WING-IN-GROUND FLIGHT AUTOMATIC CONTROL SYSTEMS

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Abstract: Seaplanes and WIG-craft are supposed to take the significant part of the projected air traffic growth without constructing new airstrips. However, a trouble-free flight at low altitude over the disturbed sea surface and also marine landing require the application of the special methods and means of motion control which are capable to solve the corresponding specific problems. Methods of stability providing and solving some other problems of WIG flight by means of automatic control are analyzed[1]. The criteria for control systems improving are given. 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.

Keywords: flight control, low altitude flight, sea waves, radioaltimeter, sensors integration.

1. INTRODUCTION

The bottom of the atmosphere close to the ground or sea surface is constantly gaining in importance as the zone of flying vehicles operation. Hovercraft and other undisplacement vessels successfully use advantages of motion close to the supporting surface long ago. Aviation also aims to master better the denoted border layer of atmosphere in accomplishing the precise maneuvers with reference to vessels, in arranging the search & rescue operations over the sea, in sounding the underwater space, in using sea as a platform for take-off and landing. However, especially interesting is the new promising class of vehicles for low altitude flight, which was named as WIG-craft or ekranoplanes. For these flying machines the flight near the surface is the natural mode of motion, but many control problems arise at providing the safety and effectiveness of such flight.

Ekranoplane may be considered as a flying vehicle with the special structural distinctions providing low altitude flight possibility when using wing-in-ground effect (WIG-effect). It consists in substantial wing lift force increase and air drag decrease 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 due to different speeds of airflow about upper and lower surfaces of wing. The velocity of WIG-flight may be around 400 km/h depending of vehicle dimensions. The altitude has to be in the range from 0.5m for small vehicles to 5-10m for big ones.

It is essential that the majority of human settlements and industry centers are located close to coasts and other water areas, 80% of the global economy are concentrated within 250 km of the coasts. Needs of passenger and cargo transportation rise permanently in 6.5% per year, while it becomes difficult and extremely expensive to build new aerodromes near cities. It raises the significance of sea surface in realizing the aviation needs.

The important advantages of ekranoplanes are:
- absence of necessity for a runway and possibility to perform special transport operations using amphibian property (ekranoplanes can fly, float on water and creep out to the shore);
- 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;
- tight cabin and special life-support systems for crew and passengers are not necessary;

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- possibility to achieve higher level of comfort for passengers;
- ability to carry the payload of very large weight and overall dimensions.

Probable areas of the most effective application of ekranoplanes are:
- passenger and cargo transportation between seaside cities and in insular areas;
- transportation of a perishable cargo from the outland regions with undeveloped transport network;
- year-round cargo transportation in the Arctic regions;
- wrecking at the sea;
- assist at sea launch and landing of aerospace vehicles (Nebylov,. Ohkami and Tomita, 1999; Tomita, *et al.,*1999).

2. PECULIARITIES OF MOTION CONTROL

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). 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.2, this ekranoplane was designed for cargo and passenger transportation by "Central Design Bureau on Hydrofoils" named after R.E.Alexeev.

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.

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 (Nebylov and Wilson, 2001).

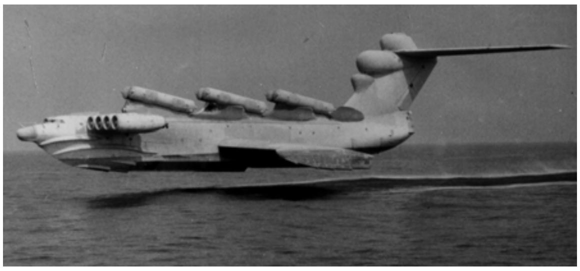

Fig.1. Ekranoplane Lun

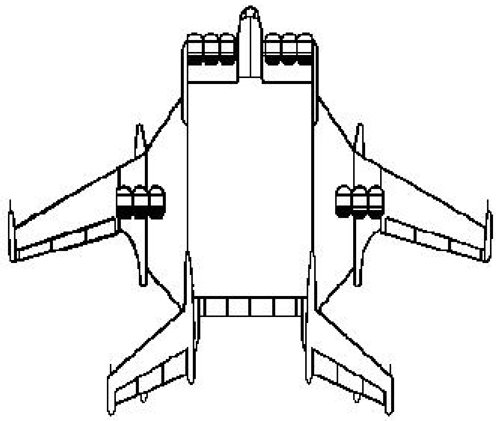

Fig.2. Promising ekranoplane with “combined wing” configuration

For such heavy machines (in 140 ton and 400 ton respectively) the automatic control systems are required certainly (Diomidov, 1996). 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 degrades 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.

Trouble-free 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 (Nebylov, 1996, 2002):
- 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.

At the high speed and low altitude of motion, proper to ekranoplanes, the problem of collision avoidance with conflict vehicles in the circumstances the time scarcity for maneuvering also originates and has a great peculiarity in compare with planes.

3. STABILITY PROBLEM

Ekranoplane as the controlled plant has an essential specificity in compare with an ordinary plane, connected with a sharp non-linear dependence of all aerodynamic coefficients and character of their correlation on a relative altitude of flight $h_r = h/b$, where h is an altitude of gravity center of ekranoplane concerning an average level of wave surface, and b is a chord of wing. 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.

4. 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 the 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.

It is important to maximize the seaworthiness of the vehicle. Though it is accepted to consider that for hydroplanes and ekranoplanes in the mode of cruise motion the sea conditions may not be 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 a route. It is evident that the seagoing ability is defined by the size and mass of a vehicle and by the peculiarities of its construction. However, even insignificant rise of seaworthiness and the safety of motion accounted for the optimization of motion control under the concrete characteristics of wave disturbances is very advisable, since it can noticeably heighten the effectiveness of vehicle application by the comparatively simple means. These facilities let, in particular, to ensure the acceptable seagoing ability of the marine fast vehicles of comparatively small size that is very important for the widening of their application on the transport lines with limited freight traffic at high frequency of sailing. At the same time it is clear that the increase of seaworthiness by means of motion control automation is possible only at a rather high level of intellectuality of the control complex.

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 (rocking, reduction of speed, increasing of fuel consumption);
- likelihood of dangerous situation due to the impulsive action of too strong;
- 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 (Nebylov and Wilson, 2001).

The exact calculation of wave disturbances has the special significance at optimization of modes of take-off and landing of ekranoplane. For example, at landing on a strongly disturbed sea surface the course angle with reference to the general direction of the spread of sea waves should be optimized. At the choice of this angle it is necessary to allow for peculiarities of aerodynamics and hydrodynamics simultaneously. Explicitly, that with the attitudes of aerodynamics the best mode of landing corresponds to the motion against the wind, when landing speed maybe minimal, and the effectiveness of aerodynamic control elements makes maximum. At windy sea waves the general direction coincides with the direction of wind, i.e. aerodynamically it is advantageously to land with the direction, contrary to general one. However, with the attitudes of hydrodynamics this direction exceptionally disadvantageously, since the frequency of meeting with sea waves and the bending of waves are maximal and the likelihood of vehicle crash because of excessive overloading is great. Hydrodynamically it is advantageously to land in the direction perpendicular to general one. That is why the optimization of the landing direction is an extreme task, and motion control at landing must be fulfilled with the allowance for current information on the characteristics of wave disturbances. Profile and the integral characteristics of sea waves can be measured together with the flight parameters of ekranoplane.

5. THE CRITERIA OF CONTROL QUALITY OF MOTION ABOVE DISTURBED SEA SURFACE

It is advisable to consider the following criteria:
- rise of seagoing ability of a vehicle, i.e. its capability to move in given direction and to decide another functional tasks at the largest number of sea conditions;
- reduce 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 concrete case requires appointing the only main criterion of control effectiveness, transforming other ones to the rank of limitations. In the number of limitations is necessary to denote also the necessity of economical expenditure of control elements resource.

6. MODELS OF WAVE DISTURBANCES

The models of sea wave disturbances have a principal significance at the examination of the algorithms of estimation and control. The method of calculation of spectral and correlation characteristics of wave disturbances on the base of three-dimensional irregular model has been developed. It is shown that the 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 (Nebylov, 2002). It is also shown, that at the 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.

7. 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 – three, four or more) sensors of sea waves profile each of which includes high-precise positioning altimeter and accelerometers. 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 (Nebylov, 2002). The created phase radioaltimeter has the following technical characteristics:

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);
radiated power - 20 mW;
power consumable - 2 W;
mass - 1.5 kg;
dimensions of hybrid strip-line antenna – 110x160 mm.

The device has appreciable advantages against ordinary radio, ultrasonic, radioisotopic and laser altimeters in application at ekranoplanes.

8. ALGORITHMS OF SENSORS INTEGRATION

The methods and results of algorithms synthesis for processing of the of indications of several radioaltimeters, several accelerometers, gyro vertical

GPS receiver in the interests 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 (Ambrtosovski and Nebylov, 2000). Author develops approach to synthesis teaming up Kalman filtration and robust filtration (Nebylov, 2004), 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 (Nebylov and Wilson, 2001).

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 structure of integration algorithm for altimeters and vertical accelerometer output signals is shown in fig.3 and involves:

- The unit of recalculation of altimeters outputs to a point of INS installation (Unit 1);
- The unit of recalculation of the altitude estimations to the point of centre of gravity CG and to the points of altimeters installation (Unit 2);
- The filter of an altitude (Filter 1);
- The filter of a vertical acceleration (Filter 2).

The recalculation of altimeters outputs to CG is executed under the formula

$$h_{GC\_K} = h_k - x_k\psi + z_k\theta - y_k,$$

where the index k=n,l,r (n - nose altimeter, l - left side altimeter, and r- right side altimeter.

For recalculation of altitudes from a point of CG to a point of INS installation the relation

$$\hat{h}_{INS}^{Ail} = \underset{k}{med}\,(h_{GC\_k} + x_{INS}\,\psi - z_{INS}\,\theta + y_{INS}\,)$$

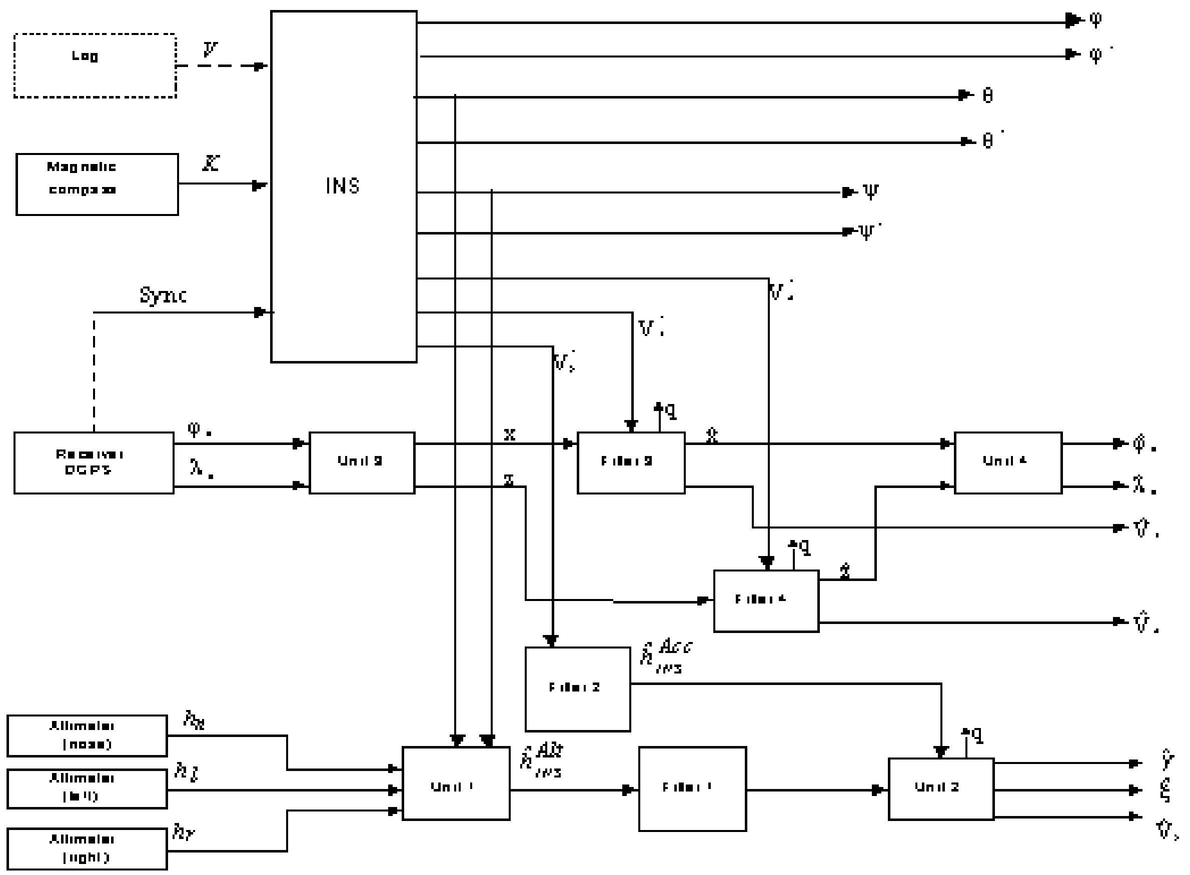

Fig.3. Block-diagram of integrated measurement system

is used, where med (.) is the operation of median definition. The formula for recalculation of the filtered value of an altitude from a point of the INS installation to CG (Unit 2) looks like:

$$\hat{h}^{f}_{GC} = \hat{h}^{f}_{INS} - x_{INS}\,\psi + z_{INS}\,\theta - y_{INS}\ .$$

The filters of an altitude and vertical acceleration have the transfer functions

$$H_1(s) = \frac{\tau^2 s^2 + 2\tau k_3 s + k_3}{s^3 + \tau^2 k_3 s^2 + 2\tau k_3 s + k_3},$$

$$H_2(s) = \frac{s}{s^3 + \tau^2 k_3 s^2 + 2\tau k_3 s + k_3},$$

where $k_3 = 0.035\ \mathrm{s}^{-3}$, $\tau = \frac{1.32}{\sqrt[3]{k_3}} = 4.035\mathrm{s}$.

In discrete time the structure of filters is described by the formulas

$$H_1(z) = \frac{b_2^1 z^2 + b_1^1 z + b_0^1}{z^3 + a_2^1 z^2 + a_1^1 z + a_0^1},$$

$$H_2(z) = \frac{b_2^2 z^2 + b_1^2 z + b_0^2}{z^3 + a_2^2 z^2 + a_1^2 z + a_0^2}.$$

The measuring system allows to track the profiles of sea waves ξ_n, ξ_l, ξ_r in three points, corresponding to the points of 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 propagation with the use of three radioaltimeters outputs will be lighted separately, that is important for optimization of a mode of landing approach and splashdown.

Separately the problem of automatic estimation the general direction of sea waves spread was solved, that important for the optimization of landing on water.

9. ALGORITHMS OF COMBINED CONTROL ON ERRORS AND WAVE DISTURBANCES

Obtained current data on the field of wave disturbances can be used (1) for the adaptation of the main motion control loops and (2) for the realization of the principle of combined control. This lets to arise the quality of motion control as to each criterion, mentioned in the item 1. However, main difficulty in the building 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.

7. CONCLUSION

The demanded characteristics of vehicles for flight close to surface can be achieved only at use of the new capabilities of perfecting the systems of navigation and motion control created by modern means of supplying with flight information and by resources of on-board computers. 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. The most important in these results are the principles of automatic digital system construction and primary sensors choice. Fast improvement of digital devices creates more perfect base for the construction and use the automatic control systems at prospective ekranoplanes, which are available to increase the effectiveness of ekranoplanes use as transport means.

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