WING-IN-GROUND EFFECT FLIGHT CONTROL: NEW ROLE OF AUTOMATIC SYSTEMS

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

1. ABSTRACT[1]

A trouble-free flight in the zone of wing-in-ground effect (WIG) action requires application of the special methods and means of motion control which are capable to solve the corresponding specific problems. Methods of stability provision and solving some other problems of WIG flight by means of automatic control are analyzed. The requirements for motion control systems are reviewed and the criteria for their improvement are given. The statement of the main problems of equipment and software design for flight control at small altitude above the disturbed surface is performed. The aim of investigation is to define the way for operational performance improvement of the vehicles of advanced design. A promising way is by implementation of modern navigation and motion control systems. The experience and achievements in this field of high technology are described. Probable areas of the most effective application of vehicles with such equipment are indicated.

2. INTRODUCTION

WIG-craft or Ekranoplane may be considered as a flying vehicle with special structural distinctions providing low altitude flight ability when using wing-in-ground effect (WIG-effect). It consists of substantial wing lift force increasing and air drag decreasing when moving close to the supporting surface. In this case the air-cushion action in the space between wing and supporting surface is added to the normal mechanism of lift force formation. The velocity of WIG-flight may be around 200-400 km/h depending on vehicle dimensions. The altitude has to be in the range from 0.5m for small vehicles to 5-10m for big ones.

Ekranoplanes 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 at great altitude due to dependence of all aerodynamic indexes on the flight altitude regarding the ground or water surface. It is usually accepted to consider the relative altitude $h_r = h/b$ as the important index of WIG-flight, where h is an altitude of gravity center of ekranoplane concerning an average level of wave surface, b is the wing chord. If h_r=0.5, practically all aerodynamic indexes depend on the h_r value, including the aerodynamic coefficients c_x and c_y. Complex character of these dependences often gives the loss of the vehicle stability at some mismatch of flight parameters values for certain vehicle aerodynamic configuration.

It is necessary to remember that the idea of ekranoplane may be considered as the inverse of hydrofoil with shallow submerged foils both of which Russian designer Rostislav Alexeev suggested. Hydrofoil has a submerged wing, ekranoplane has a wing above the water. The tandem scheme of such hydrofoil is very effective and gave a good account of itself during many realized projects.

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The first ekranoplane constructed by R. Alexeev SM-1 was also of tandem. Then Alexeev suggested the well known presently “plane-like” scheme of ekranoplane with high T-like rear tail taken out from the zone of aerodynamic interference with the main wing. It provided the vehicle longitudinal stability, but only at rather narrow array corridor of flight parameters values.

However, originally Alexeev expected to hold the mode of flight inside this permissible corridor by experienced pilots and without application of any automatic control systems. The autopilots Smena-4 and Smena-3 [1] were created later, in seventies and eighties, mainly under the formal requirements of the Navy. It was the analog systems for damping and stabilization of 5 main parameters of flight, but without adaptation and using the facilities of modern control theory. Unfortunately, the principles of digital control and integrated multi-channel systems were not realized in the first prototypes of Smena, and crash of Soviet Union in 1992 stopped the development of any ekranoplanes and their equipment under the order of Navy.

Two features could have characterized the fifteen years passed from that time. The commercial rather small ekranoplanes were developed in several countries, but any serious attempts to construct the automatic control system for ekranoplanes motion control were not done. The main aim consisted in creation of the cheapest vehicles under the request of the market, and automation means did not correspond to this concept.

Step by step it became clear that this concept cannot permit to solve the problem of perfect commercial ekranoplane creation and the modern means of automatic control must be the essential part of the vehicle. Automatic control system must 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 own good stability can be considered as admissible or even optimal if the lift-to drag ratio is great and fuel consumption is least. Providing of flight stability can be imposed entirely on the automatic control system which reliability must be without a shadow doubt.

3. MOTION CONTROL PRINCIPLES

WIG-effect is an interesting physical phenomenon with multilateral characters, having positive and negative influence for providing the flight in WIG-mode. 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 the ordinary airplanes:
- wing with small aspect ratio that is relatively lowly attached to the body, or “flying wing” configuration;
- boundary plates on wing ends 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;
- special equipment to expedite taking off from the water and water landing.

Notice, that the modern ekranoplanes have in the majority a plane-like aerodynamic configuration with a wing of small outstretch index and highly raised tail stabilizer (Fig.1,3). However, the promising large ekranoplanes are designed under the scheme “combined wing” having a number of advantages. The appearance of the ekranoplane-catamaran of such a scheme with mass of 1500 tons is shown in Fig.3, this ekranoplane was designed for cargo and passenger transportation by "Central Design Bureau on Hydrofoils" named after R.E.Alexeev.

Unfortunately, ekranoplane has the essential instability of motion in the longitudinal plane and perfect automatic control system is necessary first of all for providing the flight stability. It has been proofed during the operation of the big Russian ekranoplanes Orlyonok and Lun [2].

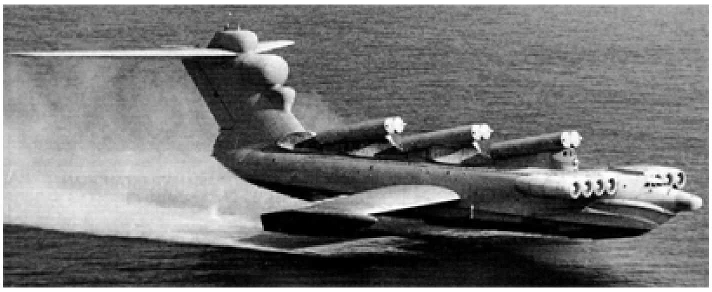

Fig.1. Ekranoplane Lun

Fig.2. Small ekranoplane Ivolga

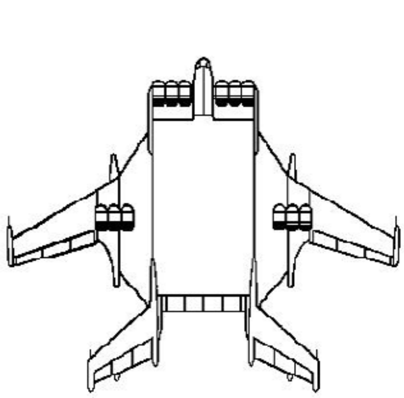

Fig.3. Ekranoplane with “combined wing” configuration

For such heavy machines (in 140 ton and 400 ton respectively) the automatic control systems are required definitely [3]. For smaller ekranoplanes many attempts to exclude any automation of motion control are known, but only the grim necessity to lower the cost of commercial vehicles causes such attempts that certainly degrade the safety of motion. When the means of automatic control will be more perfect and cheap, the automation of motion control will become callable for all ekranoplanes.

Stable motion close to disturbed sea surface may be guaranteed by the application of special methods and means of navigation and control, which must have capability to solve the following specific problems [3,4]:

- the 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;
- ensuring of the vehicle stability in the circumstances of the action of flake non-linear aerodynamic effects attributed to nearness of surface;
- non-contact measurement, tracking and prediction of ordinates and biases of the field of sea waves for the rising of motion control effectiveness.

4. STABILITY PROBLEM

Ekranoplane as the controlled plant has an essential specificity in comparison to ordinary plane, connected with a sharp non-linear dependence of all aerodynamic coefficients and character of their correlation on a relative altitude of flight h_r Great specificity exists also in the wave disturbances.

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. At correct center of gravity positioning, aerodynamic center in airplane flight depending slightly on angle of attack provides fulfillment of this condition with a certain margin. In the supporting surface action zone the longitudinal stability can be disturbed because the aerodynamic force depends 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.

As the lift force of a wing increases with h_r decreasing, the achievement of the natural stabilization of a flight altitude is possible. However, the range of inherent stability in the space of flight parameters is usually very narrow. In this connection the automatic control system must not only prevent escaping this range, but also essentially correct the dynamic properties of ekranoplane for increasing a stability margin for all controlled parameters of motion. The activity of the channels of damping and stabilization of altitude and pitch is especially relevant.

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 for ekranoplane.

5. ADVANTAGES OF LARGE COMMERCIAL EKRANOPLANES AGAINST THE SMALL ONES

The evolution of planes, hovercraft, hydrofoils and many other types of transport vehicles went "from small to large". But in the case of WIGs the inverse way could be more successful. Several reasons could prove up this thesis.

1. Wing-in-ground effect is especially effective when the altitude of flight is less then 10-15% of the wing chord value. In this case the lift-to-drag ratio may be almost two times more comparably the case of great altitude of flight. If the wing chord is 30-50m and the vehicle configuration is "flying wing", such ekranoplane practically will not have any limitations for flight at stormy sea.

2. Only rather large WIG-craft can perform take-off and landing at stormy sea, and also float as a ship among the great sea waves.

3. The price of perfect autopilot for WIG-craft could be approximately 70,000-100,000 US Dollars [5], and it increases slowly with increasing the vehicle mass (mainly at the account of more developed actuators). If the reasonable market price for simple in construction 6-8 seater WIG-craft is 300,000-400,000 US Dollars, it is impossible to involve good autopilot in this frame. So, automatically controlled WIG-craft has to be rather large. But as the digital electronics and mechatronic devices became cheaper, after some years the autopilots developed for large WIG-craft will be possible to apply also at smaller vehicles.

6. CONTROL LAWS SYNTHESIS

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 velocity 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 several criteria, but their general structure appears to be almost similar in the majority of cases. The estimations of the vehicle stabilization errors, linear and angular rates and also wave 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 swivel nozzles of engines.

The effect of wave disturbances on the vehicle motion at a small altitude above water surface can have the following consequences:
- appearance of the periodical forces and moments exciting the trajectory of motion;
- likelihood of dangerous situation due to too strong impulsive action;

- creation of significant interference for radar sensors of the parameters of low altitude motion due to tracking by them the profile of large sea waves.

It is necessary to allow for all these factors at the optimization of motion control laws and ensuring the potential characteristics of vehicle seagoing ability. Indeed, it is essential not only the optimization of control laws in the common mean, but also the reasoned choice of controlled parameters of motion and the parameters of wave disturbances, optimization of a set and placing of the diverse transducers, synthesis of algorithms of their integration and the structures of control channels, determination of the tactics of all accessible piloting-navigational information use and the criteria of choice of phase trajectory of motion. The methods of analysis of spectral and correlation characteristics of wave disturbances on the base of the three-dimensional irregular model of sea waves are described in details in [2].

The exact calculation of wave disturbances has the special significance at optimization of modes of take-off and landing of ekranoplane. At landing on a strongly disturbed sea surface the course angle with reference to the general direction of the distribution of sea waves should be optimized. At the choice of this angle it is necessary to allow for peculiarities of aerodynamics and hydrodynamics simultaneously.

Obtained current data on the 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 increasing the quality of motion control as to each criterion, mentioned in the item 6. However, main difficulty in the building of the channel of control by 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. However, positive effect may be guaranteed in any case.

7. DESIGN OF HIGH PRECISION INSTRUMENT FOR MEASUREMENT OF SMALL ALTITUDES

Especially constructed for low altitude measuring, the isotope altimeters have a principle of γ-beam radiation measuring, reflected from the underlying surface. Advantage of isotope altimeters is in its construction simplicity.

However, intensity of measured γ-radiation will depend not only on object altitude, but also on slope structure steepness, situated under the object. Therefore at operation above a structure with large roughness there will be additional errors. The specified lacks of isotope altimeter are essentially irremovable, while in case of radioaltimeter when the information parameter of a radio signal is not energy, theoretically there is an opportunity to improve the measurement accuracy by decreasing a directional pattern of stabilized antenna.

High accuracy of altitude measurement is reached at laser altimeter use, which is caused by an opportunity of extremely narrow beam. However, its lack is unreliable operation at hard meteorological conditions, for example at a fog. Besides, the pulse modulation mode as a rule is used currently in laser altimeters, and the effective separation of direct and back beams in the receiver is connected with technical difficulties if the time interval between them is too short. It limits the minimal possible altitude measured by a laser altimeter.

The non-contact measurement of the characteristics of sea wave disturbance may be produced on the base of processing of indications of several (really – three or four) sensors of sea waves profile each of which includes high-precise positioning altimeter and accelerometer. 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 such the principal parameters of flight as altitude, and 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 has been solved [4]. The created phase radioaltimeter (Fig.4) has the following technical characteristics:

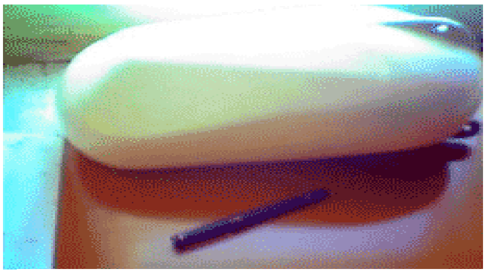

Fig.4. Precise Phase Radioaltimeter

altitude (or distance) measured - 0-10m;
measurement error - not greater than 5 cm,
measured parameter frequency range of - 0-20 Hz;
the operating RF - from X-range (9000 MHz);
power consumable - 2 W;
mass - 1.5 kg;
dimensions of hybrid strip-line antenna – 110x160 mm.

8. LANDING MODE OPTIMIZATION CRITERION

The take-off and landing modes at rough sea are the most difficult and dangerous stages of ekranoplane flight. Ekranoplane landing on the disturbed sea surface provokes the essential mechanical loads applied to vehicle body during the bottom contact of a water surface when hydrodynamic breaking starts. Irregular rough sea does these influences non-uniform and stochastic. With the purpose of decrease of these specified loads designers try for lower landing speed of seaplanes in comparison with planes which perform landing on air-strip, however it can be made only due to impairment of other parameters of flying vehicle efficiency or due to the elaborate mechanization of a wing. On the other hand, the opportunity of mechanical breakage at contact with a wave increases at elaboration of wing mechanization. Therefore optimization of the landing trajectory direction regarding the main direction of sea waves' propagation that allows to lower the mechanical loads in more simple way, has the great importance.

The criterion and methods of seaplane landing mode optimization in rough sea conditions, provide the minimal mechanical strain at hydrodynamic braking, are offered in the paper. The key factor is automation of landing approach direction selection in relation to a general direction of sea waves' propagation, leading to extremum the criterion pointed. The rather simple criterion of "softness" landing, which is represented by the r.-m.-s. value of vertical velocity of vehicle bottom immersing into water σ_V , was accepted as the most successful one after consideration several variants of formal criteria. This criterion is formularized:

$$\sigma_V = V\sigma_\alpha ,$$

where V is the vehicle landing horizontal velocity, σ_α is the r.-m.-s. value of waved surface bias along the landing trajectory.

When deducing a resulted expression for criterion σ_V, the rather adequate mathematical model of completely developed windy sea is necessary, as only this general occasion of sea wave disturbances is of great interest and allows to do the widest conclusions. The formulae of Pierson-Moskowitz as the basic spectral models of irregular sea waves, the r.-m.-s. values of waved surface bias along a landing trajectory and the expression for the spatial spectrum $E(k, \psi)$ were used[6].
The resulted formula is:

$$\sigma_V = (V_l - \upsilon\cos\psi)\times\sqrt{\int_0^\infty \left(\begin{aligned}&\int_0^{\pi/2}(\cos^2\psi\cos^4\chi P(\chi,k)d\chi + \\ &+\sin^2\psi\cos^2\chi\sin^2\chi P(\chi,k))d\chi\end{aligned}\right)dk} ,$$

were

$$P(\chi,k) = \frac{1.03\cdot 10^{-2}}{k}\exp\left[-\frac{0.112\cos^2\chi}{\left(k(0.391)\left(\upsilon^2/g\right)\right)^2}\right];$$

χ is the angle in relation to a wind direction, k is a spatial frequency, υ is a wind velocity, ψ is the angle in relation to a wind direction, V_l is the air velocity.

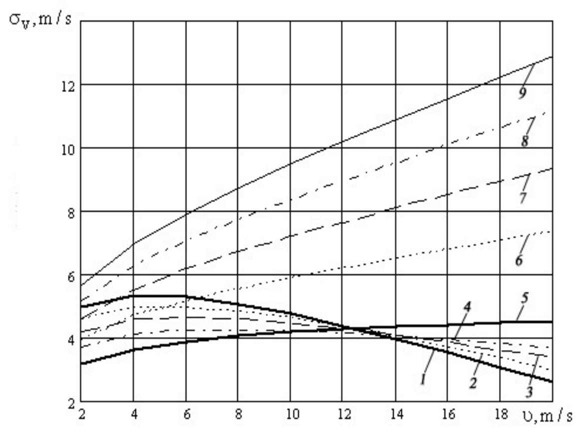

Fig. 5. Criterion σ_V at landing velocity 40 m/s and at different landing directions:
1 - ψ =0, 2 - ψ = 30°, 3 - ψ =45°,
4 - ψ =60°, 5 - ψ =90°, 6 - ψ =120°,
7 - ψ =135°, 8 - ψ =150°, 9 - ψ =180°.

The obtained expression permits to investigate the "softness" value dependence on many factors, firstly, on the landing direction in relation to a wind direction coinciding with the general sea waves' propagation. As a result the 2D and 3D-plots have been constructed. The required parameter σ_V was calculated at an angle between a landing approach direction and a wind direction values from 0 up to π; landing velocity of 30 m/s and the wind velocity from 1 m/s up to 20 m/s.

The analysis of the constructed plots allows drawing a conclusion that the optimal landing approach direction depends on wind velocity which for completely developed windy sea waves' defines all its characteristics. At wind absence (in the case of υ=0) the landing mode is equally favorable ball-park for all directions. It is possible to note also that at small wind velocity and, accordingly, small power of sea waves disturbance the complexity of landing practically does not depend on a direction.The most important is optimal landing conditions dependence on a direction at various sea roughness numbers. At the small disturbance at wind velocity of 2-10 m/s the most favorable landing approach direction is ψ =90°. At the moderate disturbance corresponding to the wind velocity of 10-14 m/s all directions in the interval 0-90° are acceptable for landing approach and provide rather similar conditions in the sense of mechanical loads on the body. In rough sea, corresponding to the wind velocity of 14 m/s and above, the situation sharply varies, and the most favorable direction of landing approach will be against the wind (ψ =0). The difference in loads at favorable and adverse landing approach directions can exceed an order. The disturbance load at landing decreases approximately twice in the cases of a direction choice ψ equal to 0° or 30°, in comparison with the case of ψ =90°. At any wind velocity the most adverse for landing approach is the direction 180°. Any direction between 90° and 180° could not be favorable at any significant disturbances. It is interesting that the approach direction ψ =60° is rather favorable at any wind velocity.

9. AUTOMATIC MEASUREMENT OF SEA WAVES PARAMETERS

For the realization of the elaborated recommendations concerning a landing direction of flying marine vehicle it is desirable to have onboard a complex of instruments for estimation of intensity of sea disturbance (r.-m.-s. heights of sea waves) and the general direction of sea waves propagation. There are some types of sensors, capable to solve such problems. It is important to estimate an opportunity of the problem decision with the use of simpler means. In [5,6] the opportunity of the use of three radioaltimeters with magnitude and Doppler channels for the general direction estimation is analyzed. Joint processing of such altimeters and inertial sensors signals allows definition in real time of the general direction of waves propagation, intensity of wave disturbance, and also the altitude of vehicle flight in relation to an average level of the disturbed sea surface and roll and pitch angles.

Another way of determining the general direction of waves' propagation is correlation analysis of disturbed sea surface pictures, obtained by on-board camera. Permanent development and markdown of photo and video cameras, improvement of picture's quality in spectrum of photography conditions must be taken into consideration. At the same time airborne and radar devices do not have a tendency towards price reduction.

Nowadays digital cameras provide very high level of extensional resolution and dynamic spectrum luminosity. Data processing can be in any of the colour channels R, G, B, and on its combinations according to photography conditions. As a rule for getting sharp images of sea surface the most informative channel is the "blue" channel but the other ones can give useful information too.

Certainly, in conditions of calm sea the high-quality images of a sea surface are unreachable, but thus the problem of optimization of landing approach is not necessary. The specified problem arises only at essential wave disturbances when the structure of sea waves is easy to be analyzed by their photos.

By considering the wave surface as a three-dimensional casual field anisotropic in a direction, the general direction can be determined as such one along which the interval of spatial correlation between eminences of a wave surface is minimal. Accordingly, the correlation interval should be maximal in a perpendicular direction.

Instead of defining the interval of correlation, it is actually possible to transform the image into black-and-white mode and then count up the number of transitions n_0 from black to white and back along the different directions. At the analysis of the black-and-white image the value n_0 is proportional to the r.-m.-s. frequency of a spatial spectrum of a wave surface $k_{r.m.s.}$ and hence is in inverse proportion to an interval of spatial correlation. For Gaussian casual process which corresponds to the eminence of a wave surface along the certain direction, the value n_0 is expressed by the formula: $n_0 = \frac{k_{r.m.s.}}{\pi}\exp(-\frac{C_0^2}{2D_\xi})$,

where D_ξ is the dispersion of wave ordinate, and the level C_0 depends on adapted picture contrast.

The example of a wave surface image is shown in Fig.6. Its transformation into the black-and-white image is represented in Fig. 7, allowing to count up the number of transitions n_0 and to define a general direction of waves propagation (shown by an arrow) along which the value n_0 is maximal.

Fig.6. Picture of sea surface

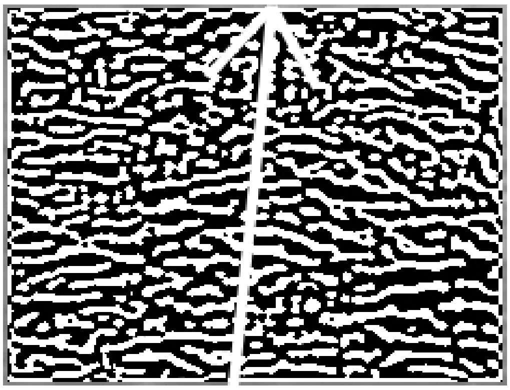

Fig.7. B&W picture of sea surface with waves' general direction

Let's notice also that tracking of sea waves' profile under the vehicle or a little ahead it can give the information for improvement the quality of vehicle vertical motion parameters control at landing.

The algorithm for estimation the general direction of sea waves propagation in a brief description can be presented in the following 5 stages:

- The RGB-image is transformed into the grey map with 256 intensity levels. Meaning of the grey is determined as the average arithmetical value of three RGB colour channels for each pixel. Thus the common brightness and picture contrast is saved, but data about colour are lost.
- A certain threshold of brightness is installed, and the transition to the black-white map is carried out. Some versions of this threshold selection are possible. For example, threshold height can be determined as

an average arithmetical meaning of brightness of all points of the map. In an alternative version the brightness minimum and maximum in a concrete photo is estimated and their mean value gives the threshold. The actual interval of brightness is useful for expanding to the greatest possible interval in 256 gradations by performing of scaling with a floating adaptive scale factor. It is important as thus the quality of the black-white map after treatment may be increased. [7]

- The number of black-to-white transitions along the selected direction (by default the initial direction is taken as 0°) is calculated.
- The map is turned step by step (the step is selected depending on necessary precision of estimation and powerful of an on-board computer, for example in 1°) for direction finding with the peak number of black-to-white transitions for a segment of the selected length.
- The determined direction which corresponds to the maximum number of black-to-white transitions has to be accepted as the general direction of sea waves propagation.

10. ALGORITHMS OF SENSORS INTEGRATION

The methods and results of algorithms synthesis for processing of indications of several radioaltimeters, several accelerometers, gyrovertical and GPS receiver with the aim of estimation of the current meanings of the main parameters of low altitude flight above sea as well as of the characteristics of wave disturbances, are mainly given in [5]. Author develops the special approach to synthesis by teaming up the Kalman filtration and the robust filtration [8], 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 vehicle motion. The dependence of the estimation accuracy on flight parameters and sea conditions are presented by the aggregate of graphs [2].

With the use of three described radioaltimeters, the integrated system for measurement of parameters of motion close to a sea surface was built, the compact INS was also included in the system. This INS involves three angular-rate sensors, three linear accelerometers, calculator and temperature transmitter for compensation of temperature drift of angular-rate sensors and accelerometers.

The measuring system allows tracking the profiles of sea waves ξ_n, ξ_l, ξ_r in three points, corresponding to the points of three radioaltimeters installation at a nose and both sides of the vehicle, with the accuracy 10 cm at seaway number 4.

The problem of automatic estimation of the general direction of sea waves distribution may be highlighted separately, that is important for optimization of a mode of landing approach and splashdown. Two ways seams to be the most hopeful for such estimation performing. The first one consists in use of three radioaltimeters with range and Doppler channels whose outputs carry the necessary information [3]. The second one is connected with processing of digital pictures of disturbed sea surface [9].

11. COLLISION AVOIDANCE PROBLEM

At the high speed of motion, proper to ekranoplanes (similar to planes), the problem of collision avoidance with interfering vehicles in the circumstance of the time scarcity for maneuvering also originates, which is not characteristic to displacement ships. Low altitude of ekranoplane flight gives point to this problem, as the obstacle could be recognized only at rather small distance. From the other side, the task of going round an obstacle became easy as it becomes the single-agent one against the multi-agent approach, which is demandable for relative motion control of ships.

Another peculiarity of collusion avoidance problem for ekranoplanes consists in ability of maneuver not only by course and velocity, but also by altitude of flight. In critical case of numerical obstacles at sea surface when the avoidance maneuver in horizontal plane is impossible, ekranoplane with perfect motion control system could jump over the obstacle. This maneuver is not desirable due to additional fuel consumption and complexity, but it could increase the flight safety in general case. The decision for any maneuver has to be automatically produced at analyzing the radar and other kinds of navigational information [10, 11].

Some special regulations are necessary to be adopted by IMO and ICAO for juridic providing of traffic control for WIG-craft and other high-speed undisplacement marine vehicles in the areas of maritime traffic, and this work was already initiated.

12. CONCLUSION

The possible effectiveness of the development and application of ekranoplanes with automatic control facilities was stated. Some new results in this field have been already achieved.

The demanded characteristics of ekranoplanes can be available only at use of the new capabilities of perfecting the systems of navigation and motion control created by modern means of supply with flight information and by resources of on-board computer. 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 have been described in this paper.

When improved, price-reduction and lightening of the on-board automatic control equipment the small ekranoplanes would also become automatically controlled and increase their marketability.

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