Optimization of ekranoplane flight control over the waved sea

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Abstract. The paper proposes to minimize the average altitude of the ekranoplane due to the desire to circumvent the low-periodic components of sea waves with smooth vertical maneuvers. To evaluate the effectiveness of the proposed method for optimizing the trajectory, a model was developed consisting of four blocks: simulation of sea waves, simulation of the operation of the measurement and control system of a ekranoplan, modeling the dynamics of the movement of an UAV, and evaluating the effectiveness of altitude minimization. The simulation results showed the possibility of reducing the average altitude of ekranoplane by 0.65m in 6-point sea waves. Also, the overload caused by vertical maneuvers did not exceed 0.16 g, which is acceptable for the transportation of most goods and people.

1. Introduction
The main danger of low-altitude movement of an aircraft over the sea surface is the possibility of collision with other marine vehicles and crests of sea waves. It is possible to prevent a collision with another object by joint breeding of their trajectories or by timely detection of a potentially dangerous object, evaluating the parameters of its movement and plotting its own trajectory at a safe distance from it.

The problem of collision with the crests of sea waves is currently solved by increasing the flight altitude. Because of this, the advantages of low-altitude traffic are lost. In [1-3], it is shown that using smooth lateral maneuvering, it is possible to plot the trajectory of a ekranoplan over the lowest sections of the sea surface. To minimize the altitude, lateral maneuvering must be combined with vertical maneuvering to optimize the 3D trajectory. In a simpler case, it is possible to minimize the altitude of an ekranoplan by optimizing the 2D trajectory using vertical maneuvering, without using lateral maneuvers. For example, when moving along the shortest straight path in the horizontal plane. Flight under such conditions is considered in this paper.

The purpose of this work is to show the possibility of minimizing the altitude of a highly maneuverable ekranoplane moving near an agitated sea surface, due to the desire to circumvent low-period components of sea waves by vertical maneuvers. In this case, minimizing the absolute altitude can be considered as a task to stabilize the true geometric altitude of the ekranoplane set by \( h_{req} \) relative to only the low-frequency components of the spatial spectrum of sea waves, with the accuracy of stabilization limited by the maneuvering characteristics of the ekranoplane. Stabilization is carried out by controlling the Elevator and flaps so that the ekranoplane tries to repeat the low-frequency components of the sea waves as accurately as possible. The problems of reducing radar visibility and improving aerodynamic quality are separate volume studies and are not considered in this paper.

Movement in the wave-skirting mode at low average altitude increases the probability of touching the sea surface. Most low-flying marine vehicles can withstand light touches of the sea surface. If the device moves by using the dynamic principle of support, the upper part of the sea waves is slightly...
pushed through by an air cushion, preventing the crests from touching. Also, for such vehicles, minimizing the height in addition to reducing radar visibility increases the aerodynamic quality, and, as a result, the load capacity.

By simulation in MATLAB-Simulink has been obtained realization of the trajectories of low-flying camera, moving in conditions 4 and 6-point irregular sea waves and estimated the magnitude of the decrease in average altitudes of these trajectories compared to the trajectories with a constant absolute altitude without maneuvers.

When modeling, the following simplifications were made: the speed of propagation of sea waves was not taken into account; wind gusts were also not simulated. The first assumption is acceptable, since the speed of propagation of sea waves is significantly lower than the speed of movement of a low-flying vehicle and therefore does not have a significant impact. The study of the effect of wind gusts is planned for the next step of the study.

Sea waves were simulated using a fractional-rational approximation of the irregular sea wave spectrum. A fractional-rational order function was taken as the transfer function of a low-flying vehicle. This model is acceptable, since nonlinear effects in the formation of wind sea waves begin to act only when a strong storm wave has a score greater than 6. the transport objects Considered in this article are not used in such a heavily stormy sea. Some researchers consider nonlinear effects to be more significant even with a lower wave score, but they do not describe in detail the physics and mathematics of these effects, which makes modeling difficult. Their results are based on statistical processing of experimental data, which cannot be comprehensive and reflect the current properties of a non-stationary random field in General.

Since this paper substantiates the relevance of more detailed studies in the direction of trajectory optimization through maneuvering, and does not analyze the effectiveness of minimizing the height of any particular model of a ekranoplan, the above simplifications are acceptable.

The simulation results showed the possibility of reducing the altitude of a highly maneuverable ekranoplan in a 6-point sea wave, when the height of h3% =6m, by 0.65 m. The effectiveness of the proposed method of height minimization should be evaluated for a specific model of a ekranoplan.

It should be noted that the authors do not propose to provide the envelope of long-period waves at any cost, including afterburning engines. In the case of ekranoplan control, the main mechanism of wave envelope should be based on its natural property of self-stabilization in altitude, which is manifested only at infra-low frequencies. These include a small part of the spectral components of waves in a mobile coordinate system, especially when flying in a direction perpendicular to the General direction of wave propagation, with wind waves whose General direction of propagation coincides with the wind direction. There is no need to use afterburner mode, since the effect of saving fuel and low location visibility is more important. If the flight mode does not contribute to at least partial circumference of the waves, then you need to fly without circumference, and when it is possible to turn on the circumference mode. Special energy costs are not required for this.

2. Modeling

To assess the possibility of lowering the average altitude of the ekranoplan due to smooth vertical maneuvers, a Simulink model was developed, consisting of the following blocks: simulation of sea waves, simulation of the operation of the measuring and control system of a ekranoplan, modeling of the dynamics of the ekranoplan movement, and evaluating the effectiveness of altitude minimization. The structure of the model using these blocks is shown in Fig. 1. Since the model is applicable not only for ground effect vehicles but also for low-altitude vehicles (LAV) of other types, the abbreviation LAV is used for abbreviations in block diagrams.
The simulation of sea waves block produced at the output the sea wave height $\xi(t)$ determined by the shaping filter method for the sea wave spectrum. The variable parameter of this block is the intensity of sea waves $h_{3\%}$, by which the desired spectrum of sea waves and the transfer function of the shaping filter $H_B(s)$ are finally determined. The estimated value of the sea wave ordinate $\xi(t)$ is fed to the input of the unit for simulating the operation of the measurement and control system, in which the angle of deviation of the Elevator $\delta_b(t)$ is calculated and then transmitted to the input of the ekranoplan motion simulation unit. The block of modeling the movement forms the path so that it tends to pass at the minimum height with the minimum number of surface touches. The curvature of the trajectory depends on the inertial characteristics of the ekranoplan. A more detailed block diagram of the low-flying vehicle motion simulation system is shown in Fig. 2. Here, PCU1 and PCU2 denote the units for calculating parameters for the generating filter and the block for modeling the dynamics of ekranoplan, respectively, M-array consisting of the elements $M_{Z0}^{a_5}$, $M_{Z0}^{a_6}$, $M_{Z0}^{a_7}$ and $I_z^{Y_0}$.

$$S_h(\Omega) = \frac{4D_r \alpha \sigma^2}{\sigma^4 + 2(\alpha^2 - \beta^2)\sigma^2 + (\alpha^2 + \beta^2)^2},$$  \hspace{1cm} (1)
where $\Omega$ is the spatial frequency of sea waves. The frequency of the maximum spectrum $\Omega_m$ is determined by the ratio $\Omega_m = 1.42 \sqrt[3]{h_3} \%$ and practically coincides with $\beta$, since $\Omega_m = \sqrt{\alpha^2 + \beta^2} = \beta \sqrt{1 + (\alpha/\beta)^2} = 1.02 \beta$.

The transfer function of the shaping sea wave filter has the following form

$$H(s) = \frac{2\sqrt{\alpha D_s s}}{s^2 + 2\alpha s + (\alpha^2 + \beta^2)}$$

(2)

To calculate the control action, it is necessary to evaluate the difference between the current height of the ground effect vehicle and the desired one through a given distance $r$ (Fig. 3). The height difference is calculated using the formula

$$\Delta h_{abs}(t) = \xi(t) + h_{zad} - H_{abs}(t).$$

After that, the angle of inclination of the trajectory is determined, which must be taken in order to change the height to the desired one for the distance $r$. The ratio of $\Delta h_{abs}(t)$ to $r$ is the tangent of the desired trajectory angle.

The angle of deviation of the Elevator $\delta$ is calculated based on (3) from the calculated $\theta$. In fig. 3 illustrates the method of minimizing the height of the ground effect vehicle due to smooth vertical maneuvers seeking to stabilize the true geometric height at a given value. To compensate for the control delay, the height is measured at a distance $r$ in front of the ekranoplan.

![Figure 3](image-url)

The principle of stabilization of the true geometric altitude of the vehicle due to vertical maneuvering.

The equations of longitudinal motion of the aircraft in the images have the form

$$s^2 \dot{\theta}(s) + a_1 s \theta(s) + a_2 \alpha(s) = -a_3 \delta_{e}(s) + a_4 M_{be}(s)$$

$$-s \alpha(s) + a_5 \alpha(s) + s \theta(s) = a_6 F_{by}(s)$$

We exclude the variable $\alpha(s)$ from them and determine the transfer function of the dependence of the trajectory inclination angle on the elevator deflection angle.

$$H_{\theta \delta}(s) = \frac{a_3 a_5}{s^2 + (a_1 - a_5)s + (a_2 - a_1 a_5)}$$

(3)

where $a_1 = M_{by}^{\alpha} / I_Z, a_2 = M_{by}^{\alpha} / I_Z, a_3 = M_{by}^{\alpha} / I_Z, a_4 = Y_0^{\alpha} / mV_0, a_5$ is the specified coefficient, $\alpha - s$ is the angle of attack, $M_{by}(s)$ is the perturbing moment, and $F_{by}(s)$ is the perturbing force.

$I_Z$ – moment of inertia of the aircraft relative to the OZ axis, $M_{by}^{\alpha}$ – time damping pitch moment, $M_{by}^{\alpha}$ - static longitudinal stability, $M_{by}^{\alpha}$ is control torque that appears when the deflection of the tail horizontal tail, $Y_0^{\alpha}$ - lifting ekranoplan when the unperturbed motion, $m$ is the mass of the aircraft, $V_0$ is the speed of the aircraft.

Using the angle of inclination of the trajectory, obtained using formula (3), as well as the known speed of movement of the ground effect vehicle, its absolute height is determined.
The accumulated dependence of the absolute height of the ground effect vehicle on time is its trajectory, which is transmitted to the efficiency evaluation unit. The block for evaluating the effectiveness calculates the average difference and the ratio of heights between the optimized and non-optimized trajectories.

3. Simulation results

Two-dimensional images of sea waves were obtained by Simulink simulation. For a 4-point sea wave, \( h_{y5} = 2 \) m, which means that \( D_r = 0.143 \) m\(^2\), \( \beta = 1.004 \) s\(^{-1}\), \( \alpha = 0.21 \) s\(^{-1}\).

\[ H(s) = \frac{b_0 s}{s^2 + a_1 s + a_2} \]  

(4)

For a wave of 6 points, \( h_{y6} = 6 \) m, which means that \( D_r = 1.289 \) m\(^2\), \( \beta = 0.5683 \) s\(^{-1}\), \( \alpha = 0.1193 \) s\(^{-1}\), correspondingly \( b_0 = 0.7843 \) s\(^{-1}\); \( a_1 = 0.2386 \) s\(^{-1}\); \( a_2 = 0.3372 \) s\(^{-2}\). The coefficients of the transfer function (3) took the following values: \( a_1 = 1.154 \) s\(^{-1}\); \( a_2 = 1.4 \) s\(^{-2}\); \( a_3 = 0.427 \) s\(^{-2}\); \( a_5 = 0.415 \) s\(^{-1}\). These values were determined based on the average inertial characteristics of small and medium-sized ekranoplans taken from open sources. Some of the characteristics are given in [5-9]. A fragment of the optimized trajectory during flight in conditions of 6-point sea waves is shown in Fig. 4.

![Figure 4. Fragment of the trajectory of the vehicle (dotted line) and sea waves (solid line).](image)

It was assumed that in the usual mode the ekranoplan moves in a straight line at a constant height of 3 m, which ensured an average frequency of touching the surface no more than once every 200 seconds. When optimizing the trajectory by the proposed method, the average height of the ground effect vehicle decreased to 2.35 m, and the frequency of surface touches increased on average up to 1 time in 50 s, which is permissible for the ground effect vehicle and practically does not affect the quality of control and safety. The influence of the air cushion was not taken into account in the simulation.

To assess the possibility of movement in conditions of continuous maneuvering to minimize the height, it is necessary to assess the overload of the ekranoplan. The transfer function of the overload is related to the transfer function of the angle of inclination of the trajectory by the following formula

\[ H_{n_{\theta}}^{g}(s) = -\frac{V_s}{g} H_{\theta}^{g}(s) \]  

(5)

A fragment of the time dependence of the device overload is shown in Fig. 5.

![Figure 5. Fragment of the time dependence of the ekranoplan overload.](image)
During the simulation during the entire flight, the overload did not exceed 0.16 g. In [10] it is indicated that during turbulence, the overload on an aircraft is usually 0.8–1.2 g, and in a storm it can exceed 2 g. The most unpleasant for humans are overloads at frequencies of 0.1-0.5 Hz [11]. Therefore, the overloads arising from the use of the proposed method for minimizing the altitude are acceptable even during long flights. Additionally, it is possible to protect the crew and passengers from overloading by using the anti-overload protection, the method of operation of which is described in [12-15].

4. Conclusion
The results of the study showed the possibility of reducing the altitude of a highly maneuverable small ekranoplane in 6-point sea waves (three percent security of sea waves \( h_{3\%} = 6 \) m) by 0.65 m. The effectiveness of the proposed control method should be evaluated separately for each model of an ekranoplane, since their maneuverability characteristics may differ significantly. Since the estimated overload during the entire simulation time did not exceed 0.16 g, it can be argued that the proposed method of trajectory optimization can be used on passenger ekranoplanes and for the transportation of most cargo.

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