured parameter frequency range of 0-20 Hz;
the operating RF frequency - from X-range (9000 MHz);
radiated power - 20 mW;
power supply - 12 V± 3%;
power consumable - 2 W;
output signal– digital and analog;
mass - 3.5 kg;
dimensions of SHF-modules - 110x90x60 mm;
dimensions of each of two hybrid strip-line flat antennae – 110x160 mm.

7. The algorithms of navigation sensors integration

The methods and results of algorithms synthesis for processing of indications of several radioaltimeters, several accelerometers, gyro vertical and GPS receiver in the interests of estimation of the main parameters of low altitude flight above sea as well as of the characteristics of wave disturbances were described in [4,5]. Author develops 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 aircraft motion. The dependence of the estimation accuracy on flight parameters and sea conditions are presented by the aggregate of graphs.

Separately the problem of automatic estimation the general direction of sea waves spread was investigated that important for the optimization of the mode approach and landing on water [9,10].

8. The algorithms of combined control on errors and wave disturbances

Obtained current data on the field of wave disturbances can be used for adaptation of the main motion control loops and for realization of the principle of combined control. This lets to arise the quality of motion control as to each criterion, mentioned in the item 1. However, main difficulty in the design of the channel of control on wave disturbances is the complexity of 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 may be solved successfully, however in general case of three-dimensional waves it is necessary to use approximations. But positive effect may be guaranteed in any event.

Notice, that if for displacement ships the disturbing effect of sea waves practically impossible to lower using the facilities of control, the flying vehicle have the considerably larger possibilities to parry the disturbances from sea waves at expense of the creation powerful controlling forces, including vertical. This is appertains not only to hydro-airplane and to ekranoplanes but also to hovercraft, controlled hydrofoils and others.

9. Prospective developers of automatically controlled large ekranoplanes

The list of possible developers of large ekranoplanes can become more definite taking into account the geographical location and strategic interests of different countries. Large ekranoplanes have to fly above seas and oceans, and inland countries hardly have an interest to develop them. The volume of cargo and passengers transportation for a long distance, across the seas is important. At last, the announced plans for ekranoplanes development and the existing of rather long history of such technologies investigation has to be taken into account. It gives a few countries that could construct large and even great ekranoplanes in the short-term future.

Russia has great experience in ekranoplanes development for the Navy and the modern ambitions for commercial vehicles design. During 20 years Russian Government has not supported this branch at all, but in 2009 the first information about changing such policy appeared. The famous "TsKB on SPK" changed the owner and presently "Radar MMS" JSC (Saint-Petersburg) holds 51% shares in TsKB and makes essential investments. Renovation of the old projects of Russian large ekranoplanes on the basis of modern technologies and creation of the new digital systems for large ekranoplanes navigation and motion control are among the short-term plans. A few other Russian firms also have plans for ekranoplanes of different dimensions development. Beriev firm announced the project of creation a great flying vehicle Be-2500 (Fig.3), but it may be possible only in international consortium. The idea to write this paper was appeared under analyzing of all these news.

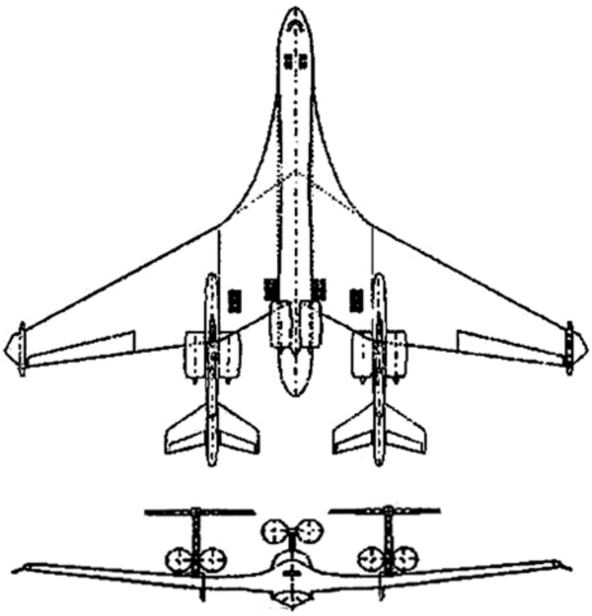

Figure.3. Be-2500 plane with wingspan 147m

The USA has a long history of WIG-craft development, but the majority of old projects including Airfoilboat X-112 and Weinlandcraft were commercially unsuccessful. But the project of great WIG-craft "Pelican ULTRA" was announced in 2002 with the following characteristics [9]: length -122 m, wingspan - 152 m, height - 6 m, useful load -1,400 tons, take-off mass – 2,700 tons, powerplant - 8 (4 coupled) turboprop engines in (60-80)10^3 horsepower, cruise speed - 445 km/h, range (10-12)10^3 km. Its main mode would be to fly 6-15 m over water, with take-off from the conventional runways and landing again on the runway. Boeing Phantom Works was announced as a manufacturer [12].

The image of the vehicle is shown in the Fig.4. Any information about the advance in this great vehicle construction or its reduced model is not available. Nonetheless, it is quite understandable that such great WIG-craft, especially without a highly raised tail stabilizer, has to be equipped with the perfect automatic control system, and Boeing certainly develops it on the basis of excellent experience in heavy planes automatic control.

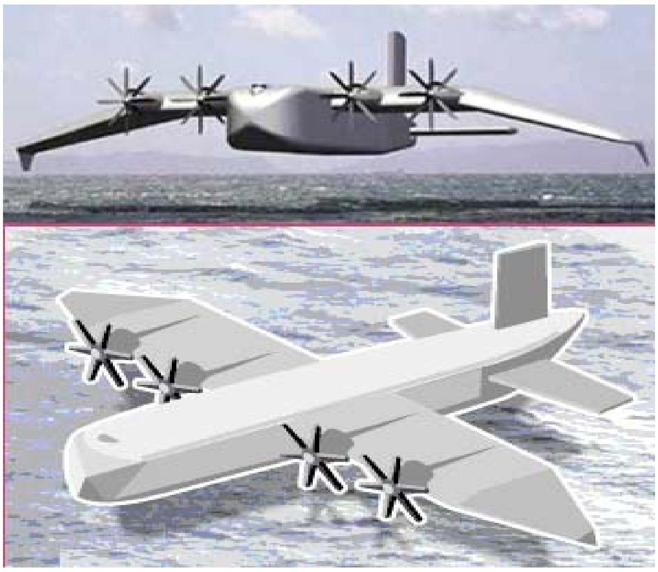

Figure.4. Boeing PELICAN concept WIG-craft

A few recent papers on WIG-craft control are devoted to control problems of small vehicles only. Large vehicles control is not analyzing at all.

10. 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 [1]. 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 [10]. 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 [5].

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.

11. 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 for adaptation of the main motion control loops and for 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 [8]. 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 [9].

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. This equipment can be cheaper against radioaltimeters, but the reliability at the full spectrum of possible conditions of operation is still under investigation.

12. Software package “Big Ekranoplane”

Taking into account, that development of motion control system for WIG-craft is a very complex and knowledge-intensive task, the decision on advanced developing of the great software package with the name “Big Ekranoplane”, was made. This work is going successfully. The complete structure of this specialized software package for Computer Aided Design will include:

1. The perfect dynamic and kinematic multidimensional model of WIG in view of its aerodynamics and the effect of the screen, as well as effects due to the non-rigidity body, aeroelasticity.

2. Simulators of motion parameters sensors of WIG-craft (specially designed altitude meter, radioaltimeter, INS and their components (accelerometers, gyro sensors of angles and angular velocities), receivers of satellite navigation systems GLONASS / GPS, Doppler velocity sensor, Air Data System, a compass and other sensors.

3. Imitators of wind and wave disturbance for winged systems and sensors of WIG-craft motion parameters.

4. Imitators of distributed computing devices for combining disparate sensors into a joint integrated information-measuring complex.

5. Electrical and hydraulic simulators and other devices to create control signals.
6. Central computer simulator for the formation of multi-dimensional control laws for WIG-craft (inter-connected channels of altitude, pitch angle, roll angle, yaw angle, ground speed, thrust vector of engines, etc.).

7. Simulator systems to convert data during their transfer from the computer system for motion control simulators of WIG-craft.

8. Simulators of electromechanical devices, providing fault tolerance control system.

9. The display system of flight control and navigation information, designed for the displayed mode of motion.

10. Human-machine interface, comprising means of forming the commands by crew and intelligent means of checking the correctness of the crew team, based on motion estimation.

11. Simulators of built-in test system performance and fault localization elements.

12. The simulator system to prevent collisions with any conflicting objects.

The software package "Big Ekranoplane" is intended for solving the following tasks:

1. Computer simulation of the measurement of current values of angles of pitch, roll and yaw (slip), the angular velocities with respect to three related axes, altitude relative to the mean undisturbed sea level, vertical speed, wave height under the wing, ground speed, airspeed.

2. Display of current values of all parameters of motion with a choice of display modes, selection of the most convenient mode in the simulated flight.

3. Simulation of WIG-craft damping in the angles of pitch, roll and yaw, as well as movement in vertical plane.

4. Simulation of automatic stabilization of the zero roll and set by the crew values of course, pitch and altitude.

5. Simulation of automatic stabilization of airspeed.

6. Simulation of semi-automatic control (via the setpoint of adjusters software instrument) of rate, pitch angle and altitude in the mode of stabilization, as well as air velocity.

7. Alarms at the approaching of WIG-craft to the maximum allowed values for roll, pitch and altitude.

8. Simulation output constraints WIG-craft limit values for roll, pitch and height in a semi-automatic operation.

9. Simulation of the combined control of the course and altitude when the mode of stabilization.

10. Imitation of winged rudder trim.

11. Simulation of automatic remote thrust vector control (nozzles) engines during takeoff and landing.

12. Predicting changes in altitude while maneuvering in the vertical plane, forecasting emergency flight modes.

13. Automatic self-test of equipment with indication of performance and fault isolation.

After the “Big Ekranoplane” completing it will provide not only optimization of control laws but seminatural flight simulation also.

13. Conclusions

The demanded characteristics of large ekranoplanes 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 essentially from airborne ones and require the special research and design. Some new results in this field have been described in this paper. The essential difference exists also in principles of design of small and large ekranoplanes. The development of autopilots for WIG-craft has been slow due to the complicated technology issues surrounding the vehicle and its mathematical models. Ekranoplane is a hybrid vehicle that combines marine and aviation theory, wing theory and air cushion theory, aerodynamic and hydrodynamic theory, modern control theory and methods of adaptive control laws optimization.

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