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Optimization of WIG-craft 3D-trajectory near the rough sea surface

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Abstract

Intense sea disturbance create difficulties for movement of low-altitude marine aircrafts. An algorithm is proposed for controlling a low-altitude apparatus to minimize flight altitude due to waves following with the use of lateral motion control channel. Reduction of average flight altitude provides a positive effect on fuel efficiency and expands the range of tasks to be completed by means of this class of vehicles, among which are high-speed intercontinental cargo and passenger transportations. This paper shows possibility of applying the proposed control algorithm for of small and medium class maneuverable ekranoplans, but does not consider its effect on movement of any particular model.

1. Introduction

At present, solution of many transportation tasks is entrusted to low-altitude naval aviation and non-displacement vessels. Their advantages over displacement vessels include high speeds and often amphibiousness and high maneuverability. In comparison with conventional aircrafts (AC) they have larger load capacity at the same engine power.

This type of vehicles can be used for cargo and passenger transportation, as amphibious, striking and rescue means, but for development of their mass use, new ideas and serious research are needed [1-11]. The ekranoplan control system (CS) should take into account peculiarities of flight close to surface, which results in its complication and significantly higher cost compared to conventional aircraft CS [12].

An important subclass of low-altitude vehicles are ekranoplans. In this article, based on their example, feasibility of using the proposed control algorithm will be justified. But its use for other vehicles also increases flight safety in conditions of intense sea disturbance.

Advantages of ekranoplans are achieved due to use of ground effect consisting in pressure buildup under lower plane of aircraft wing, steep increase of lifting force and improvement of other aerodynamic characteristics during flight close to screening surface (usually water, snow, ice or ground). Unlike air cushion, the ground effect arises naturally, due to dynamic ram air flow, rather than its forced blowing. Value of aerodynamic quality increase for vehicle moving close to screen surface K, with respect to aerodynamic quality of aircraft moving outside of its action zone K_∞ shall be calculated by formula

$$K/K_\infty = 1 + b/25h \; at \; h/b \geq 0.03$$

where b is the wing chord, from which it is seen that the smaller is h, the higher with altitude descent is the ratio K/K_∞, which is inversely proportional to fuel costs.

Unevenness of underlying surface prevents altitude lowering, increasing probability of collision when it decreases. If there is no control of aircraft flight in horizontal plane, height of the lowest element of vehicle's design with allowance for stabilization errors should be greater than the highest point of reference surface. In conditions of heavy sea disturbance this fact greatly reduces positive influence of the ground effect.

Fuel consumption primarily affects the cost factors, which in many cases are crucial in formation of transport development strategy, decision making on design, choice of tactics for transport vehicles operation.

The article proposes an algorithm for low-altitude vehicle flight control close to uneven surface and determines the value of increase in aircraft mileage during controlled flight with maneuvering along the course relative to uncontrolled flight. There is also estimated decrease in average wave height under AC and gradient of altitudes under the flight path. The algorithm actuality is justified by decrease in fuel consumption of ekranoplan while controlling its horizontal movement above the sea surface to reduce distance between it and supporting surface. The proposed control law can be also implemented for other low-altitude vehicles and non-displacement vessels that have

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sufficient maneuverability. Fuel economy, achieved due to the ground effect with the flight altitude descent, is only one of advantages that can be obtained by following big waves.

2. Features of low-altitude fly

Low-altitude flight has a number of specific peculiarities that distinguish it from a high altitude flight performed outside the coverage area of ground effect and at altitude at which probability of collision with underlying surface by influence of control errors, with good on-board equipment, is close to zero. Particular attention should be paid to stabilizing the vehicle, because even a small change in the angle of roll or pitch affects the altitude measurements and other flight parameters. With poor stabilization of the aircraft, probability of its collision with the underlying surface increases. Designs of some low-altitude marine aircrafts allow for occasional short-term water touches, but such touches adversely affect flight dynamics, introducing various disturbances and increasing likelihood of damage to hull and overturning of the vehicle. Ekranoplans, air-cushion vessels and some other types of low-altitude vehicles (LAV) have the property of self-stabilization in flight altitude, because due to increase in lifting force, with reduction of distance to the underlying surface at certain height, there is an equilibrium between the lifting force and the vehicle weight. Since the flight parameters measurement is usually associated with local sounding, geometric characteristics of the underlying surface irregularities largely determine operating conditions of measuring equipment. Size of the area allocated for sounding is limited by radar angular aperture and can be substantially smaller than the sea waves dimensions, therefore profile of wave surface with variable elevations, gradients and orbital velocities is tracked practically without averaging. General operation principles of on-board motion parameters sensors are well covered in reference literature [13-15]. In order to increase dynamic properties of aircraft control system, measurements should be carried out without delay and smoothing, and this means that effective interference cancellation is possible only in complex measuring systems with different types of sensors.

When flying close to reference surface, accuracy and reliability of control over altitude h, roll γ and pitch θ angles, have the biggest impact on possibility of the vehicle altitude descent, while moving within the limits of specified safety level. Values of these parameters stabilization error have a major influence on minimum possible flight altitude in cruising conditions and, therefore, on the aircraft's functionality and fuel economy. Requirements for measuring accuracy of altitude and inclination angles are assigned more strict than for accuracy of their control. Maximum errors in their measurement may have values of 10^{-1} m and 10^{-1} deg. respectively, which is difficult to ensure when flying over wave-covered water. In addition to the absolute measurement error values, it is important to consider their spectral composition. The most dangerous are low-frequency components falling into the control loop passband, whose width can be about 0.5-3 Hz depending on the aircraft type. The high-frequency components of measurement error spectrum can adversely affect operating modes of elements with limited linear range, reduce steering controls service life and impair quality of flight information display to the crew. Another important parameter used by automatic pilot systems for airplanes and ekranoplans is air speed V_a, its change due to wind gusts leads to vertical accelerations and changes in wing lifting force. Stiff stability of the vehicle flight altitude is achieved by parrying these accelerations, due to deviations of the aircraft steering controls. This increases requirements for accuracy and time of air speed assessment. In order to control condition of trouble-free movement, it is advisable to estimate accuracy of the above-listed flight parameters assessment by the maximum error rate. The root-mean-square error rate can have a supporting role in the control quality study. The following parameters, which measurement quality is less related to accident-free flight, are the ground speed V, course ψ, gliding angle β and drift correction angle β_c. To characterize their measurement accuracy, root-mean-square error rates are sufficient

3. Altitude measurement

Physical height of flight is measured by the method of active location. Hereafter as altimeter it will be understood an altitude measuring instrument of arbitrary type, which provides value of average range to a small area of underlying surface below it. Dimensions of this area should be small enough to distinguish upper and lower parts of waves (crests and hollows) during low-altitude movement.

It is necessary to have minimum two altimeters at a certain distance from each other. It is assumed that the LAV is ideally stabilized and has zero roll and pitch angles, otherwise the measured heights shall be adjusted with allowance for the roll and pitch angles.

4. Description for algorithm of waves rounding

The proposed AC movement control algorithm is to find the most advantageous direction, in which the height of underlying surface relative to current location will be minimal.

There are two difficulties in using this algorithm in its pure form, the first is that there is no guarantee of getting the vehicle into desired final area ofthe route, and secondly, limitations connected with its inertial characteristics are imposed on the aircraft maneuvers. The aircraft coming into the desired area can be ensured by limiting the range of possible movement directions and narrowing it as it approaches the end point. The non-linear dependence of the waves height on their spatial coordinates suggests that by measurements of true heights of two points on the aircraft hull it is difficult to determine the best movement direction, which makes necessary to choose it approximately. It is possible to implement relay control by selecting angle of rotation and frequency of taken measurements and correcting the aircraft course by this angle in direction of minimum height (or minimum gradient) after obtaining each measurement. It is also possible to change direction by value proportional to the difference in measurements taken from the two sensors.

The relay law of formation of the aircraft movement trajectory over the minimum heights shall be mathematically determined by formula

$$\psi(t) = \psi(t - \Delta t) + sgn\big(h_{\text{п}}(t) - h_{\text{л}}(t)\big) D_{\text{к}}, \tag{1}$$

where $sgn(x)$ is signum function; $h_{\text{п}}$ - altitude measured by the right sensor; $h_{\text{л}}$ - altitude measured by the left sensor; $D_{\text{к}}$ - the aircraft course change value at difference in readings of altimeters; Δt - period of taking measurements from altimeter. With proportional regulation the course shall be defined as

$$\psi(t) = \psi(t - \Delta t) + \big(h_{\text{п}}(t) - h_{\text{л}}(t)\big) K. \tag{2}$$

The coefficient K is selected depending on the sea disturbance magnitude, distance between the sensors and inertial characteristics of the aircraft. To reduce frequency of measurements is possible by increasing number of sensors, placing them along the arc on the aircraft body, and choosing direction of movement at the minimum height

$$\psi(t + \Delta t) = \psi(t) + \alpha_{min\,h}. \tag{3}$$

Here $\alpha_{min\,h}$ is the angle between longitudinal axis of the aircraft and straight line drawn between the altimeters group center and the altimeter having minimum distance to the underlying surface in comparison with the others

$$min_h = index\big(\min(h_i)\big), \; at\; i = 1 \dots N \tag{4}$$

where N is the number of sensors; $index(x_i)$ - operation of taking index; h_i - height of the i-th sensor above the sea surface.

Formula 4 describes the relay control principle of the aircraft flight during measurements by a group of altimeters; in this case we can generalize proportional control too by substituting in the formula (4) two minimum heights obtained by sensors from the group, with typical form of developed sea disturbance these meters will be neighboring.

The relay control algorithm consists of the following sequence of actions:

1. Based on the current weather conditions, aircraft flight characteristics and trajectory length limitations, to determine dependence of the vehicle allowed motion sector width on the distance to the route final point (center of the sector is directed to this point). Starting from some distance between the vehicle and point of arrival, it is proposed to narrow the allowed motion sector so that at zero distance the sector width was equal to zero, then the exact arrival of the vehicle at destination point is guaranteed.
2. Taking into account all the previous indicators and frequency of altitude measurements, to determine frequency of the movement direction correction, threshold value of difference in altitudes measured by location altimeters and the value of change in the vehicle course when this threshold is exceeded. The last two parameters also depend on relative positions of space-based location altimeters;

During the flight:

3. Find the difference in estimates of true heights of on-board radar altimeters;
4. If it exceeds the established threshold, summarize the vehicle current course with specified value of course changes (paragraph 2). When finding the received value of intended course within the allowed motion sector (item 1), turn the vehicle using direction rudder to the received course, otherwise move at the direction closest to the allowed one;

Dependences of the algorithm parameters on the environment and the vehicle characteristics are not considered in this article. The width of allowed motion sector, threshold value of difference in altitude estimates and the course change value can be calculated adaptively by estimating the sea disturbance parameters. Identification of such dependencies is the direction of further work.

The primary objective of aircraft control is to determine deviations of controls under current flight conditions. Movement of an aircraft, as a solid body in bound coordinate system, is described by Euler equations. Forces and moments involved in these equations, in a complex manner depend on altitude, speed and flight regime and vary in time, along with changes in flight conditions, for example, the aircraft mass and moments of inertia. Thus, the proposed control law shall be realized on each aircraft, depending on its physical characteristics and arrangement of controls.

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5. Simulations of disturbed sea

Since the proposed control law is planned to be used primarily for marine low-altitude vehicles, when simulating underlying surface there was imitated disturbed sea. Properties of wind waves depend on the wind speed, duration of its action and other peculiarities of wave formation. Insufficient knowledge of the wave formation laws forces us to consider the model of wave-covered water as a problem of identifying random three-dimensional field characteristics by experimental data. In the general case, this field is inhomogeneous and unsteady. To facilitate the modeling problem, it is possible to represent, with allowable accuracy, the developed sea disturbance as uniform and steady. About half a century ago, a probabilistic approach was applied to study of sea disturbance. At present, the sea disturbance ordinate is usually described as a stationary ergodic centered random function with normal distribution law, and the wave surface as a stationary normal random field that is anisotropic in directions. The of wind waves process normality is confirmed by experiments for the main part of probability density curve [16-18]. It is a superposition of large number of random wave systems and is in accordance with the Lyapunov limiting theorem. Exception is a very strong wind wave, in which there are such non-linear effects as wave crests breaking, asymmetry of their slopes, etc. This leads to slight deviation of the ordinates probability density from the normal, but for the problem under consideration validity of the Gaussian model of sea disturbance is beyond doubt. This implies the Rayleigh law of wave heights distribution.

A measure of the distribution intensity is considered to be the height of waves with occurrence of 3%. As the wave height there is meant vertical distance between two consecutive maximum and minimum levels. Due to the Rayleigh law of wave heights distribution, the value h_3 is associated with dispersion of wave ordinates σ_y^2 by the formula

$$h_3 = 2\sqrt{-2\sigma_y^2 ln 0.03} = 5.27\sigma_y \qquad (5)$$

Modeling of the disturbed sea surface is carried out according to the V. Pearson formula [18]. Wind waves in it are represented as superposition of a set of elementary two-dimensional cylindrical waves with different amplitudes, frequencies, phases and propagation directions.

$$\xi(x, y) = \sum_{i=1}^{n}\sum_{j=1}^{m} r_{ij}\, cos\big(k_i x cos(\alpha_j) + k_i y sin(\alpha_j) + \varepsilon_{ij}\big), \qquad (6)$$

where $\xi(x, y)$ – wave height as a function of spatial coordinates, n – number of harmonics with different frequencies, m – number of harmonic waves with different propagation directions, k_i – spatial frequency of wave, α_j – angle characterizing the propagation direction of harmonic wave, r_{ij} – wave amplitude with i-th frequency and j-th propagation direction, ε_{ij} – phase represented by random number with uniform distribution.

Spatial frequencies are determined by formula [8.9]

$$k_i = \Omega_i^2/g, \qquad (7)$$

where Ω is the mean square frequency of spectrum

$$\Omega = 0.77 \times \left(\frac{g}{h_3}\right)^{\frac{1}{2}}, \qquad (8)$$

In the ideal case, n and m must be are very large values, however, in [19] there is shown that in order to simulate developed irregular sea disturbance with high confidence it is sufficient to accept $n = m = 7$.

To simulate the LAV movement close to the sea surface, a program has been developed that simulates developed sea disturbance of indicated magnitude and aligns the vehicle trajectory based on its characteristics and input parameters of the control law. It is also possible to evaluate efficiency of control by change in fuel costs, flight time, increase in distance relative to unguided flight. This allows to experimentally select control parameters that are close to optimal by specified criterion.

6. Fly simulation

Figure 1 shows trajectory realization of LAV controlled by relay principle on the basis of measurements obtained from two physical height sensors mounted on the aircraft wings. Elevations are indicated in red, depressions in blue. There was simulated 6 points sea disturbance, wind direction coincided with the wave propagation direction, wind force vector did not vary in modulus and direction, which made it possible to compensate for drift by changing yaw angle.

The simulated vehicle characteristics primarily affect its linear and angular speeds and accelerations. Based on characteristics of medium and small size ekranoplans, speed of their movement at simulation was assumed to be 40-200 km/h. Since at high speeds aircraft does not have time to enter wave troughs, their consideration does not make sense. The angular velocity modulus was limited to 10-30 deg./s. Such upscale of the vehicle movement model has little effect on accuracy and allows us to cover larger area in the modeling objects characteristics space.

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To display the sea surface, a rectangular area is distinguished from the start point to the last point of trajectory, after that the maximum and minimum valuesof wave heights within this area are determined. The entire range of heights is displayed using combinations of red, green and blue colors. From zero height to the lowest point, intensity of blue color increases to the topmost red, the green color is distributed in -0.5hmin – 0.5hmax range of heights. And its intensity is the greater, the smaller is $|h|$.

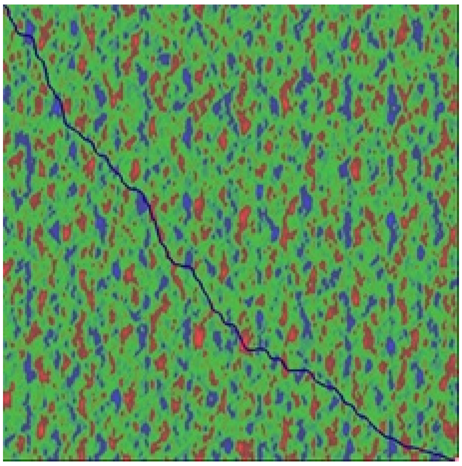

Figure 1 - LAV flight trajectory over disturbed sea surface

With approaching the path end, the vehicle trajectory is straightened by narrowing the allowed motion sector. During simulation, at the beginning of the path the allowed motion sector was 70 degrees. Its center is always directed towards the end point. While approaching the arrival point closer than 450 meters, the allowed motion sector began to be 0.1 from the distance to the end point. The aircraft control reduced the true altitude by almost 10% and increased the path slightly more than by 10%.

Poor predictability of disturbance complicates the task of LAV movement control over the sea surface. In some parts of flight, due to strong inertia the vehicle does not have time to turn to sufficient angle for wave following and hits the very peak of it. By complicating the measuring systems and supplementing the proposed algorithm with special blocks of surrounding situation analysis, it is possible to improve quality of control. It is also possible to expand the allowed motion sector in some areas, in cases where the current sector is not enough to pass-around high waves. In the event of proportional law control, it is necessary to determine dependence of turning angle on the disturbance degree, distance between sensors and other characteristics of the environment and aircraft. Study of such dependencies is the subject of further research.

Another difficulty of control is the problem of choosing solution to follow the wave crest or pass-around it. In some cases, according to criterion of minimum average wave height under the trajectory, it is better to go through the wave than to round it. Passage through the wave crest along the shortest path violates the above mentioned condition of movement in the minimum height direction.

Conclusions

As a result of simulating series of ekranoplan flights over disturbed sea surface, under various environmental conditions, speeds and maneuvering characteristics, it is established that the vehicle movement control according to the proposed algorithm allows to reduce average movement altitude by up to 13%, with increase in trajectory length by up to 12%, aerodynamic quality increases by up to 15%. When direction from start point to final point of the route is close to the waves propagation direction, the vehicle altitude practically does not decrease, therefore it is advisable to plot the AC trajectory along the wave troughs only when modulus of their values difference is within a certain range determined experimentally for particular vehicle and weather conditions. The authors believe that in general this range can be 135-180 deg.

The present algorithm can be used not only with ekranoplanes, but also for other types of aircrafts and non-displacement vessels.

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