A review of the problem of modeling the aerodynamics of small-sized ekranoplanes

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Abstract. A characteristic trend in the development of modern transport systems is the widespread introduction of unmanned technologies. One of the new vehicles that are promising for use as high-speed unmanned aerial vehicles are ekranoplanes (WIG crafts). Such devices use the principle of dynamic support above the surface. Therefore, the processes of aerodynamics are decisive for their reliable and effective operation. The presented work considers the problem of modeling aerodynamic processes during the movement of the vehicle near the surface. In contrast to studies in an unrestricted flow, the presence of a surface leads to a number of features that determine the need for special approaches to both physical and mathematical experiments. It is established that each of the methods can ensure the similarity of the modeled processes to the real ones within the defining limits. A brief review of methods of numerical modeling of ekranoplane aerodynamics is presented. The approaches, which based on the Navier-Stokes equations and method of discrete singularities, are considered. There are examples of calculation of the processes of wing aerodynamics herein. The advantages and disadvantages of viscous and inviscid models for research are shown.

1 Introduction

Ekranoplanes are high-speed vehicles designed for operation near the ground or water surface, but don’t come into contact with it. Despite the fact that today such devices have not found wide commercial use, many experts believe [1-3] that they are a promising vehicle capable of occupying the niche of speeds of 200-500 km/h. Such vehicles acquire special importance due to the development of unmanned technologies. It should be noted that the known ekranoplane developments refer to large and medium-size devices [4]. However, the use of ekranoplanes as unmanned systems requires the study of small-sized devices. The geometric factor is one of the determining factors affecting the aerodynamics of the device.

The creation of promising vehicles of ekranoplane type is in the development stage. It would be a mistake to consider the level of this knowledge to have reached its peak. The methodology of aerodynamic design of transport vehicles is far from perfect and the main work is still ahead. The basis of the methodology for the formation of aerodynamic layouts is mathematical and physical modeling. Achievements of theoretical and experimental aerodynamics, development of methods of aerodynamic analysis, mathematical modeling and processing of experimental results provide an opportunity to develop rational aerodynamic layouts of transport vehicles depending on their purpose and flight modes [5, 6]. Today, these problems are solved in an evolutionary way: a prototype vehicle is selected and, by modifying its components, a new one is created. The development of transport vehicles based on new physical principles requires new approaches, because there are no prototypes. This problem can be solved by modeling, which is generally a powerful method of scientific knowledge. When using it, the studied object is replaced by a simpler object, which is called a model. The model is described by a certain number of physical quantities that depend on a large number of variable and constant parameters, and those that are subject to determination. The role of mathematical modeling has especially increased with the progressive development of computing equipment and computer technologies.

The purpose of modeling is to predict the behaviour of the process in the system being studied. It allows you to recreate processes in the system and identify optimization criteria with extremely low material costs. But it is impossible to create a model that would correspond to all the characteristics of the object under study. However, the modeling of physical phenomena is being improved and helps speed up the process of developing vehicles for various purposes.

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2 State-of-art of problem

The development of promising high-speed transport vehicles requires optimization of their aerodynamic characteristics. Today, the study of their aerodynamic characteristics is possible using the following approaches:
- full-scale tests [7, 8];
- modeling in wind tunnels [9-12];
- modeling on special tracks [13];
- mathematical modeling using numerical methods [14-17].

Full-scale tests of transport vehicles allow obtaining the most accurate technical characteristics. They are possible after the production of a full-scale transport device. Full-scale tests are widely used at the final stage of vehicle development. This approach is associated with significant financial and material costs and requires full release of technical documentation. Design practice shows that the use of full-scale testing is advisable before the start of mass production to obtain a comprehensive assessment of technical characteristics.

Modeling on special tracks is extremely difficult. When using it, a number of difficulties arise with determining aerodynamic characteristics. Practice has shown that in a number of attempts to use it in laboratory conditions, it is of little use.

Determination of the aerodynamic characteristics of transport vehicles in wind tunnels is the most widespread and perfect. However, modeling the aerodynamics of bodies near the ground has a number of advantages and disadvantages.

Recently, the methods of mathematical modeling have been extremely widely used. The progress of computer technology contributed to the development of mathematical modeling methods.

When modeling the flow around high-speed transport vehicles moving near the surface of media separation, a number of difficulties arise, which are related to the implementation of real flow conditions. Ideally, relative movement is realized between the transport device and the separation surface. Ensuring the similarity of relative motion is an extremely difficult task and requires a well-founded analysis of experimental methods and searching ways to develop physical and mathematical models suitable for use in their design with the provision of time and functional criteria.

3 Overview of physical modeling methods

The influence of the ground on the aerodynamic characteristics of aircraft occurs only in take-off and landing modes. The proximity of the runway, like a surface, is taken into account by correcting the lifting force coefficient \( \Delta C_y^{\text{ground}} \), the drag coefficient \( \Delta C_x^{\text{ground}} \), and pitch moment coefficient \( \Delta m_{\text{ground}} \) which depends on the distance to the ground surface. The influence of the ground leads to a change in the inductive resistance and a shift in the focus of the wing and, as a result, a change in the magnitude of the longitudinal moment coefficient. As experiments with ekranoplanes show, the influence of the water surface leads to the need to increase the area of the horizontal feathering to about 40% of the wing area to ensure the necessary stability and controllability. This, in turn, leads to an increase in the weight of the aircraft.

It is considered that one of the most accurate approaches to the study of the aerodynamic characteristics of transport vehicles moving over the boundary of media separation is modeling on special tracks [11]. It allows obtaining the results of experimental studies with an accuracy close to full-scale tests. Although there are difficulties in determining integral characteristics, but the development of electronics and mathematical modeling allows obtaining acceptable distributed characteristics with certain limitations. Compared to research in wind tunnels, the use of modeling on special tracks allows to eliminate a number of problems related to the fulfillment of boundary conditions on the track structure. Thus, the use of the track method for the study of the aerodynamic characteristics of ground transport vehicles made it possible to obtain sufficiently accurate values of the lifting and drag forces during operation [18]. The analysis of studies shows the high accuracy of the obtained data when using the track approach.

Wind tunnels are the most common way to study the aerodynamics of transport vehicles. To simulate the influence of the track structure on the aerodynamic characteristics of the vehicle, the following wind tunnel research methods are used:
- fixed track structure (Fig. 1a, Fig. 2a);
- mirror reflection of the model (Fig. 1b, Fig. 2b);
- boundary layer control (Fig. 1c, Fig. 2c);
- mobile belt (Fig. 1d, Fig. 2d).

Fig. 1. Simulation of the movement of a vehicle near the ground in a wind tunnel:
- a - using a fixed plate,
- b - mirror reflection of the model,
- c - suction or blowing of the boundary layer,
- d - using a mobile belt.
However, it should be noted that different schemes of the experiment lead to different speed profiles between the surface and the research object (Fig. 2).

![Fig. 2. Speed profiles in the simulation of the vehicle movement near the track structure: a - using a fixed plate, b - mirror reflection of the model, c - suction or blowing of the boundary layer, d - using a mobile belt.](image)

How it can be seen from Fig. 2, the selection of the experimental method significantly affects the physical picture, which requires careful analysis when formulating the problem.

The use of a fixed track structure is the most common and the simplest method \[19, 20\]. The model of the transport device is fixed above the track structure at a distance that makes it possible to take into account the growth of the boundary layer on the surface of the track structure. With such modeling, circulation may occur around the combination "track structure - model" \[20\]. But this problem can be eliminated thanks to the use of various aerodynamic devices.

It is possible to remove the boundary layer from the surface of the track structure by applying methods of boundary layer control (BLC). \[21\]. It is implemented by tangential blowing or suction of the boundary layer from the surface. This method was not so widely used in comparison with other approaches to modeling the influence of the track structure on flow parameters \[22\].

The application of the method of mirror reflection of models allows to avoid the process of formation of a boundary layer, which is typical for a stationary track structure \[3, 14\]. However, mixing of the main and mirror-reflected flows can occur in the plane of symmetry. This process can take place when modeling separated flows. The work \[14\] gives the results of experimental studies of aerodynamic characteristics of CLARK-Y-4% profile near the ground. The experiments were conducted in the wind tunnel T-3 of Department of Aerodynamics of Kharkiv Aviation Institute using the method of mirrored models.

![Fig. 3. Aerodynamic characteristics of Clark-Y-4% thin profile near the ground: a – aerodynamic quality; b – longitudinal moment coefficient; c – drag coefficient; d – coefficient of lifting force.](image)

The results of the research confirmed that the application of the method of mirror reflection of models allows obtaining a symmetrical flow relative to the line of the imaginary earth.

The use of a mobile belt makes it possible to ensure the fulfillment of speed boundary conditions on the surface of the track structure \[12\]. However, when using this method, there are difficulties in modeling movement over...
a track structure with a complex cross-sectional profile. However, this method requires precise synchronization of the flow velocities and the mobile belt. In addition, there are a number of difficulties in conjugating the belt with a fixed screen. According to the similarity theory, there must be a similarity between the physical processes in the experiment and the real phenomenon. This is determined by Reynolds number. The complexity of the design of the simulation setup is a serious problem for conducting such experiments.

The analysis of various schemes of the experiment for the study of the aerodynamic characteristics of long bodies moving near the ground shows that the mirror reflection method is more accurate in determining the indicators of lateral stability, but gives underestimated values of the pitch moment. The magnitude of the lifting force is approximately the same for different methods. When the clearance is reduced, the mirror reflection method gives underestimated values of the drag force.

A more detailed analysis of the methods of modeling the movement of ground transport vehicles is carried out in [25].

3. The problem of mathematical modeling

Mathematical modeling of the aerodynamics of transport vehicles is a rather complex and relevant task. Today, the most advanced mathematical models of aerodynamics are built on the physical properties of a viscous compressible gas and are based on the Navier-Stokes equations. The legitimacy of their use is confirmed by numerous studies. Complexity is added by the fact that the real movement of the vehicle takes place in a turbulent air.

Modeling the turbulent movements of air masses is a fundamental problem of both theoretical physics and practical aerodynamics. The lack of a universal theory for describing turbulent flows creates problems with determining aerodynamic loads. This issue is one of the key points in the design of high-speed vehicles, because at high speeds, it may take up to 90% of total energy costs only to overcome the air resistance. Thus, fundamental research in the aerodynamics of high-speed transport is necessary.

As shown in [26], the structure of the flow and the correct definition of turbulence are the determining factors when modeling the aerodynamics of a wing near the ground. Methods of modeling turbulent flows, conventionally, can be divided into three groups: approaches based on the use of Reynolds-averaged Navier–Stokes equations (Reynolds Averaged Navier - Stokes - RANS); two classic approaches - direct numerical modeling of turbulence (Direct Numerical Simulation - DNS) and the method of modeling large eddies (Large Eddy Simulation - LES); hybrid approaches that are based on the joint use of RANS and LES approaches for different areas of the flow [27].

Today, the most common approaches are methods based on the use of Reynolds-averaged Navier-Stokes equations (Reynolds Averaged Navier - Stokes - RANS). They are closed using one or another semi-empirical model of turbulence.

Classic vortex approaches are the most perfect. This is a direct numerical simulation of turbulence (Direct Numerical Simulation - DNS) and the method of modeling large eddies (Large Eddy Simulation - LES). The DNS method is based on the direct numerical solution of the three-dimensional unsteady Navier-Stokes equations with the distinction of all spatio-temporal scales of turbulence. This method is based on the physical principles of aerodynamics and is completely free from empirical assumptions.

In the framework of LES method, the equations are solved directly after their previous spatial filtering. This allows us to exclude part of the spatio-temporal scales from consideration. The performed operation makes it possible to significantly reduce the requirements for spatio-temporal distinction. In this way, the requirements for the necessary computing resources are reduced.

Some semi-empirical models are used to take into account the influence of filtered ("sub-mesh") turbulence scales.

In the scientific literature, features called "sub-mesh" are used to highlight the cardinal differences of LES method from the approaches used for RANS closure.

The third group includes hybrid approaches based on the joint use of RANS and LES approaches in different areas of the flow. They are the most widespread for practical use, based on computing capabilities.

Therefore, the analysis of turbulent flows still remains one of the most difficult problems, and the reliable prediction of the characteristics of turbulent flows of practical interest is still the exception rather than the rule, which is explained by the exceptional complexity of turbulence as a physical phenomenon.

4. Mathematical model of wing aerodynamic processes based on Reynolds-averaged Navier-Stokes equations

To solve the problem of determining the aerodynamic characteristics of the vehicle, a viscous compressible gas flow model described by the Reynolds-averaged Navier-Stokes equations was chosen. The estimated area around the vehicle is complex, so it is advisable to use a multi-block approach and a curvilinear coordinate system. The Reynolds-averaged system of Navier-Stokes equations for an arbitrary curvilinear coordinate system will be written as

\[ \frac{\partial \hat{Q}}{\partial t} + \frac{\partial \left( \hat{E} - \hat{E}_0 \right)}{\partial \xi} + \frac{\partial \left( \hat{F} - \hat{F}_0 \right)}{\partial \eta} + \frac{\partial \left( \hat{G} - \hat{G}_0 \right)}{\partial \zeta} = \hat{H}, \] (1)

where \( \hat{Q} \) is a vector of unknown variables; \( \hat{E}, \hat{F}, \hat{G} \) – vectors of non-viscous flows; \( \hat{E}_0 = \xi E_x + \xi F_x + \xi G_x \); \( \hat{F}_0 = \eta E_F + \eta F_F + \eta G_F \); \( \hat{G}_0 = \zeta E_G + \zeta F_G + \zeta G_G \) – vectors of viscous flows; \( \hat{H} = 1/j H \) is a vector of source terms.
In the system of equations (1), n-component vectors \( \tilde{Q}, \tilde{E}, \tilde{F}, \tilde{G}, \tilde{E}_v, \tilde{F}_v, \tilde{G}_v \) have the appropriate form depending on the turbulence model.

Vectors \( \tilde{Q}, \tilde{E}, \tilde{F}, \tilde{G}, \tilde{E}_v, \tilde{F}_v, \tilde{G}_v \) are defined by the following relations

\[
\begin{align*}
\tilde{Q} &= \frac{1}{J} \begin{bmatrix}
\rho u

\rho u

\rho u

\rho u + \xi_x p

\rho u + \xi_y p

\rho u + \xi_z p

(E_i + p)U - \xi_x p

\end{bmatrix},
\end{align*}
\]

\[
\begin{align*}
\tilde{F} &= \frac{1}{J} \begin{bmatrix}
\rho v

\rho v

\rho v

\rho v + \eta_x p

\rho v + \eta_y p

\rho v + \eta_z p

(E_i + p)V - \eta_x p

\end{bmatrix},
\end{align*}
\]

\[
\begin{align*}
\tilde{G} &= \frac{1}{J} \begin{bmatrix}
\rho w

\rho w

\rho w

\rho w + \zeta_x p

\rho w + \zeta_y p

\rho w + \zeta_z p

(E_i + p)W - \zeta_x p

\end{bmatrix},
\end{align*}
\]

\[
\begin{align*}
E_v &= \frac{1}{J} \begin{bmatrix}
0

\tau_{xx}

\tau_{yy}

\tau_{zz}

u \tau_{xx} + v \tau_{xy} + w \tau_{xz} - q_x

\end{bmatrix},
\end{align*}
\]

\[
\begin{align*}
F_v &= \frac{1}{J} \begin{bmatrix}
0

\tau_{xx}

\tau_{yy}

\tau_{zz}

u \tau_{xx} + v \tau_{xy} + w \tau_{xz} - q_y

\end{bmatrix},
\end{align*}
\]

\[
\begin{align*}
G_v &= \frac{1}{J} \begin{bmatrix}
0

\tau_{xx}

\tau_{yy}

\tau_{zz}

u \tau_{xx} + v \tau_{xy} + w \tau_{xz} - q_z

\end{bmatrix},
\end{align*}
\]

where \( \xi_x, \xi_y, \xi_z, \eta_x, \eta_y, \eta_z, \zeta_x, \zeta_y, \zeta_z \) - metric coefficients, \( J = \partial^2 / \partial x \partial y \partial z \) - Jacobian of coordinate transformation, \( \tau_{xx}, \tau_{yy}, \tau_{zz}, \tau_{xy}, \tau_{xz}, \tau_{yz} \) - stress tensor components and \( q_x, q_y, q_z \) - heat flow vector components, \( E_v = \rho \left[ e + \frac{1}{2} (u^2 + v^2 + w^2) \right] \).

To close the system of equations (1), the turbulence model SST (Shear Stress Transport) was used [28]. In its general view, this system of equations will be written as

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho U k)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \Gamma_k \frac{\partial k}{\partial x_i} \right) + G_k - Y_k,
\]

\[
\frac{\partial (\rho \omega)}{\partial t} + \frac{\partial (\rho U \omega)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \Gamma_\omega \frac{\partial \omega}{\partial x_i} \right) + G_\omega - Y_\omega + D_\omega,
\]

where \( G_k \) - the generation of dissipation of kinetic turbulence \( \omega \) per unit \( k \); \( Y_k \) - dissipation of kinetic energy of turbulence; \( Y_\omega \) - dissipation of kinetic turbulence \( \omega \); \( \Gamma_k = \mu + \mu_\omega \sigma_k / \sigma \); \( \Gamma_\omega = \mu + \mu_\omega \sigma_\omega / \sigma \); \( D_\omega \) - cross diffusion term.

The corresponding algorithms and software were developed. The set of programs is written in the Fortran-95 programming language. For example, Fig. 4 shows the results of computing the pressure coefficient on the surface of NACA0012 profile using the Reynolds-averaged Navier-Stokes equations. A C-shaped single-block mesh was being built. Analyses were made for the number \( M=0.4 \), Reynolds number equal to \( Re=10^6 \) and angle of attack \( \alpha=0^\circ \).

![Fig. 4. Distribution of the pressure coefficient on the surface of NACA0012 profile:](image)

- computation; - experiment [29]

Methods for analysing the flow around bodies based on the ideal fluid model are widely used in computational aerodynamics due to their simplicity and low requirements for computer resources. Their use allows solving a number of applied problems and understanding the physics of flow.

In general, the task of air flow around various bodies, vehicles and their elements is quite difficult.

Among the methods based on the ideal fluid model, the methods of discrete features should be singled out, namely the method of discrete vortices (MDV). It is relatively simple, not too time-consuming, convenient for computer use, and a fairly effective method of mathematical modeling of the flow around bodies. Therefore, this method can be extremely effective for solving the problems of the aerodynamics of ekranoplanes and the dynamics of their movement.

The application of the ideal fluid model for the analysis of the load-bearing system of such a promising transport device allows us to formulate the aerodynamic problem as the Neumann problem for the Laplace equation (Fig. 5)

\[
\Phi_0 (M_0) = \frac{1}{4\pi} \int \frac{\partial U_0 (M, M_0)}{\partial n_M} g(M) d\sigma_M, \quad M_0 \not\in \sigma,
\]

\[
\Phi (M) = \frac{1}{4\pi} \int \frac{\partial U (M, M_0)}{\partial n_M} g(M) d\sigma_M, \quad M_0 \not\in \sigma,
\]
where \( \pi_{\mu} \) is unit normal to curve \( L \) at point \( M \), \( g(M) \)-density of potential of the double layer, 
\( M(x, y, z), M_{0}(x_{0}, y_{0}, z_{0}) \) - points of \( \mathbb{R}^{3} \) space,
\( M \neq M_{0}, r_{M,M_{0}} = MM_{0}, r_{M,M_{0}} = r_{M,M_{0}} \),
satisfying the Laplace equation

\[
\Delta U_{0} = \frac{\partial^{2} U_{0}}{\partial x^{2}} + \frac{\partial^{2} U_{0}}{\partial y^{2}} + \frac{\partial^{2} U_{0}}{\partial z^{2}},
\]

by the coordinates of point \( M \) for any fixed point \( M_{0} \).

Fig. 5. Previous to the formulation of Laplace's problem

The function \( U_{0}(M, M_{0}) = \frac{1}{4\pi} e^{g_{\text{cont}}} \) satisfies the Helmholtz equation on the coordinates of point \( M \) for any fixed point \( M_{0} \).

Real problems of vehicle aerodynamics are non-stationary and discrete. Let’s consider the case when the vehicle described by surface \( \sigma_{1} \) is in a non-stationary velocity field \( \mathbf{U}_{0}(M, t) = \nabla u_{0}(M, t) \). From curve \( L \) of surface \( \sigma_{1} \) a non-stationary trace descends (Fig. 6). The conditions must be fulfilled on the surface of trace \( \sigma_{2} \)

\[
\begin{cases}
 p^{+}(M) - p^{-}(M) = 0, & \text{for } M \in \sigma_{2}, \\
 V_{+}^{*}(M) - V_{-}^{*}(M) = 0,
\end{cases}
\]

where \( p^{+}(M), p^{-}(M) \) is the pressure on the vortex surface \( \sigma_{2} \) at point \( M \), \( V_{+}^{*}(M), V_{-}^{*}(M) \) - the projection of the velocity vector onto the normal to the vortex surface \( \sigma_{2} \) at the point \( M \).

Fig. 6. Scheme of descent of the trace

The medium is considered to be continuous, and at any moment of time \( \tau \) from any point \( M(s) \) of curve \( L \), a particle of liquid descends, on which there is a discontinuity of tangent components of velocities. In other words, the non-stationary trace will represent a surface consisting of points \( M(s, \tau, t) \) that move with speed \( \mathbf{U}(M(s, \tau, t)) \). To find the coordinates of surface \( \sigma_{2} \) in space, it is sufficient to solve a parametric system of differential equations.

As a test problem, the flow around Clark-YH wing profile with a relative thickness of 12% of an incompressible non-viscous fluid was analysed. Computed results were compared with experimental data [30]. When solving such a problem, it is necessary to ensure the fulfilment of Kutta (Zhukovsky-Chaplygin) condition on the back sharp edge. According to the boundary conditions, the contour of the profile is a streamline, therefore the velocity vector on its surface is directed tangentially. But according to the theory of vortices [31], the speed on the contour surface is equal to the intensity of the vortex layer.

Thus, the fulfilment of the Kutta (Zhukovsky-Chaplygin) condition comes down to equality to zero of intensity of the vortex layer at the back edge. As research has shown, this requirement is fulfilled. The simulation results are presented in Fig. 7.

Fig. 7. Distribution of the pressure coefficient over the surface of CLARK-YH-12% wing profile without ground effect

As evidenced by the data in Fig. 7, the computed results are in good agreement with the experiment.

5. Conclusions.

The review of experimental approaches to the modeling of aerodynamics of ground transport vehicles of the ekranoplane type indicates the need for further development of methods to ensure kinematic and dynamic similarity of physical processes. To date, known experimental methods in wind tunnels do not satisfy adequate similarity of physical processes of the model and real motion. Previous studies in this direction were carried out without taking into account the dynamics of the movement of the water surface and its properties.

The main difficulty when using numerical methods is the problem of turbulence. Modern computers allow the use of complex turbulence models to calculate the aerodynamics of aircraft. However, the use of complex models such as DNS, LES, RANS may not always be correct, especially at the initial stages of research. The lack of universal turbulence models and the need for
significant computing resources limit the use of models based on viscous fluids. The application of ideal fluid models for the development of methods for the study of aerodynamic processes greatly simplifies the task.

The further development of computational aerodynamics and its application will allow conducting correct numerical experiments and will provide the opportunity to study the peculiarities of physical processes of aerodynamics and dynamics of high-speed ground and surface transport vehicles.

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