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CONTROLLED FLIGHT CLOSE TO ROUGH SEA: STRATEGIES AND MEANS

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Abstract: The statement of the main problems of equipment and software design for flight control at small altitude above the disturbed surface is given[1]. The aim of investigation is to improve the operational performance of the vehicles of advanced design. The sets of primary sensors are integrated to increase the accuracy of measuring and control and to provide the fault-tolerance properties. The block diagram of the control system is described. It includes filters which permit to obtain the high-quality estimations of flight parameters and height of sea waves. *Copyright© 2002 IFAC.*

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1. INTRODUCTION

The border layer between water and atmosphere is gaining in importance as the zone of operation of flying and other type vehicles. This is arises chiefly at the expense of development of undisplacement vessels (wing-in-ground effect vehicles or ekranoplanes, hovercraft, controlled hydrofoils), for which the mode of motion and corresponding control problems are closer to the category “flight” than “sailing”. 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 sea, in sounding the underwater space, in using sea as a platform for take-off and landing of various aircraft.

As a rule, the solving of similar problems requires the extremely low altitude of controlled motion close to sea surface, 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 means of automatic control can ensure the required operational performance at stormy sea.

Trouble-free motion at the altitude of 1-10 m above disturbed sea surface may be guaranteed by the application of special methods and means of navigation and control capable to solve the following specific problems:

- the precise control of the altitude of motion with error not above 3-10 cm;
- restriction on the angles of airframe inclination for the preventing of undesirable tangency of water by the extreme points of body or wing;
- 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 as control plant in the circumstances of the action of flake essentially non-linear aerodynamic effects attributed to nearness of water surface (WIG-effect and others);
- non-contact measurement, tracking and prediction of ordinates and biases of the field of sea wave disturbances for the rising of motion control effectiveness.

At the high speed of motion, proper to planes and ekranoplanes, the problem of collision avoidance with conflict vehicles in the circumstances of scarcity of time for maneuvering also originates, which is not characteristic for displacement ships.

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All above-mentioned problems have to be analyzed for constructing the automatic motion control system which could meet the modern requirements (Nebylov, 1994; Nebylov and Wilson, 2002).

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

It is advisable to consider the following criteria:

- rising of seagoing ability of a vehicle, i.e. its capability to move in given direction and to solve another functional tasks at the largest number of sea-way conditions;
- reducing 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 other ones to the rank of limitations. In the number of limitations it is necessary to denote also criteria simultaneously and each concrete case requires to appoint the only main criterion of control effectiveness, transforming the requirement of economical expenditure of control elements resource.

The criterion of maximization of seagoing ability is of particular importance not only for undisplacement ships but also for marine aircraft. Though it is generally assumed that for hydro-airplanes and partially ekranoplanes 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 the route. It is evident, that seagoing ability is mainly defined by the size and mass of vehicle and by the peculiarities of its construction. However, even an insignificant rise of seaworthiness and the level of the safety of motion due to optimization of motion control with allowance for concrete characteristics of sea disturbances is very advisable, since it 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 vehicles of comparatively small size, that is very important for the widening of their application on transport lines with limited freight traffic, but with high frequency of sailing.

3. 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;
- likelihood of the appearance of abnormal situation or catastrophe due to the impulsive exposures of too large extent;
- creation of significant interference for sensors (radar, sonar and others) of the parameters of motion due to tracking the profile of 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. Indeed, it is necessary not only optimization of laws of control in classic meaning, but also optimization of the composition of controlled parameters of motion and the parameters of wave disturbances, the composition and the placing of diverse transducers of these parameters, the algorithms of their integration, the structures of control channels and laws, the tactics of the application of all accessible 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 such 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 (Nebylov, 1994). It is shown that the most lowest frequency spectral component of wave surface in moving reference frame have a maximum at the definite speed of motion reckoned as the function of the course of vehicle and the parameters of the disturbances intensity. It is also shown, that at the sufficiently large speed of motion the recalculation of the characteristics of wave disturbances in moving coordinate frame can be lawfully fulfilled with the application of the spatial spectra of “frozen” surface with simplified elements motion. This enables the speedy calculation of the characteristics of disturbances in real time at on-board computers and expands the possibilities of increasing the intelligence of control complex.

4. DEVELOPMENT OF 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 sensors of sea waves profile each of which includes the precise positioning altimeter and inertial means (Nebylov, *et al.*, 1995; Nebylov, 2001). Presence aboard of the 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.

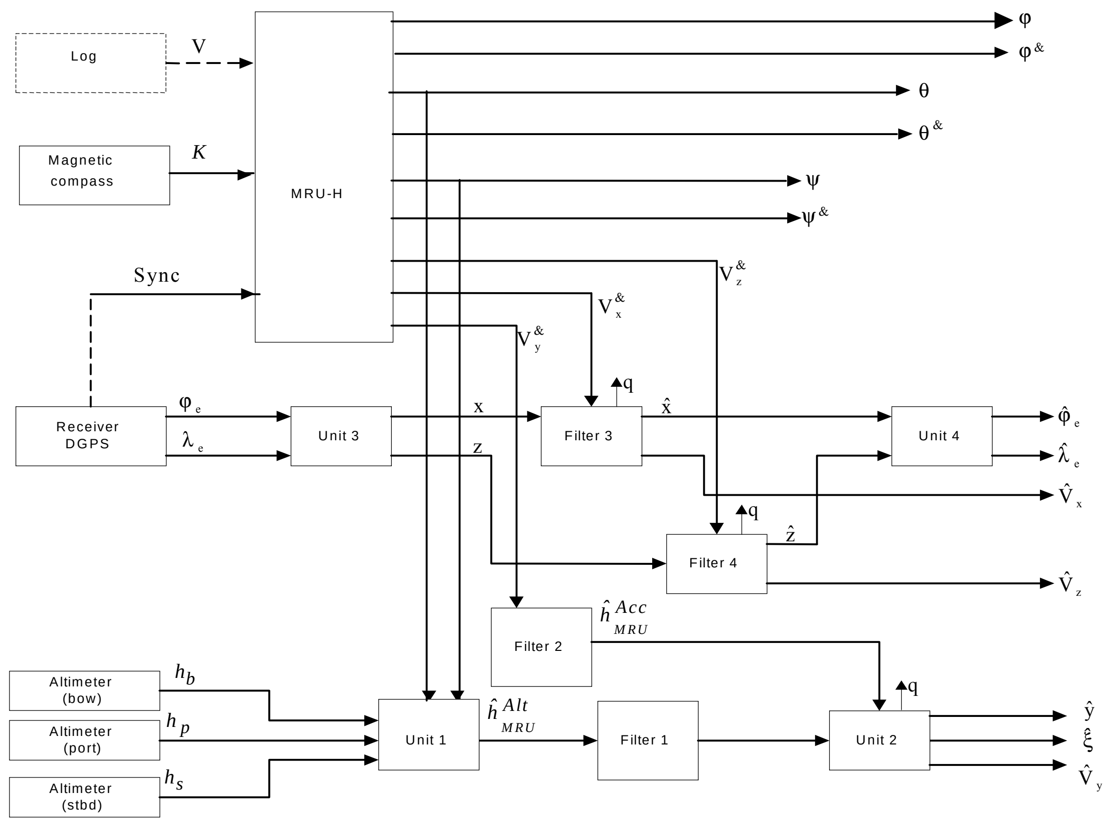

Fig.1. Block-diagram of integrated measurement system.

The advantages of application of expressly projected phase radioaltimeters in compare with ordinary ultrasonic, radioisotopic or even laser altimeters can be substantiated (Nebylov, 1994; Nebylov, *et al.*, 1995; Nebylov and Wilson, 2002).

Created under the leadership of the author the experimental specimens of such radar sensors (in integral execution, flat aerial, mass of 1.5 kg, digital and analog output) have already confirmed the required accuracy at trials in tank, and debugging as to removal 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 been achieved:
- measurement error - not more than 5 cm under sea-way of number 0-5, it is possible to measure the vertical speed with the accuracy 0.1 cm/sec;
- altitude (or distance) measured - 0-10m (at necessity - up to 100m);
- measured parameter frequency range - 0-20 Hz;
- the operating RF - from X-range (9000 MHz);
- radiated power - 20 mW;
- power supply - 12 V± 3%;
- power consumption - 2 W;
- output signal– digital and analog;
- mass - 1.2 kg;
- dimensions of SHF-modules - 110××90×60 mm.

5. ANALYSIS AND DEVELOPMENT OF FLIGHT PARAMETERS MEASURING SYSTEM

The system was designed for a small experimental WIG-craft of length about 14m (Ambrosovski and Nebylov, 2000). The complex was intended for the control and record of parameters of WIG-craft flight in a test period and during exploitation of a craft. The sensors of motion parameters, on-board computer of marine design and special software were included in the system structure. The system was installed on board of the craft in a nominal 19" rack for instrumentation. The power supply was implemented from on-board grid 24V of direct current.

The following main parameters of flight were controlled:
- co-ordinates of the WIG-craft position;
- flight speed;
- altitude of flight;
- head, roll and pitch angles;
- vertical overloads in a passenger saloon and center of gravity of the craft.

It was required to measure also a wave height.

The following requirements to the range and measurement accuracy of parameters were showed:
- measurement of motion velocity up to 120 knots with accuracy 0.1-0.2 knots;
- measurement of heading with accuracy 0.1-0.2 deg;

- roll and pitch angular measurement up to 45 deg with accuracy 0.1-0.2 deg;
- measurement of an altitude of flight up to 5 m with accuracy 5 cm;
- measurement of vertical overloads up to 3g with accuracy 0.06g;
- measurement of a considerable wave height up to 1.5 m with accuracy 10 cm.

Record of main controlled flight parameters with the frequency of 5-10 Hz, and record of co-ordinates of vehicle position with frequency of 0.5-1.0 Hz were provided.

The designing of measuring complex structure was carried out taking into account the reviewed requirements, necessity of fault-tolerance providing, the cost and capability of repairing. Three versions of the block-diagram were analyzed:

In view of the full set of multilateral requirements [1-3] and carried out marketing investigations the selection was done on the block-diagram grounded on usage of an integrated meter, with the meter MRU-H of the Norwegian production being selected. Such selection of the basic sensor was determined in many respects by outlooks of coming-out to the world market of on-board control equipment.

The described above precise radioaltimeters specially designed in the International Institute for Advanced Aerospace Technologies of SUAI were used as altitude sensors. They ensure high accuracy of measurement of small altitudes and low sensitivity to angular oscillations of the underlying surface.
The designed block-diagram of the measuring complex is represented by Fig. 1.

6. ALGORITHMIC MAINTENANCE OF THE COMPLEX

The most relevant part of algorithmic means providing complex operation is the algorithm of filtration of altimeters and vertical accelerometer measurements, which involves:
- the unit of translation of altimeters measurements into the point of MRU installation (Unit 1);
- the unit of translation of the altitude estimation from a point of MRU installation into center of gravity CG (Unit 2);
- the filter of the altitude (Filter 1);
- the filter of the vertical acceleration (Filter 2).

The structure of filtration algorithm is shown in Fig.2.

The translation of values of altitudes obtained by altimeters into CG was executed under the following formula:

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

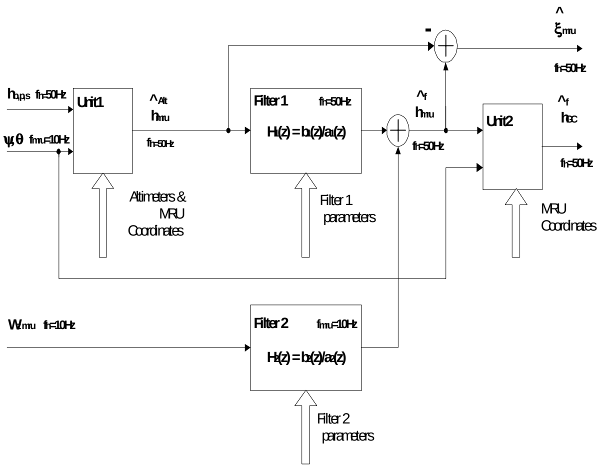

Fig.2. Algorithm structure for filtration of measurements of altimeters and vertical accelerometers.

where an index $k = b, p, s$. (b - nose altimeter, p-portside altimeter and s - starboard altimeter, and for translation of values of altitudes from CG point into a point of MRU installation the following ratio was used:

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

where med () is the operation of median definition.

The formula for translation of the filtered value of an altitude from a point of MRU installation into CG (Unit 2) looks like:

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

The filters of an altitude (Filter 1) and vertical acceleration (Filter 2) were synthesized on the base of robust dynamical filtration theory under the criterion of ensuring the necessary accuracy of measurement (Nebylov, 1998). Their transfer functions are

$$H_1(s) = \frac{W(s)}{1+W(s)}, \quad H_2(s) = \frac{1}{s^2(1+W(s))},$$

where $W(s) = k_3(1+\tau s)^2 / s^3$ is the transfer function of the open loop, $k_3 = 0.035c^{-3}$, $\tau = \frac{1.32}{\sqrt[3]{k_3}} = 4.035c$,

or

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

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

In discrete time the filters will look like:

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

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

In the case of failures appearing in the roll and pitch channels, for example, due to an error of integrating, the capability of recovery of angular variables in the measuring complex with the use of altimeters was stipulated.

7. THE STRUCTURE OF ALGORITHM FOR FILTRATION OF MEASUREMENTS OF ALTIMETERS AND ANGULAR RATE SENSORS IN ROLL AND PITCH CHANNELS

The algorithm of filtration of altimeters and vertical accelerometer measurements includes:
- the unit of calculation of roll and pitch angles using the measurements of altimeters;
- the filter of angular variables (Filter 1);
- the filter of angular rate (Filter 2).

The filters of angular positions and angular rates are identical to filters in an altitude channel, the only difference is an additional variable *s* in the numerator of transfer function which the filter of angular rate has. This fact is determined by including this filter in a channel of speed, instead of acceleration.

The software of the measuring system is made out as a single exe-file, designed on Borland C ++ 3.1 under the operating system MS DOS 6.22. The software consists of the following parts (Ambrosovski and Nebylov, 2000):
- transcription of the ini-file (distribution of the data, given by user);
- processing (obtaining, decoding) of the input information in the standard NMEA (DGPS, MRU);
- processing (obtaining, scaling) of the input information from the plate A-821 PGL (altimeters);
- digital filtration of signals from altimeters and MRU;
- on-line estimation of the significant height of sea waves;
- displaying on a screen (in a text mode, with the multi-window interface) obtained and processed information;
- record of output data on the disk;
- test modes (for internal debugging by implementator) - formation of sendings in the standard NMEA (emulation of MRU and DGPS activity);
- signals supply on plate A-821-PGL (emulation of altimeters activity);
- simulation of motion of vehicle, simulation of sea-way.

The hardware of a complex allows to hook up the integrated sensor MRU-H of the SeaTex corporation, receiver DGPS of the Trimble corporation and altimeters. The data exchange was implemented with the use of the interface plates A-821PGL and Moxa 104. The capability of further retrofit of the scheme by hooking up of output analog signals of the unit MRU, indication of a signal 5V for the information on presence of a power supply in a record system, loading information about a flying speed and course of ekranoplane is stipulated.

Separately the problem of automatic estimation the general direction of sea waves spread can be studied, that is important for the optimization of the mode approach and landing on water.

8. 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 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.

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

9. OUTLOOKS OF THE RISE OF TRANSPORT VEHICLES EFFECTIVENESS AT THE EXPENSE OF IMPROVING THE FACILITIES OF MOTION CONTROL

It is expedient to produce the estimation of the state and outlook of development of some types of marine transport vehicles which could define the potential area of application of described methods and facilities.

Hydrofoils with controlled wings are good objects for the demonstration of new possibilities of automatic

facilities of motion control. However, the problem of cavitation for foils limits the speed of motion. The other limitations bound with the presence of underwater elements exist as well. The market of these vehicles seams to be in relative depression.
Unfortunately, hovercraft generally have no advanced quick in response actuators for creation of the forces and moments with the band of frequencies corresponding to the frequencies of wave disturbances. The development of new executive elements in matching with the improving of the algorithms of navigation and motion control can give the tangible results.

Hydro-airplanes require the creation of control equipment of the new generation, especially for the optimization of the mode of landing. At landing on the disturbed sea surface the trajectory of motion has a complementary parameter to be optimized - the course angle with reference to the general direction of the spread of sea waves. At the choice of this angle it is necessary to take into account the 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 may be minimal, and the effectiveness of aerodynamic control elements - maximal. At developing windy sea waves the general direction coincides with the direction of wind, i.e. aerodynamically it is most advantageous to land in the direction, contrary to general direction. However, with the attitudes of hydrodynamics this direction is exceptionally disadvantageous, since the frequency of meeting with sea waves and the bending of waves are maximal and the likelihood of vehicle destruction because of excessive overloading is great. Hydrodynamically it is most advantageous to land in the direction perpendicular to general one. That is why the optimization of the landing direction is a complex extreme task, and motion control at landing must be fulfilled with allowance for current information on the characteristics of wave disturbances.

At flight control of helicopters it is important to improve the mode of hanging or motion at an extremely small altitude over sea surface.

In relation to ekranoplanes, practically all projects of small and middle sizes known now at world, unfortunately, do not suppose the applications of the advanced facilities of the automation of short-periodical motion control, it is generally attributed by the economic demands of a market. However, bigger vehicles require necessarily their application. Apparently, significant outlooks may be connected with the new possible area of the application of heavy ekranoplanes in executing the search & rescue operations in oceans, as well as at horizontal launch and landing of aerospace plane (Nebylov, at al., 1999; Tomita and Nebylov, 1999). For the realization of these projects the application of the entire possible conceptual resources of the facilities of navigation and automation of motion control is required.

10. 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 supply 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.

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