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RATIONALE FOR CHOOSING THE AIRFOIL OF A UAV WING USING A DYNAMIC GROUND EFFECT PRINCIPLE

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Vehicles that use the principle of dynamic ground effect principle are innovative vehicles that have prospects for use as high-speed unmanned vehicles. It is known that when an aircraft moves near the ground, the phenomenon of increasing lift occurs, which allows for contactless movement at high speeds. However, the effectiveness of this ground effect depends on the airfoil shape. The object of this study is the aerodynamic processes that occur during the movement of an unmanned aerial vehicle near the ground. The influence of the effect of approaching the ground on the aerodynamic characteristics of four airfoil of different shapes has been considered: Clark YH-12, NACA-M6, USA-35B, TsAGI-721, which are used in subsonic high-speed aircraft, including unmanned aerial vehicles. The aim of the work is to evaluate the performance of these aerodynamic airfoils in near-surface operation and to determine the most promising shape for use in small unmanned WIGs. CFD modeling methods were used as a research tool. The pressure and velocity fields around the wing airfoils were determined and the influence of the distance to the ground and the angle of attack on the aerodynamic characteristics was established. It was found that the best aerodynamic quality for all airfoils is achieved at angles of attack of 4–6°. It is not recommended to use airfoils with angles of attack close to 0° as the ground may have a negative effect on lift. The USA-35B airfoil demonstrated the greatest increase in aerodynamic quality when approaching the surface, with a maximum increase of 67 %. This makes it possible to recommend USA-35B as small unmanned aerial vehicles with a dynamic ground effect principle

Keywords: airfoil, ground effect, CFD modeling, unmanned WIG vehicle, aerodynamic quality

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1. Introduction

Vessels that are equipped with wings and use the principle of non-contact movement over water due to a dynamic air cushion that is formed when approaching the surface (ground effect) are called WIG craft (Wing-In-Ground craft) or ekranoplanes [1]. According to the classification of the International Maritime Organization (IMO), such devices belong to marine vehicles and occupy an intermediate position between slow-moving water tonnage ships and aircraft. A dynamic air cushion makes it possible to increase the speed of movement and the weight of the payload. So, in a number of cases, ekranoplanes are more efficient than traditional water transport.

Despite the fact that currently such devices are not widely used in the practice of transportation, a number of experts [2, 3] believe that such vessels may become a platform for the next generation of marine transport systems. Note that WIG craft have prospects as unmanned vehicles [4–6].

Such vessels have a number of advantages, in particular, the possibility of airfield-free basing, the possibility of use under amphibious mode, higher seaworthiness compared to seaplanes, high aerodynamic quality, better environmental friendliness. In the case of combat use of such systems, inconspicuousness for radar surveillance should be added. The emergence of new lighter and relatively cheap structural materials opens up new opportunities for the development and implementation of WIG craft.

The war waged by russia against Ukraine demonstrates the extraordinary effectiveness and, in many cases, the irreplaceability of the use of unmanned systems. In particular, the low number of successful military operations of the defense forces of Ukraine against the aggressor in the waters of the Black Sea with the use of unmanned boats made it possible to inflict significant losses on the navy of the aggressor [7].

In this context, designing the newest innovative marine unmanned aerial vehicles is an urgent task. In particular, in work [8], ukrainian specialists considered the concept of such an apparatus with a dynamic principle of support above the surface.

The methodology for designing WIG craft [9] requires determining the aerodynamic characteristics of the vessel. First of all, such characteristics are determined by bearing surfaces that have a certain aerodynamic shape – an airfoil. Currently, a large number of airfoils have been developed [10]. The choice of a specific airfoil is determined by various factors: the purpose of the device, the necessary aerodynamic characteristics, requirements for strength, speed, and maneuverability, structural requirements, etc. It should be noted that in the case of the creation of small-sized unmanned WIG craft, the scale factor becomes important since the effectiveness of using a dynamic air cushion depends on the absolute values of the geometric dimensions of the wing. Therefore, given the dimensional and mass limitations inherent in small unmanned aerial vehicles, an important task is to choose the shape of the wing profile, which should most effectively use the effect of approaching the surface.

2. Literature review and problem statement

The performance of the wing is determined by studying the flow around the wing and is determined by the airfoil shape. For unbounded flow, there are many experimental and CFD studies on the performance of wings of various profiles. For example, in [11], a comparative analysis of the aerodynamic characteristics of ten airfoils of the NACA series, which are often used in aviation equipment and wind turbines, was performed. The object of study [12] was seven airfoils of different series, where the influence of the angle of attack on the aerodynamic coefficients of airfoils of different shapes is shown. In general, the issue of aerodynamics of airfoils in an unbounded flow is well studied in the literature. However, during movement near the surface, the task of choosing a wing profile becomes more complicated since the aerodynamic coefficients depend not only on the angle of attack but also on the distance to the surface, which requires separate studies.

For example, symmetric airfoils NACA0015 and NACA0012 near the ground were the objects of experimental research in a low-speed wind tunnel in works [13, 14]. It was found that both the angle of attack and the ground clearance of the airfoil have a strong influence on the aerodynamic characteristics of the configuration. However, even though symmetrical airfoils can provide some lift near the surface, the use of symmetrical airfoils has poor performance at low angles of attack.

The aerodynamics of symmetric and asymmetric airfoils of the NACA series under the influence of the ground effect was studied in [15]. Aerodynamic characteristics of NACA0006, NACA0009, NACA0012, NACA2412, and NACA4412 airfoils were studied using a computational experiment as a research tool. The authors note that the performance of the wing during the approach to the ground is determined by the shape of the curvature of the lower surface of the wing profile. Also, the influence of the ground effect on the aerodynamic coefficients of airfoils from different series is studied in [16]. Airfoils NACA6409, NACA4412, Clark-Y, N60R were studied, and it was shown that the choice of a specific model significantly affects the characteristics of the WIG craft. The results of these studies show that the search for the optimal airfoil shape remains an unsolved problem, under the conditions of flight in close proximity to the surface.

Increasing the effectiveness of the ground effect is possible with the application of airfoils used in high-speed aviation. For example, the RAE2822 airfoil in the area affected by the ground effect is considered in [17]; the DLR-F6 airfoil at different flight heights and at different angles of attack is studied in [18]. However, airfoils of these types are more oriented to use at high Mach numbers and are not target wings for WIG craft. Therefore, it is expedient to conduct a study on airfoils that, on the one hand, demonstrate high quality at subsonic speed regimes, and on the other hand, can be effective in the surface impact zone.

It should be noted that the airfoils discussed above have proven to be efficient in traditional aviation and on relatively large aircraft. As it follows from work [19], for small subsonic aircraft-type UAVs, it is advisable to investigate a wider range of airfoils. At the same time, the use of the principle of a dynamic air cushion imposes additional requirements on the shape of airfoils. Under the conditions of operation of small unmanned aerial vehicles near the surface, the scale factor plays an important role since the effective zone of the ground effect is limited by the dimensions of the wing chord. Therefore, for the most effective use of the ground effect, it is interesting to consider the airfoils used in sports aviation, seaplanes, gliders, unmanned vehicles, and which are promising from the point of view of use as wings for WIG craft.

3. The aim and objectives of the study

The purpose of our work is to evaluate the performance of four airfoils used in subsonic high-speed aviation in the area affected by the ground effect. This will make it possible to reasonably recommend the most promising shape for use in small-sized unmanned WIG craft.

To achieve the goal, the following tasks were set:

– on the basis of computer simulation, determine the aerodynamic characteristics of four selected airfoils moving near the surface;

– to conduct a comparative analysis of the aerodynamic quality of airfoils near the ground.

4. The study materials and methods

The object of our study is the aerodynamic processes that take place during the movement of an unmanned aerial vehicle near the support surface.

In the first approximation, an assumption is accepted that the underlying surface is perfectly flat and undeformed, and the flow speed is significantly lower than the speed of sound. The problem is considered in a stationary statement, which corresponds to the cruise flight mode of the WIG craft. Also, in this work, stability issues are not considered; accordingly, the aerodynamic moment is not considered.

One of the main approaches to the study of hydro aeromechanics processes is the use of mathematical modeling and computer simulation methods. Calculation procedures for determining the aerodynamic characteristics of airfoils differ in accuracy and complexity of implementation. For example, work [20] proposed a simplified methodology for calculating the aerodynamic characteristics of airfoils in wind turbines. However, to study the impact of ground effect on the aerodynamic characteristics of aircraft and their elements, mathematical models based on the Navier-Stokes equations for an incompressible fluid are typically used, which can be written in vector form [21, 22]:

$$\begin{cases} \dfrac{\partial \mathbf{V}}{\partial t}+(\mathbf{V}\nabla)\mathbf{V}=-\dfrac{1}{\rho}\nabla p+\nu\Delta\mathbf{V}, \\ \operatorname{div}\mathbf{V}=0, \end{cases} \tag{1}$$

where $\mathbf{V}$ is the velocity vector; ρ – density; p – pressure; ν is the coefficient of kinematic viscosity.

For an unambiguous solution of system (1), boundary conditions must be set. In this work, we use the following boundary conditions.

On the surface of the airfoil, we set the "sticking" conditions: equal to zero components of the velocity vector $\mathbf{V}=0$. In this work, a symmetry condition is set on the surface of the ground. This setting of the boundary condition is based on the "mirror reflection" approach of the airfoil model, which makes it possible to prevent the effect of the formation of an unphysical boundary layer on the surface of the ground, which will not occur in the case of a real flight of the wing over the surface [23]. Unperturbed flow conditions are set at the outer boundary of the calculation area. The parameters of the undisturbed flow are set at the inlet boundary, and the condition of normal atmospheric pressure is set at the outlet boundary.

Four types of airfoils were chosen for the study. Fig. 1 shows the general view of airfoils.

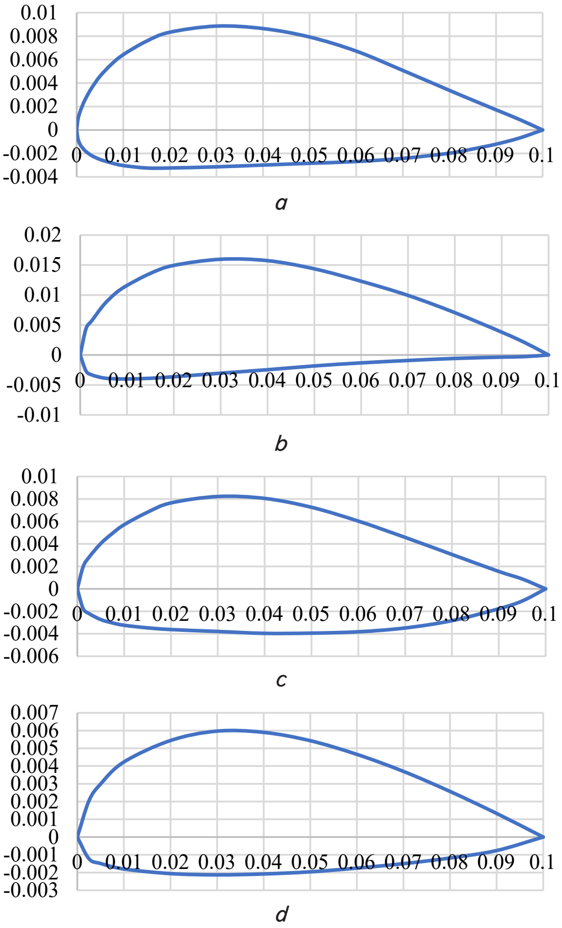

Fig. 1. General view of airfoils:
a – Clark YH-12; *b* – USA-35B; *c* – NACA-M6;
d – TsAGI-721

The Clark YH airfoil is widely used in general purpose aircraft designs and has been extensively studied in aerodynamics over the years. The Clark YH-12 wing has a thickness of 12 % chord and is flat on the lower surface from 30 % chord back. Although a flat lower surface is suboptimal for flight in unconfined flow, it is used in WIG wing designs.

The NACA-M6 profile is used in flying wing aircraft and has a certain S-shape. According to [24], airfoils of this shape can be effective in the area of the ground effect.

The USA 35B airfoil has a concave lower surface and is designed specifically for sport aircraft; it is also used in experimental sport and record aircraft.

The TsAGI-721 airfoil is used in sport gliders and other aircraft, including unmanned aerial vehicles. It is characterized by a thickening of the front edge and a smooth change of shape from the front to the rear edge, which contributes to the reduction of vortex resistance and allows it to function effectively at high angles of attack.

The main factors affecting the airfoil aero dynamics near the ground are the angle of attack a and the relative distance from the trailing edge of the wing to the surface *h*:

$$\bar{h} = \frac{h}{c}, \tag{2}$$

where *c* is the average aerodynamic chord of the wing profile.

Another determining parameter is the Reynolds number:

$$\mathrm{Re} = \frac{V \cdot c}{\nu}, \tag{3}$$

where *V* is the velocity of the oncoming flow; ν is the coefficient of kinematic viscosity of the flow.

The aerodynamic characteristics of airfoil are characterized by the corresponding coefficients of aerodynamic forces:

$$c_x = \frac{X_a}{\frac{\rho V^2}{2} S_M}, \tag{4}$$

$$c_y = \frac{Y_a}{\frac{\rho V^2}{2} S_M}, \tag{5}$$

where X_{aa}, Y_{aa} are the aerodynamic drag force and lift force, respectively; c_x – drag coefficient; c_y – coefficient of lift force; S_M is the characteristic area of the wing profile (cross-sectional area of the midpoint).

The aerodynamic quality of airfoil is defined as the ratio of the lift coefficient to the drag coefficient:

$$K = \frac{c_y}{c_x}. \tag{6}$$

Turbulence modeling was performed using the SST (Shear Stress Transport) model, which is recommended in [25] for calculating the aerodynamics of wings near the ground. Numerical implementation of model (1) with appropriate boundary conditions was carried out using the ANSYS Fluent software package. At the same time, near the surface of the airfoil, the computational mesh was split in such a way that at least 10 nodes of the computational mesh were located within the viscous sublayer. The thickness of the viscous sublayer was determined as:

$$y^+ = \frac{u_\tau \Delta y_1}{\nu}, \tag{7}$$

$u_\tau = \sqrt{\tau_w / \rho}$ – friction speed; $\tau_w = 0.5 C_f \rho V^2$ – near-wall tangential stress; $C_f = 0.058 / \mathrm{Re}^{0.2}$ – coefficient of surface friction; Δy_1 is the absolute distance to the wall.

The accuracy of the computer model was evaluated by comparing the results of the calculation of the aerodynamic characteristics of the selected airfoils with data on the unrestricted flow given for these airfoils in works [10, 26]. The average error for all airfoils based on the results of test calculations to determine the coefficient of drag in an unbounded flow was 16 %, the coefficient of lift force was 10 %. Therefore, the selected model was used to evaluate the aerodynamic characteristics of airfoils under the influence of the ground.

5. Results of investigating the aerodynamics of airfoils near the ground

5. 1. Computer simulation of the flow around airfoils moving near the surface

As a result of computational experiments, the pressure and velocity fields during the flow around the airfoils near the surface were determined. Calculations were performed for the following initial parameters: Re number=500,000; average aerodynamic wing chord $c=100$ mm; standard atmospheric parameters, in the range of angles of attack $\alpha=0\div10°$. Fig. 2 shows examples of the results of computer simulation of pressure fields and velocity vectors during flow around the studied airfoils near the ground at an angle of attack $\alpha=6°$.

In general, the results of our calculations showed that when approaching the surface and increasing the angle of attack, the flow slows down in the gap between the lower surface of the airfoil and the pressure on the lower surface increases. This effect occurred for most calculated cases, except for small angles of attack. Fig. 3 shows the results of calculating the pressure fields for $\bar{h}=0.12$ and angle of attack $\alpha=0°$.

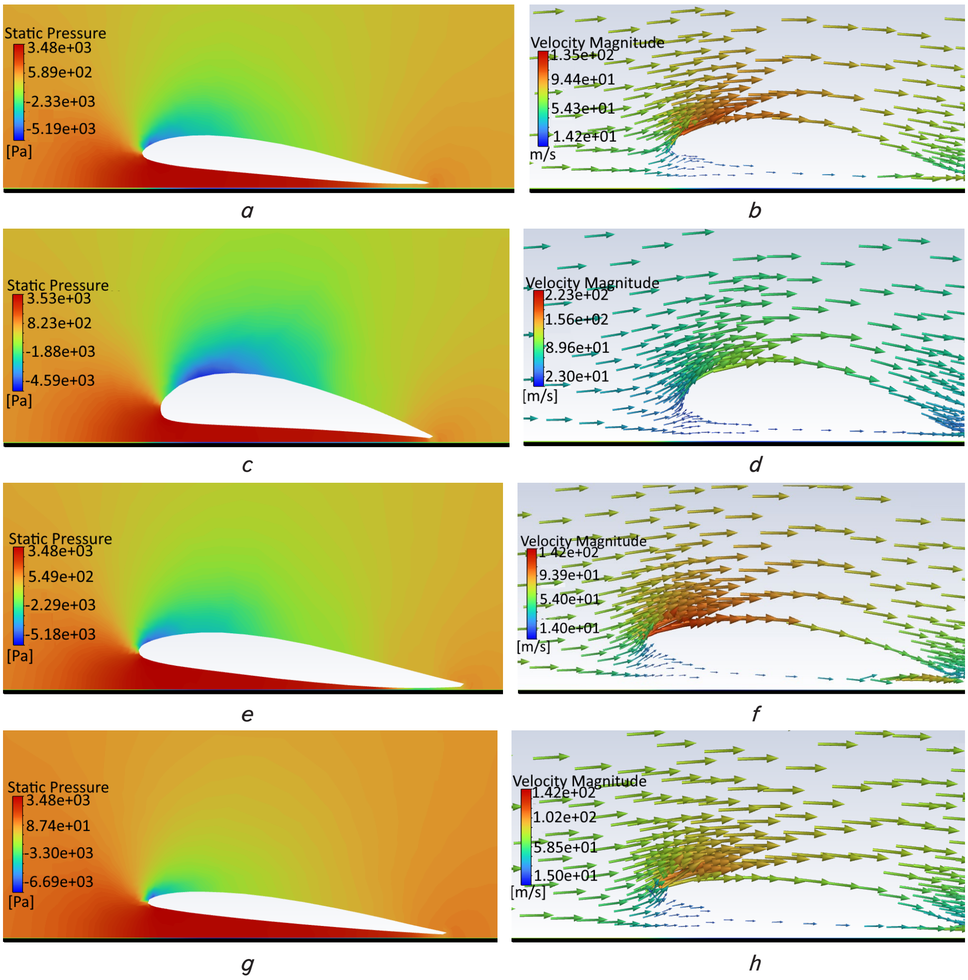

Fig. 2. Pressure fields (*a, c, e, g*) and velocity vectors (*b, d, f, h*) around airfoils at $\alpha=6°$: *a, b* — Clark YH-12; *c, d* — USA-35B; *e, f* — NACA-M6; *g, h* — TsAGI-721

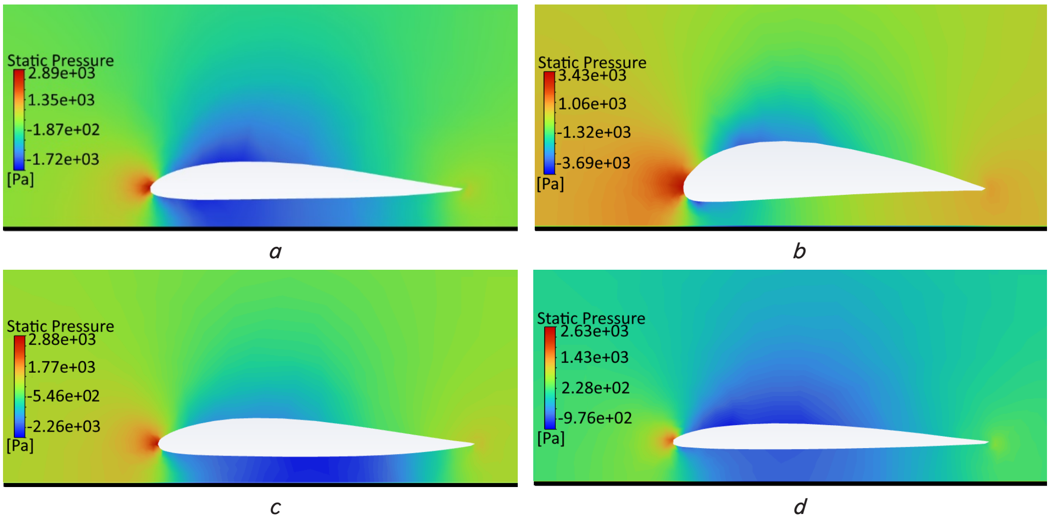

Fig. 3. The pressure field around airfoils at $\alpha=0°$: *a* — Clark YH-12; *b* — USA-35B; *c* — NACA-M6; *d* — TsAGI-721

The results of the calculation of the pressure and velocity fields made it possible to calculate the aerodynamic coefficients of airfoils. Fig. 4 shows the results of calculating the aerodynamic drag coefficient for airfoils depending on the distance to the surface $\bar{h}$ for different angles of attack.

Fig. 5 shows the results of calculating the lift coefficient for airfoils depending on the distance to the surface $\bar{h}$ for different angles of attack.

The obtained values of the aerodynamic coefficients make it possible to determine the aerodynamic quality K.

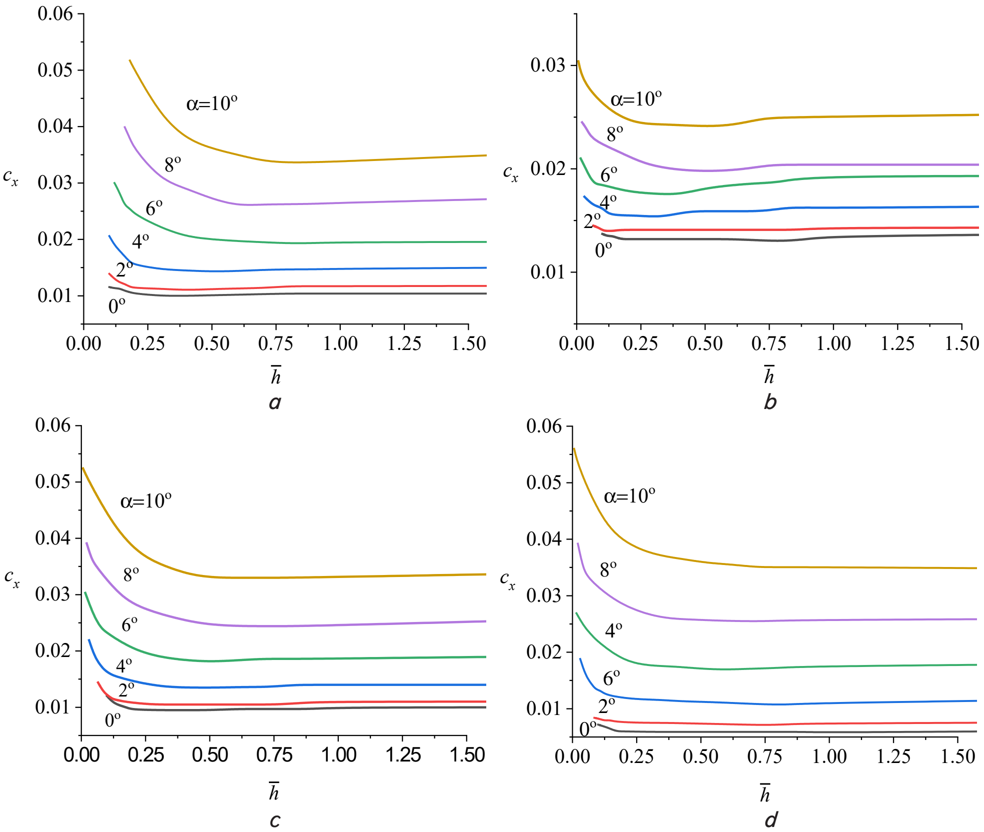

Fig. 4. Dependence of aerodynamic drag coefficients on the distance to the ground and the angle of attack: *a* – Clark YH-12; *b* – USA-35B; *c* – NACA-M6; *d* – TsAGI-721

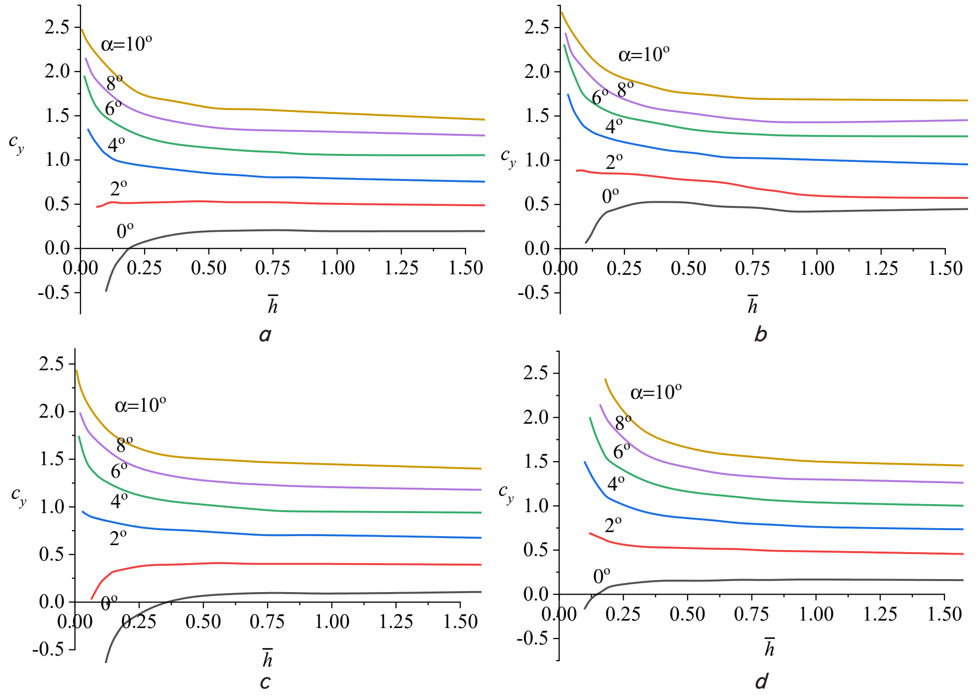

Fig. 5. Dependence of lift coefficients on the distance to the ground and the angle of attack: *a* – Clark YH-12; *b* – USA-35B; *c* – NACA-M6; *d* – TsAGI-721

5. 2. Analysis of the aerodynamic quality of wing profiles in an unmanned aerial vehicle moving near the surface

Fig. 6 shows the results of calculating the aerodynamic quality of airfoils depending on the angle of attack for the relative distance $\bar{h} = 0.18$.

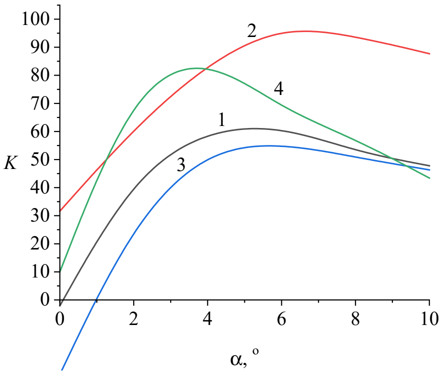

Fig. 6. Dependence of the aerodynamic quality of airfoils K on the angle of attack α for $\bar{h} = 0.18$: 1 – Clark YH-12; 2 – USA-35B; 3 – NACA-M6; 4 – TsAGI-721

Table 1 gives values of the maximum aerodynamic quality and the corresponding determining parameters obtained from the results of data processing in Fig. 3, 4. In the second column of Table 1, there are the values of aerodynamic quality for conditions of unbounded flow.

Table 1

Comparison of the maximum aerodynamic quality

Airfoil	K_∞	K_{max}	α_{max}	$\bar{h}_{max}$
Clark YH-12	48	66	4°	0.03
USA 35B	65	109	6°	0.02
NACA M6	49	57	6°	0.29
TsAGI 721	62	88	4°	0.01

The data given in Table 1 demonstrate that the aerodynamic quality of all studied airfoils increases near the surface.

6. Discussion of results of investigating the aerodynamics of WIG craft near the surface

The results of our calculations shown in Fig. 2 demonstrate that in the area between the lower surface of the airfoil and the ground surface, an area of increased pressure is created – a dynamic air cushion, while on the upper surface of the airfoil, the flow accelerates and the pressure decreases. The pressure imbalance on the upper and lower surfaces of the airfoils creates prerequisites for or increase in lift force. The pressure difference depends on the shape of airfoils. The USA 35B airfoil, which has a more curved shape on the upper surface and a concave lower surface, shows the largest pressure difference. This influence of the surface is typical for angles of attack greater than 2°.

However, at angles of attack close to 0° (Fig. 3), the approach to the surface for the given airfoils and for the given number of Re has a negative effect, from the point of view of the generation of lift force. This can be explained by the Venturi effect, when the flow that passes through the narrowed area between the airfoil and the ground is accelerated, which leads to a decrease in pressure. This effect is more pronounced for Clark YH-12 and NACA-M6 airfoils, to a lesser extent for TsAGI-721 and almost absent for USA-35B. Therefore, the shape of the lower surface of the Clark YH-12 and NACA-M6 contributes to the appearance of this effect at zero angle of attack.

As the data in Fig. 4 show, frontal drag depends on the angle of attack and to a lesser extent depends on the distance to the surface. An increase in frontal drag for all considered airfoils is observed at $\bar{h} < 0.5$. It should be noted that this statement of the problem implies only frontal drag without taking into account the inductive component.

The lift coefficients (Fig. 5) depend on both the angle of attack and the distance to the surface. It can be seen that at an angle of attack of 0°, the approach to the surface has a negative effect on the lift force due to the factors indicated above. In particular, for the airfoils Clark YH-12 and NACA-M6, TsAGI-721, a negative lift force appears at $\bar{h} < 0.5$ at the considered Re number. As the angle of attack increases, the lift coefficient increases. When the influence of the surface is almost not felt, and the coefficients of lift force tend to the corresponding values in the unrestricted flow. The maximum lift force is obtained for the USA 35B airfoil.

The parameter that determines the performance of airfoil is the aerodynamic quality. As shown in Fig. 6, this indicator depends on the angle of attack and has an optimal range of angles for which the quality acquires the greatest values. This range for all types of airfoils is within 4–6°. The best quality is demonstrated by the USA-35B and TsAGI-721 airfoils.

Therefore, the greatest increase in aerodynamic quality during approach to the surface occurs for USA 35B – 67 %. The NACA-M6 airfoil gives a smaller increase in lift, only 16 %, but it achieves this value at much greater distances from the surface, which is important for ekranoplanes.

The considered airfoils have not previously been studied in the zone of influence of the ground effect. Known results, for example [10], contain data on aerodynamic characteristics only under conditions of unbounded flows. Therefore, our research expands the knowledge base about the characteristics of airfoils and substantiates the determining parameters under which their use in unmanned WIG craft is expedient. However, it should be noted that the results are limited to a given range of angles of attack corresponding to the precritical mode of flow around the airfoils.

It is advisable to direct further research to investigating the behavior of airfoils under the conditions of an uneven surface, studying the influence of the Reynolds number and geometric parameters, and determining the aerodynamic moment. This will make it possible to state the problem of multi-parameter optimization of the aerodynamic processes of the wing in an unmanned aerial vehicle with the dynamic principle of support over the surface.

7. Conclusions

1. The results of our study show that the shape of the airfoil, the distance to the surface, and the angle of attack significantly affect its aerodynamic characteristics. At angles of attack close to 0°, the Venturi effect occurs due to the shape of the airfoil and the proximity of the surface, which

negatively affects the aerodynamic quality. The USA-35B airfoil, due to its more curved upper surface and concave lower surface, exhibits the largest pressure difference between the upper and lower surfaces.

2. Aerodynamic quality reaches the highest values at angles of attack of 4–6°. The USA-35B airfoil exhibits the greatest aerodynamic quality and the greatest lift during approach to the surface (67 % increase). The USA-35B airfoil can be recommended for small unmanned aerial vehicles with a dynamic principle of support over the surface. The airfoil TsAGI-721 also shows a good improvement in aerodynamic quality (41 % increase), but at shorter distances from the surface. Under low angle of attack conditions, the Clark YH-12 and NACA-M6 airfoils are recommended for use at $\bar{h}>0.25$. The recommended angle of attack range for all airfoils is 4–6°.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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