Features of synthesis of ekranoplane control systems

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Abstract. The article deals with the theory of designing ekranoplane control systems, taking into account the features of their dynamic properties and operating conditions. Flying at low altitude over an uneven surface is accompanied by powerful periodic and pulse loads caused by the roughness of the underlying surface. In addition, with small changes in altitude, the controllability and stability of the ekranoplane changes significantly up to loss of stability. For the synthesis of the ekranoplane control system, a new method for calculating a nonlinear mathematical model of an ekranoplane based on the CFD Comsol Multiphysics and Matlab programs is proposed. The results of simulation are presented.

1. Introduction
Ekranoplane, like planes, belong to the same class of aircraft with a single plane of symmetry. However, their properties as control plant differ significantly. This is due to different operating conditions. The main mode of flight of an ekranoplane is flight at extremely low altitude in the area of the ground effect, since this mode shows the advantages of an ekranoplane compared to a conventional aircraft. Such operating conditions lead to the continuous action of powerful periodic and pulsed loads on its hull caused by roughness of the underlying surface, especially intense when the sea surface is significantly disturbed or when ice fields are hummocky [1, 2].

Flying at low altitude determines a different feature of controlling an ekranoplane compared to a conventional aircraft. If the dynamic properties of the aircraft slowly change with changes in altitude and flight speed, the properties of the ekranoplane as an object of control change significantly with small variations in altitude above the underlying surface, varying in centimeters and decimeters. The situation is complicated by the fact that in some flight modes, the ekranoplane becomes unstable, which in some cases contributes to the emergence of critical situations. For this reason, the use of constantly working systems to increase stability and controllability for large ekranoplanes is considered mandatory [3, 4].

The design of any control system begins with the selection of an adequate mathematical model of the control plant for the entire range of operating conditions. To obtain such an ekranoplane model, it is proposed to use an original approach using the CFD software module and the Comsol Multiphysics program.

2. Mathematical model of an ekranoplane
A large number of design schemes and advanced designs of ekranoplanes determine the need to develop new approaches for operational output and analysis of the corresponding mathematical
models, their transformation, synthesis of control laws and final simulation in conditions as close as possible to real ones. The article presents a version of the software that automates this process from drawing up a virtual model of an ekranoplane, taking into account the limitations of the uneven underlying surface, output of mathematical models and design of the control system.

To achieve this goal, a specially developed software package is used, which integrates the capabilities of the latest modifications of such programs as CFD Comsol Multiphysics and Matlab [5-7]. Combining the capabilities of these programs in one package allowed us to qualitatively expand the range of tasks to be solved. Input information is entered in the form of a structural diagram of the ekranoplane. This model is placed in the air stream using the Comsol Multiphysics program. Separately, restrictions are set that simulate the actual flight conditions of an ekranoplane over water, ice, or other surface. The model was installed in the entire range of altitudes and speeds in the area of the ground effect. Then the deviations of the controls were varied and their balancing positions were determined. The resulting databases were used to calculate arrays of mathematical models of the ekranoplane of each of the studied modes. Regression analysis allowed us to obtain a single nonlinear model for the entire range of possible flight modes, which make it possible to study all the dynamic properties of the ekranoplane, its stability and controllability. At any time of design, one can go back to the design scheme and modify it. Figures 1 and 2 show the appearance of the virtual ekranoplane model and visualization of the virtual purge [3].

![Fig. 1 Shell structure of the 3D ekranoplane model](image1)

![Figure 2 Virtual purge visualization in the COMSOL Multiphysics environment](image2)

The resulting mathematical model of the aircraft control system in the area of the ground effect includes the following models (see figure 3)

- a mathematical model of solid state dynamics 6DOF (6 degrees of freedom);
- a mathematical model of the propulsion system that determines the relationship between air velocity, the gas flow rate from the engine nozzles and the jet thrust force;
- model of aerodynamic forces and torques presented in tabular form with subsequent n-dimensional spline interpolation;
- the underlying surface wave model, represented as correlation functions, a formative filter, or in another form;
- models of sensors and actuators that are part of the information and measurement complex and the control system, presented in the form of transfer functions or in another form.
Fig. 3 Model of aerodynamic and reactive forces and torques

The mathematical model of ekranoplane dynamics [3] includes the classical model of solid body dynamics, the model of aerodynamics, and the model of thrust. A nonlinear model of aerodynamics, presented as multidimensional tables of forces and torques, was obtained using the CFD Comsol Multiphysics software package. Model jet engines thrust is determined by the speed of thrust and angle of thrust, these parameters define the current reaction force and moment of force about the center of mass of the ekranoplane. The jet stream changes the flow around the ekranoplane and affects the aerodynamic forces and torques that are taken into account in the aerodynamic model.

For all acceptable combinations of altitudes above ground level and horizontal speeds, a solution to the balancing problem was found for the values of angles of attack, thrust speed, thrust angle, and flap angle. In this case, the Elevator is in the neutral position. Balancing corresponds to the compensation of all forces and torques acting on the ekranoplane.

The resulting mathematical model of dynamics includes a model of solid body dynamics, a model of the propulsion system, and a model of aerodynamic forces and torques. The model of aerodynamic forces and torques is presented in tabular form. The solution of optimal alignment and balancing problems is used in the synthesis of nonlinear laws of motion vector control and ekranoplane stabilization.

Analysis of the nonlinear model of the ekranoplane showed a significant dependence of its dynamic properties on altitude and flight speed. In some areas, the ekranoplane loses its own stability. The data arrays obtained during "virtual" purges after smoothing by regression analysis methods were used to obtain linear models in the vicinity of balancing points. Balancing points were calculated for various combinations of speed and altitude. All other parameters, such as the angles of installation of the
Elevator, engine thrust, its angle of rotation, pitch angle, attack, etc., were calculated from the condition of the balance of forces and torques acting on the ekranoplane. A special algorithm and program was developed to calculate the balancing parameters. Under the assumption of small deviations (variations) of parameters, the corresponding linear mathematical models of the ekranoplane are calculated. For 16 values of altitude and 16 values of speed, 256 multidimensional models in the state space were obtained using the Matlab program. Each of these models is represented as structures in Matlab format. The matrix of the resulting models is shown in figure 4. Each structure contains, in addition to numeric matrices, the names of input and output variables and additional information. Each structure can be converted to any other type of model, such as a transfer function matrix.

Fig. 4 Array of mathematical models of ekranoplane for different altitudes and speeds

Table 1 shows sample data for the balancing values of the pitch angle, engine thrust, its installation angle, flap deflection angle and Elevator angle for seven selected structures corresponding to the steady flight of the ekranoplane at an altitude of 5 m, 8.33 m and 10 m, at different flight speeds.

| Number of the structure | $H$, m | $V$, m/sec | $\Theta$, deg | $A_{\text{thrust}}$, deg | $A_{\text{flap}}$, deg | $A_{\text{elev}}$, deg | $V_{\text{thrust}}$, m/sec |
|-------------------------|--------|-------------|----------------|-------------------------|-------------------------|--------------------------|-----------------------------|
| 1                       | 5.00   | 83.33       | -0.012         | -8.34                   | 7.50                    | 0.00                     | 263.79                      |
| 2                       | 5.00   | 85.18       | -0.002         | -8.63                   | 7.50                    | 0.00                     | 253.39                      |
| 9                       | 5.00   | 98.14       | 0.027          | -7.39                   | 1.50                    | 0.00                     | 247.27                      |
| 164                     | 8.33   | 88.88       | -0.018         | -5.36                   | 7.50                    | 0.00                     | 304.64                      |
| 165                     | 8.33   | 90.741      | -0.010         | -5.52                   | 7.50                    | 0.00                     | 297.16                      |
| 163                     | 8.33   | 87.03       | -0.026         | -5.29                   | 7.50                    | 0.00                     | 310.51                      |
| 256                     | 10.00  | 111.11      | 0.013          | -2.45                   | 1.00                    | 0.00                     | 313.84                      |

The balancing values of the ekranoplane motion parameters and the deflection angles of the control surfaces correspond to a steady flight, i.e. a flight with zero sum of forces and torques relative to all three axes. The control system must provide automatic balancing of the ekranoplane when changing the speed and altitude of the flight in the area of the ground effect.
The transfer functions for speed $V=90.7 \text{ m/s}$ and height $H=6.3$ when the Elevator is deflected are as follows:

- for pitch angle
  $$W(s) = \frac{-0.097 s^3 - 0.004195 s^2 - 0.04532 s - 0.001117}{s^5 + 0.05322 s^4 + 0.368 s^3 + 0.01438 s^2 - 2.036 s + 0.02306}$$

- to change the altitude
  $$W(s) = \frac{-0.006239 s^4 - 0.01666 s^3 + 0.8273 s^2 + 0.4513 s + 0.3623}{s^5 + 0.05322 s^4 + 0.368 s^3 + 0.01438 s^2 - 2.036 s + 0.02306}$$

Analysis of the array of multidimensional models showed a significant dependence of the dynamic properties of the ekranoplane on variations in speed and altitude in the area of the ground effect. To illustrate this relationship, figure 5 shows a Nyquist diagram that illustrates changes in the dynamic characteristics of an ekranoplane during acceleration, deceleration, climb, and descent in the area of the ground effect.

![Nyquist Diagram](image)

Fig. 5 Nyquist diagram illustrating changes in the dynamic characteristics of an ekranoplane in different flight modes in the area of the ground effect

3. Requirements and analysis of the properties of the ekranoplane control system
The ekranoplane control system must ensure stability in all flight modes in the ground effect area, take-off from a water or solid surface and landing, as well as lifting above the screen, if such a flight mode is provided for in the technical task. The issues of designing such a control system are discussed in detail in the report. The simplest direction is the design of a robust controller that meets the minimum requirements for guaranteed stability in all flight modes, and the most effective is the design of a non-linear controller that ensures the quality of regulation close to the optimal process for each flight mode. Preliminary studies have shown that for large ekranoplanes moving under very strong variable distributed loads, the control system must fend off hull deformations, which not only reduce the life of the structure, but also synchronously change the distribution of forces along the hull and, accordingly, the dynamic properties of the control plant [8-10]. At the first stage of the work, a robust controller for the longitudinal movement of the ekranoplane was synthesized. The dynamic properties
of the control system are illustrated in figures 6 and 7. In both cases, a signal was sent to the jump control system to increase the altitude by 10 m. The initial altitude above the ground and the flight speed varied over the entire acceptable range. It is shown that the controller ensures the stability of the ekranoplane in all flight modes. Similar studies were performed when the command to change the flight speed by 10 m/s was given. The simulation results for different flight altitudes in the ground effect zone are shown in figures 8 and 9. Figures 7 and 9 show the processes of changing the pitch angle. It can be seen that the pitch angle as a result tends to the balancing mode corresponding to the speed and altitude of the flight. These values are compared with the corresponding values in the full version of table 1, corresponding to all 265 values of ekranoplane models in the entire range of possible changes in parameters in the ground effect zone and show their identity.

Fig. 6. Ekranoplane response to the command to increase the height by 10 m in the area of the ground effect under different initial conditions.

Fig. 7. Changing the pitch angle when changing the altitude by 10 m.

Fig. 8. Ekranoplane response to the command to increase the flight speed by 10 m/s in the area of the ground effect under different initial conditions.

Fig. 9. Changing the pitch angle when the flight speed increases by 10 m/sec

Conclusions
Using a specially developed software package that uses CFD, Comsol Multiphysics, and Matlab programs, a nonlinear model of the longitudinal motion of an ekranoplane is obtained for all flight modes in the ground effect zone. A control system has been synthesized that provides automatic balancing at all speed and altitude values in the area of the ground effect. The necessity of synthesizing a nonlinear control algorithm that provides close to optimal control quality for all flight modes in the ground effect zone is determined. It is necessary to study the effect of hull deformations on the stability and controllability properties.
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