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DETERMINING THE AERODYNAMIC PERFORMANCE OF A HIGH-SPEED UNMANNED MARINE WIG CRAFT

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The study object of this paper is the aerodynamic processes during the movement of an unmanned aerial vehicle flying low over the underlying surface. The ground effect is known to enhance the aerodynamic performance of low-flying aircraft, particularly larger ones. However, this effect is most noticeable for large objects. Unmanned vehicles are typically characterized by their relatively compact geometry. This study explores the aerodynamic processes involved in the flight of a small-sized vehicle using the principle of dynamic support over a surface. The particular prototype of the unmanned aerial vehicle suggested by the authors has been examined herein. The aim of the study is to evaluate the aerodynamic forces affecting a small-sized unmanned high-speed vehicle that employs the dynamic principle of support over the surface (WIG craft) by using CFD modeling. In contrast to most available studies on the ground effect, a 3D problem statement was used in this work. Computational experiments have visualized the physical fields surrounding an aircraft in flight over the ground. This study determines how the distance from the surface affects the aerodynamic properties of a small-sized aircraft, as well as the height of the effective zone where ground effect influences the small-sized WIG craft within $0.3 \le \bar{h} \le 0.7$. It has been shown that approaching the surface leads to a shift in the center of pressure of the vehicle, which leads to a change in aerodynamic momentum. This phenomenon must be taken into account when designing a control system to provide a stable flight. The study's findings are directly relevant for the development of a type of unmanned vehicles that use the dynamic principle of support over the surface

Keywords: aerodynamic forces, small-scale WIG craft, CFD modeling, unmanned systems, ground effect

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1. Introduction

Currently, there is a growing trend towards the development of unmanned technologies in the field of transport. The war waged by Russia against Ukraine and the events on the battlefield have clearly demonstrated the effectiveness, importance and, in many cases, the irreplaceability of the use of unmanned systems. An example of the most successful use of such devices is a series of operations by the defense forces of Ukraine against the aggressor on the Black Sea using high-speed unmanned boats [1].

One of the determining factors that affects the effectiveness of unmanned vehicles is speed. In the case of marine vehicles, an increase in speed is possible by reducing the contact of the vessel with water, which leads to a significant decrease in aerodynamic resistance. At the same time, there is an increase in the lift force affecting the device near the surface (ground effect). The principle of non-contact movement using the ground effect is used in the construction of WIG (wing-in-ground) vessels, or "ekranoplane" in Soviet terminology [2].

Despite a number of advantages, in particular, the possibility of providing high-speed modes, these devices have not been widely used in practice today. This is due to the "sensitivity" of WIG-vessels to changes in the parameters of aerodynamic processes during movement near the ground and the lack of a reliable flight theory of such systems. This issue is especially acute in the case of small-sized devices since the scale factor is one of the determining factors in the ground effect. At the same time, new prospects for the use of ekranoplanes, in particular unmanned aircraft [3], make the study of aerodynamic processes an actual and practically important task.

2. Literature review and problem statement

Most known actual WIG craft were quite large. According to data from [4], the main characteristics of known WIG craft range from 17 to 93 meters in length and with a span of 15 to 150 meters.

At the same time, the dimensions of the most known unmanned aerial vehicles are an order of magnitude smaller and are 4–8 m in the longitudinal direction [5]. It is known [2] that the influence of the surface effect depends significantly on the geometric characteristics, in particular on the wing chord length and elongation. This predetermines the need for research into the aerodynamics of small-sized unmanned aerial vehicles.

The concept of using WIG craft as hybrid ships for military and civilian purposes is discussed in [6]; at the same time, a number of unresolved issues are noted, in particular, the lack of an unambiguous theory of flight near the surface.

Experimental studies of the ground effect are associated with a number of technical difficulties, which are highlighted in work [7]. In [8], an engineering methodology for calculating the main design parameters of ekranoplanes is proposed. However, its use presupposes the presence of certain a priori information, in particular a number of aerodynamic characteristics. In [9], a simple power-law dependence for the lift force coefficient on the distance to the surface was obtained, but this relation does not take into account the influence of other important geometric parameters. Work [10] gives a number of semi-empirical expressions for estimating the influence of the proximity of the surface on the lift force and aerodynamic resistance of an aircraft wing. But the range of problems where this approach is effective is limited to wings of elliptical and trapezoidal shape in plan. Therefore, one of the main tools for the study of aerodynamic processes in the presence of a surface is a computational experiment that allows conducting parametric studies for a wide range of initial parameters.

Methods for simulating processes within computational fluid dynamics (CFD) have proven successful in a number of works on the study of wing aerodynamics near the ground. In particular, the aerodynamic characteristics of the airfoil operated under difficult conditions were studied in [11]. In [12], the influence of the geometric features of the wing structures on the aerodynamic characteristics near the ground was investigated. In [13], by means of a comparative analysis of various wing configurations, the influence of the proximity of the ground surface on the displacement of the center of pressure, which is a determining factor for stability, was established. The possibility of using the ground effect for UAVs is considered in [14]. However, most of these and other similar works consider the problem in a flat setting or are limited to studying the characteristics of only the wings of the apparatus. This simplifies the construction of the calculation model, makes the research independent of the design features and allows efficient use of computing resources. However, with this approach, it is not possible to determine the integral characteristics of the device, taking into account the influence and interference of other structural elements. For small WIG craft, it is important to consider the effect of the ground on the aerodynamic characteristics in a spatial setting since the scale factor is of significant importance.

Therefore, the task to determine the effectiveness of ground effect for small-sized WIG vessels, in particular those that can be used as UAVs, requires further study. Our work examines aerodynamic processes for a specific design of a flying WIG craft using a 3D computer model, which allows for a more comprehensive consideration of the impact of design features on aerodynamic characteristics.

3. The aim and objectives of the study

The aim of our work is to evaluate the aerodynamic forces that affect a small-sized unmanned high-speed WIG craft using the dynamic principle of support over the surface, using CFD simulation. This will make it possible to choose rational design parameters of small-sized unmanned WIG craft.

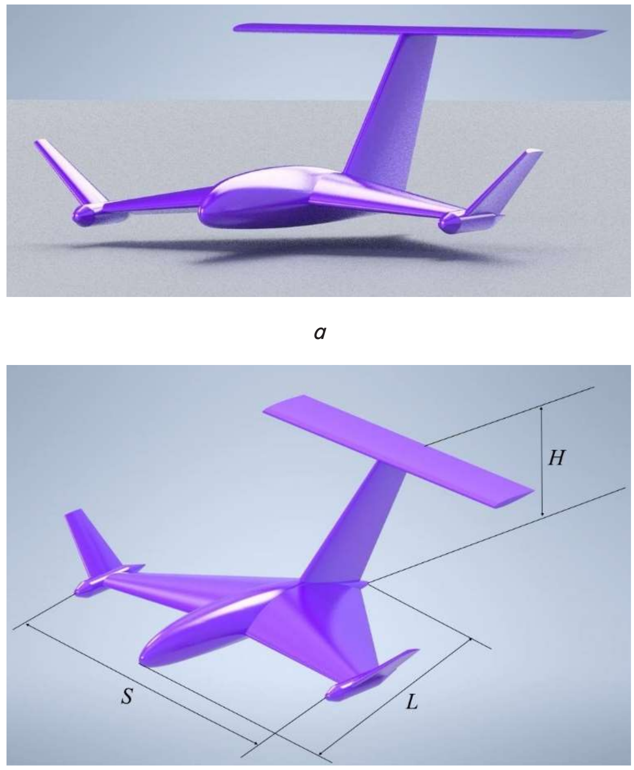
To achieve the goal, the following tasks were set:

– to determine on the basis of computer simulation the velocity and pressure fields around the unmanned aerial vehicle moving near the surface;

– to investigate the influence of the ground effect on the aerodynamic characteristics of a small unmanned aerial vehicle that moves near the surface.

4. The study materials and methods

The object of our study is an unmanned flying WIG craft whose concept was devised at the Oles Honchar Dnipro National University (Fig. 1).



b

Fig. 1. General view of WIG craft: *a* – isometry; *b* – basic dimensions

The main geometric dimensions of the WIG craft under consideration are given in Table 2.

Table 2

Geometrical characteristics

Parameter	Value
Length *L*, mm	5,100
Span, *S*, mm	6,240
Height, *H*, mm	2,550
Wing area *S*, m^2	13.85
Mean aerodynamic chord of the wing *c*, mm	1,560
Airfoil geometry	NACA6409 – airfoil root NACA6412 – airfoil ends

A number of assumptions were adopted during the construction of the computer model. In the first approximation, we assume that the underlying surface is perfectly flat and non-deformable. We shall consider only the cruise stationary mode of flight at zero angle of attack of the device. The speed of movement is much lower than the speed of sound. The presence of V-shaped airfoil ends should reduce the effect of flow from the lower surface of the wing to the upper one.

As the main parameter characterizing the effective area of action of the WIG effect, we take the dimensionless value of clearance, which characterizes the ratio of the distance between the trailing edge of the wing and the underlying surface *h* to the aerodynamic chord *c:*

$$\bar{h} = h/c.$$

From a mathematical point of view, the processes of aerodynamics during the flow of air around the device are described by the Reynold-averaged Navier-Stokes equations, which can be represented in vector form:

$$\frac{\partial \bar{q}}{\partial t} + \frac{\partial \bar{E}_i}{\partial x_i} = 0, \tag{1}$$

$$\bar{q} = \begin{bmatrix} \rho \\ \rho_A u_1 \\ \rho_A u_2 \\ \rho_A u_3 \\ e \end{bmatrix}, \quad \bar{E}_i = \begin{bmatrix} \rho_A u_i \\ \rho_A u_i u_1 + \delta_{1i} p_A - \tau_{1i} \\ \rho_A u_i u_2 + \delta_{2i} p_A - \tau_{2i} \\ \rho_A u_i u_3 + \delta_{3i} p_A - \tau_{3i} \\ (e + p_A) u_i - u_j \tau_{ij} - q_i \end{bmatrix}, \tag{2}$$

where t is time; x_i – Cartesian coordinates; u_i – Cartesian components of the velocity vector; i, j=1,2,3 – indices of the coordinate directions in the Cartesian system; ρ – density; p – pressure; e – total energy; δ_{ij} – Kronecker symbols; τ_{ij} – components of the shear stress tensor; q_i are the components of the heat flow vector.

The SST (Shear Stress Transport) turbulence model [15] was used to close the system of equations (1), (2); at has proven effective in aircraft aerodynamics calculations [16]. On the other hand, as shown in [17], the choice of the turbulence model significantly affects the result of calculating the aerodynamics of WIG craft only at small values $\bar{h}$ or negative angles of attack.

The system of equations (1), (2) is supplemented by boundary conditions, which consist of "sticking" conditions on solid surfaces, conditions of a given speed at the input cross-section of the calculation domain, and "soft" boundary conditions at the output cross-section of the domain.

The numerical implementation of model (1), (2) with the corresponding boundary conditions was carried out using the ANSYS Fluent software. The spatial model of the calculation area is chosen in the form of a parallelepiped, in the middle of which a geometric model of the craft and ground are placed. Using an unstructured calculation grid, the calculation area of the mathematical modeling of the ekranoplanes flow consisted of 7,794,177 nodes (20,728,398 elements) (Fig. 2).

When exporting the computational grid to the solver, cells were converted into polyhedral cells. Compared to tetrahedral or hybrid meshes, this transformation makes it possible to reduce the total number of cells while maintaining the accuracy of calculation on equivalent triangular meshes. In addition, increasing the number of connections of polyhedral cells improves the convergence of the calculation process compared to the triangular grid [18]. The calculation grid was thickened near the streamlined surface in such a way that there were at least 12 calculation grid nodes within the viscous sublayer. The thickness of the viscous sublayer was determined:

$$y^+ = \frac{u_\tau \Delta y_1}{\nu}, \tag{3}$$

$u_\tau = \sqrt{\frac{\tau_w}{\rho}}$ – friction velocity, $\tau_w = 0.5 C_f \rho u^2$ – near-wall tangential stress, $C_f = \frac{0.058}{\mathrm{Re}^{0.2}}$ – surface friction coefficient, Δy_1 – absolute distance to the wall, ν – kinematic viscosity, Re – Reynolds number.

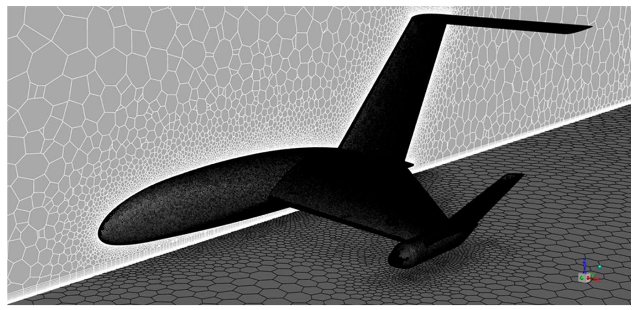


Fig. 2. Calculation area

Calculations were carried out for speeds of movement over the surface in the range of 40–100 km/h.

5. Results of investigating the aerodynamics of the WIG craft near the surface

5. 1. Determining the velocity and pressure fields around an unmanned vehicle moving near the surface

As a result of computational experiments, a pattern of the flow around the WIG craft during flight near the surface for different speeds and different flight heights above the surface was obtained. The results of the calculation of the pressure field (Fig. 3) and velocity (Fig. 4) around the device moving at a speed of 100 km/h at a distance of h=0.4 m above the surface are shown below.

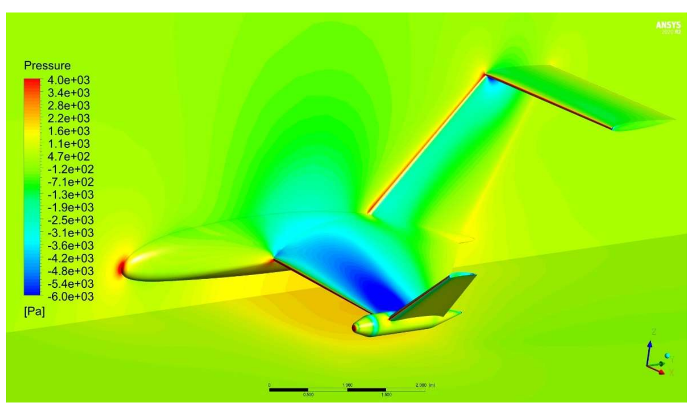


Fig. 3. The pressure field around the aircraft near the ground

Fig. 5 shows the results of streamline calculations, and Fig. 6 – the vortex structure (Fig. 4, *b*), which is formed behind the apparatus as a result of the flow around the structure.

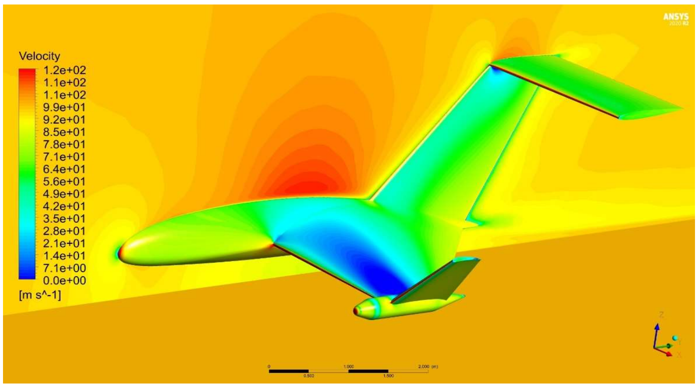


Fig. 4. The velocity field around the aircraft near the ground

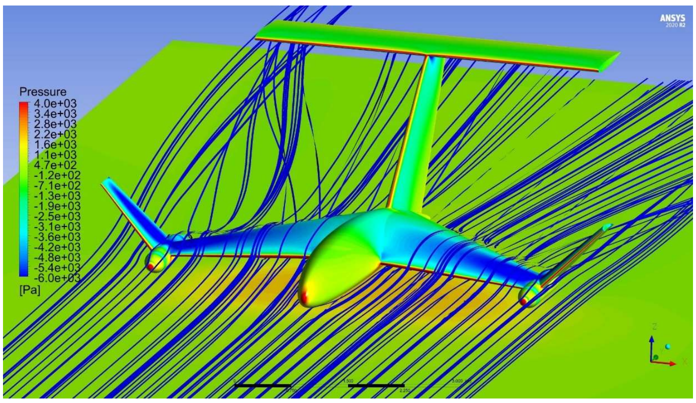


Fig. 5. A pattern of streamlines around the aircraft

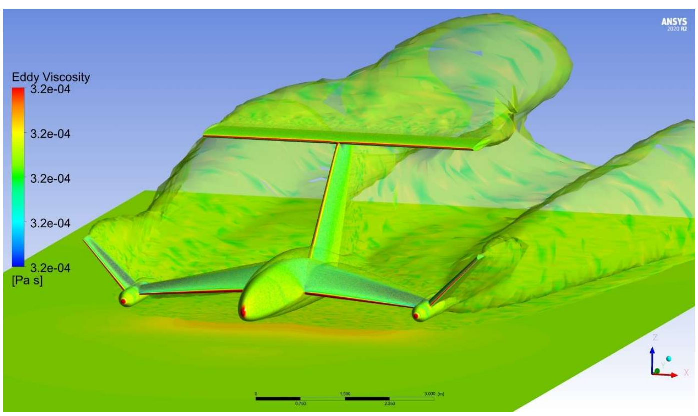


Fig. 6. A pattern of a vortex formation around an aircraft

The results of the calculation of physical fields at other velocities showed a qualitatively similar pattern of the distribution of physical quantities. Our calculation results make it possible to assess the physical pattern that occurs during the movement of the apparatus near the surface.

5. 2. Influence of the ground effect on the aerodynamic characteristics of a small-sized unmanned aerial vehicle moving near the surface

Fig. 7 shows the results of investigating the influence of the distance from the device to the ground and the speed of movement on the aerodynamic characteristics: lift coefficient, drag coefficient, aerodynamic moment coefficient, as well as the position of the center of pressure of the device. Corresponding aerodynamic characteristics must be determined

Expressions for aerodynamic coefficients take the form:

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

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

$$c_m = \frac{M_a}{\left(\frac{\rho V^2}{2} S_M \cdot c\right)},$$

where X_a, Y_a – aerodynamic drag force and lift force, M_a – aerodynamic moment; c_x – drag coefficient, c_y – lift coefficient, c_m – aerodynamic moment coefficient, ρ – flow density, V – speed; S_M is the area of the medial section of the apparatus.

For ease of analysis, the results are represented in relative values, in which the aerodynamic characteristics near the ground are related to the corresponding values in the unbounded flow. Fig. 5 shows the influence of the distance to the ground on the main aerodynamic characteristics of the device.

Fig. 8 shows the results of calculating the displacement of the position x_p of the pressure center as it approaches the ground relative to the position corresponding to the flight in the unbounded flow $x_{p\infty}$.

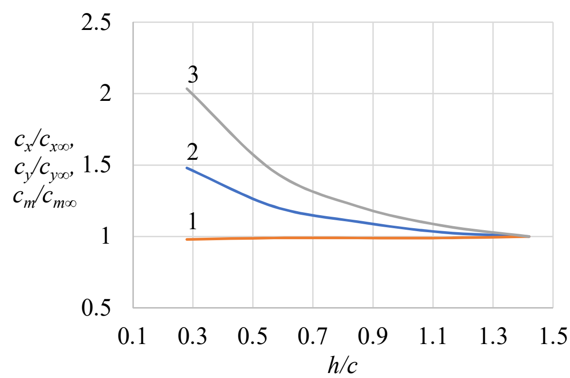


Fig. 7. Dependence of aerodynamic characteristics on the distance to the ground: 1 – $c_x/c_{x\infty}$; 2 – $c_y/c_{y\infty}$; 3 – $c_m/c_{m\infty}$

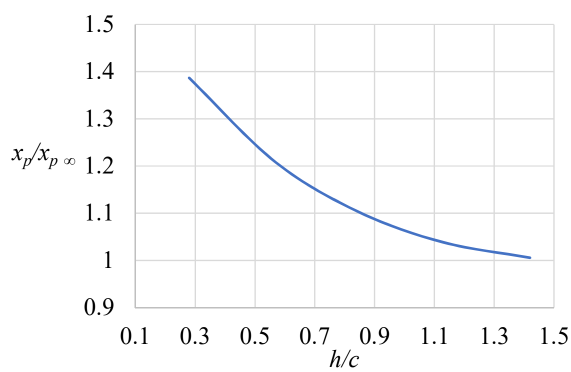


Fig. 8. Dependence of the relative coordinate of the location of the pressure center $x_p/x_{p\infty}$ on the distance to the ground h/c

Fig. 9 shows the results of calculating the ratio of lift force to the force of aerodynamic drag, which reflects the aerodynamic quality of the device, for speeds of 40 km/h and 100 km/h.

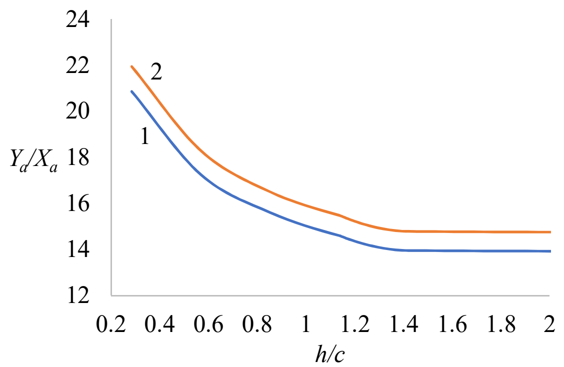


Fig. 9. Dependence of the aerodynamic quality Y_a/X_a on the distance to the ground h/c for speeds: 1 – 40 km/h; 2 – 100 km/h

Our results make it possible to evaluate the influence of the ground effect on the aerodynamic characteristics of the device under consideration.

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

The results of the calculation of the velocity and pressure fields (Fig. 3, 4) show that in the forward part of the fuselage the flow slows down and a zone of increased pressure is formed. The flow then wraps around the hull and accelerates over the top of the fuselage and over the bearing surfaces, resulting in the formation of low pressure zones. In the gap between the craft and the ground, the flow slows down, and the pressure increases, therefore, conditions are created for increasing the lift force.

The presence of V-shaped ends prevents the flow from the lower surface of the wings to the upper (Fig. 5), which prevents an increase in induced resistance. Fig. 6 shows that two large-scale vortices are formed behind the bearing surfaces, rotating in different directions. But, under the influence of the surface, both vortices are directed upwards. The vortex trail gradually increases in cross-section as the apparatus moves away.

The resistance coefficient almost does not change when the device approaches the ground (Fig. 7). At the same time, there is an increase in lift force as it approaches the ground. The effect of the ground is manifested at distances $h/c<1.3$, for $h/c\approx0.3$ the increase in lift reaches 48 % compared to flight in an unrestricted flow. Note that for small-sized WIG craft in the region $h/c<0.2$ is problematic since the absolute values of the height h will be insignificant. Therefore, in the case of minor surface distortions, risks are created for the stability of the device. A suitable range of operating heights can be recommended to be $0.3\leq h/c\leq0.7$.

According to the obtained data (Fig. 7, line 3, Fig. 8), when approaching the ground, the center of pressure shifts, and the value of the aerodynamic moment coefficient increases by more than 2 times for $h/c\approx0.3$. This fact is important from the point of view of ensuring stable flight and must be taken into account in the control system of the device. Therefore, our results create a basis for determining the aerodynamic and design parameters of small-sized WIG craft.

The aerodynamic quality increases significantly as the WIG craft approaches the surface. According to the data in Fig. 9, quality increases by 1.5 times for $h/c\approx0.3$ compared to unlimited flow. It should be noted that higher speed modes correspond to better aerodynamic quality.

It is obvious that the scope of the obtained results is limited to the structure under consideration. However, the general patterns are fully consistent with the aerodynamic theory of flight near the ground. It should be noted that, unlike many other studies of the aerodynamic characteristics of individual WIG craft elements, this study considered the complete layout of a small-sized device.

In general, our results create a scientific basis for the selection of rational design parameters for a small-sized WIG craft of the aircraft type because not only the characteristics of the bearing surfaces are determined but the layout in general is considered. The subject of further research should be the study of flight stability, taking into account the established aerodynamic, in particular moment, characteristics.

7. Conclusions

1. CFD modeling in a 3D statement was used to study the aerodynamic processes that take place during the movement of a small-sized WIG craft near the ground. It has been shown that during the movement of an unmanned small-sized WIG craft near the ground, conditions are created for an increase in the lift force compared to the case of an unbounded flow. Therefore, due to the imbalance of the pressure and velocity fields on top of the apparatus and in the gap between the ground and the lower surface of the apparatus, an additional lift force will arise. To reduce the induced resistance, it is recommended to use V-shaped ends on the bearing surfaces.

2. Decreasing the distance to the ground does not significantly affect the coefficient of aerodynamic resistance of a small-sized WIG craft while, at the same time, the coefficient of lift force and the coefficient of aerodynamic moment increase. The appropriate area of operation of a small-sized WIG craft can be recommended in the height range of $0.3\leq h/c\leq0.7$. Approaching the surface leads to a shift in the center of gravity of the vehicle, which leads to a change in the aerodynamic moment, and must be taken into account during the development of the control system to ensure stable flight. Our research results confirm the effectiveness of the proposed aerodynamic layout of the unmanned WIG craft using the ground effect.

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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