

NUMERICAL INVESTIGATION AND AERODYNAMIC CONFIGURATION OPTIMISATION OF A VTOL FLYING WING UAV

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The manuscript presents the results of the computational investigation into the aerodynamic characteristics of a Vertical Take-Off and Landing (VTOL) flying wing unmanned aerial vehicle (UAV), with particular emphasis on the aerodynamic behaviour of the lifting surface. The airflow around the model is analysed over a wide range of velocities corresponding to Reynolds numbers $Re \approx 9.66 \times 10^4 - 1.29 \times 10^6$. Special attention is devoted to the influence of the angle of attack (AOA), airflow regimes, and wing geometric parameters on the aerodynamic efficiency and stability of the aircraft.

The following tasks have been achieved in this study: the development of the geometric and computational wing model; generation of the computational domain and mesh with verification of the grid convergence; computational modelling of the flow at different velocities and AOA; determination of aerodynamic coefficients; construction of the aerodynamic

polar; evaluation of aerodynamic and energy efficiency; and analysis of stability and transition regimes, including the influence of ground effect.

The study is based on the numerical solution of the unsteady Reynolds-averaged Navier-Stokes equations using the Low Reynolds $k-\varepsilon$ turbulence model. The finite volume method has been applied for discretization. The simulations have been carried out in the SolidWorks/FlowEFD software environment using adaptive computational mesh and variable time step. The reliability of the results has been confirmed through the grid independence analysis.

It has been found that within the AOA range $\alpha = -4^\circ - 14^\circ$, the lift coefficient dependence $C_L(\alpha)$ remains linear, while the drag coefficient $C_D(\alpha)$ follows the quadratic trend. The maximum aerodynamic efficiency reaches $K \approx 11$ at AOA of $\alpha \approx 6^\circ$, corresponding to the optimal cruise flight regime. It has also been shown that the influence of the Reynolds number on the aerodynamic characteristics within the investigated range is insignificant. The static longitudinal stability of the aircraft has been confirmed by the negative slope of the pitching moment dependence. The characteristics of the VTOL transition regime have been determined, and a significant influence of the ground effect has been identified, leading to the increase in lift and the reduction in induced drag at low flight altitudes.

The results of the study confirm the high aerodynamic efficiency of the flying wing configuration for VTOL UAVs. The optimal flight parameters and transition conditions providing maximum aerodynamic and energy efficiency have been determined. The obtained dependencies and identified patterns can be applied during the design, optimisation, and development of the control systems for UAVs of this type.

The obtained results can be used not only for analysis purposes, but also as an engineering tool for the development of aerodynamically efficient UAV configurations at the early design stage, making it possible to reduce the need for experimental testing and shorten the flying vehicle development cycle.

Keywords: *Aerodynamics, aerodynamic efficiency, flying wing, ground effect, Navier-Stokes equations, numerical simulation, stability, turbulence, vertical take-off and landing, unmanned aerial vehicle.*

1. INTRODUCTION

At present, UAVs are being rapidly developed, with particular attention focused on the hybrid configurations that combine the advantages of fixed-wing aircraft and rotorcraft systems. The flying wing concept combined with VTOL capability is of special interest due to its reduced aerodynamic drag, extended flight range, and improved energy efficiency. Such flying vehicles are capable of operating in confined take-off and landing conditions while maintaining

high aerodynamic efficiency in different flight regimes. Among the most promising configurations are UAVs designed according to the flying wing scheme and equipped with VTOL system [1]–[3].

Such flying vehicles are in demand for monitoring, mapping, cargo delivery, and military applications, especially in situations where take-off and landing space is limited [4], [5]. However, the complex aerodynamics, unsteady operating condi-

tions, and interaction between propeller flows and the lifting surface require detailed numerical analysis [6]–[9].

The design and configuration of UAVs are often based on a sequential combination of parameters and individual components, usually without considering their mutual interaction within a unified aerodynamic system. As a result, this leads to significant flow interference effects, especially in multirotor configurations [6]. Various assumptions, together with the lack of the information about the complete flow structure and the interaction between the individual aerodynamic elements limit the possibility of optimising UAV configurations during the engineering design process and achieving the required performance characteristics. Parameters obtained using this method remain approximate and require further refinement through full-scale testing, which leads to considerable material costs. This is the reason why modern engineering practice combines classical analytical methods, computer-aided design (CAD) systems [10], computational fluid dynamics (CFD) methods [11]–[13], experimental verification, and full-scale testing.

Computational modelling makes it possible to significantly reduce the requirement for full-scale testing, improve design accuracy, and optimise the configuration during the early stages of the development. In modern aircraft engineering, computational modelling has become an important design tool that allows optimal aerodynamic solutions to be identified before conducting expensive experimental studies.

Unlike most existing studies, the present work focuses on the quantitative relationship between aerodynamic efficiency, longitudinal stability, and the parameters of the VTOL transition regime. This approach makes it possible not only to evaluate aerodynamic performance, but also to determine

optimal transition conditions for horizontal flight while taking energy limitations into account.

The aim of this study is to perform a numerical calculation of the aerodynamic characteristics of VTOL flying wing type UAV in order to evaluate its efficiency, optimise the configuration, and develop engineering recommendations applicable to the design and development of UAVs of this type.

Analysis of the recent studies shows that the aerodynamics of VTOL UAVs is being actively investigated in the context of transition regimes, stability, and configuration optimisation. Review papers on VTOL UAVs emphasise that the main challenges remain maintaining cruise efficiency, ensuring stability during the transition from vertical to horizontal flight, and accounting for the aerodynamic interaction between lifting surfaces and propulsion systems [14].

Considerable attention has also been devoted to numerical modelling of UAV aerodynamics. CFD-based studies have shown that variations in AOA, flight speed, and altitude significantly affect lift and drag coefficients, as well as the overall aerodynamic efficiency of the aircraft. This confirms the effectiveness of computational modelling as a tool for the early-stage design and optimisation of UAV configurations [15].

Longitudinal stability is of particular importance for the flying wing configurations of flying vehicles due to the absence of the conventional tail assembly, which complicates aircraft trimming and control. The studies of the flying wing type UAVs show that the analysis of the pitching moment dependence on AOA and lift coefficient are necessary to evaluate the static stability of such configurations [16].

A separate area of research is related to the VTOL transition regime. Studies on tilt-

wing and tilt-rotor UAVs indicate that the transition from vertical to horizontal flight is one of the most challenging operating conditions due to the simultaneous influence of wing lift, propulsion thrust, and unsteady aerodynamic effects [17].

An important factor for UAVs operating close to the ground is the ground effect. Studies of the wing-in-ground-effect UAVs and near-ground VTOL configurations have shown that proximity to the surface can significantly affect lift, induced drag, and pitching moments, which must be taken into account during take-off, landing, and

transition flight regimes [18].

Despite the existing studies on VTOL UAV aerodynamics, flying wing UAVs, and ground effect phenomena, the combined relationship between aerodynamic efficiency, longitudinal stability, and transition regime parameters for VTOL flying wing UAVs has not been sufficiently investigated in the literature. Therefore, the present study is focused on a comprehensive numerical analysis of these characteristics over a wide Reynolds number range, with the aim of determining optimal operating conditions.

2. MATERIALS AND METHODS

2.1. Geometry and Computational Model

The aerodynamic wing profile is one of the key elements determining the flight characteristics of an aircraft. The geometry of the wing profile affects the lift and drag coefficients, flight stability, and wing performance under different operating conditions. Among the wing profiles used in aircraft modelling and light aviation, the MH61 wing profile developed by Martin Hepperle for the flying wing configurations occupies a special place. Its main advantages include low drag, high lift coefficient, and

low pitching moment coefficient [19]–[21]. This is the reason why MH61 wing profile is considered an efficient aerodynamic profile for low-speed aircraft, especially in tail-less configurations and flying wings.

The basic geometric and aerodynamic characteristics of the MH61 wing profile in a two-dimensional problem statement can be evaluated using the XFOIL software package [19]. The flying wing model is shown in Fig. 1.

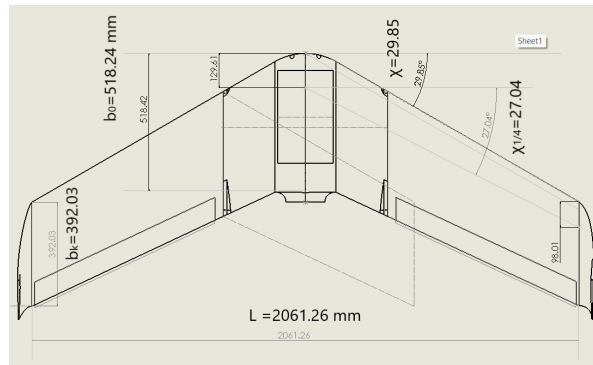


Fig. 1. The flying wing model.

The main parameters of the flying wing model used for the development of the three-dimensional (3D) geometry and sub-

sequent computational calculations are presented in Table 1.

Table 1. The Main Parameters

Parameter	Value
Wing area (S)	0.938 m
Mean aerodynamic chord of the wing (b_x)	0.455 m
Wing aspect ratio (λ)	4.529 m
Wing taper ratio (η)	1.32 m
Sweep angle (χ)	29.06°
Wing airfoil	MH61
Maximum thickness (c) at 27.6 % of the chord	10.2 %
Maximum camber (f) at 37.3 % of the chord	1.4 %

The 3D model of the flying wing was developed in the SolidWorks parametric modelling environment (see Fig. 2). In gen-

eral, the model consists of the centre section, left and right wing panels, and winglets. The geometry was created at full scale.

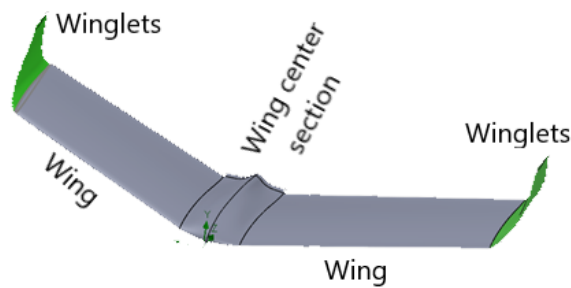


Fig. 2. 3D model of the flying wing. Geometric model of the VTOL flying wing UAV.

The considered flying wing type UAV model was developed at the Institute of Automation and Information Technologies of Satbayev University within the framework of the BR24992908 project “Support System for Agricultural Crop Production Optimisation via Remote Monitoring and

Artificial Intelligence Methods (Agro-scope)”.

In the present configuration, the model is analysed without considering the propulsion system, which makes it possible to focus specifically on the aerodynamic characteristics of the lifting surface.

2.2. Numerical Method

Computational modelling was performed using the FlowEFD CFD software package in the classical problem statement of the external flow problem around

a stationary body. The flying wing model is considered stationary within this approach, while the airflow is generated by an incoming airstream with a specified velocity and

direction. Such a formulation is equivalent to the motion of an aircraft in a stationary air environment and is widely used in computational modelling of the aerodynamic characteristics [22].

The external flow problem statement makes it possible to investigate the pressure distribution, streamline structure, flow vortices, and to determine the main aerodynamic coefficients, including lift, drag, and pitching moment coefficients. Such a modelling approach is considered a standard framework for CFD analysis of the flying vehicles and is widely applied in aerodynamic studies of wings, UAVs, and flying wing configurations [23].

The mathematical modelling of the flow is based on the unsteady Navier-Stokes equations, the energy equation (the first law of thermodynamics), and the equation of state [24]–[27]. The governing equations for turbulent flows are averaged using Reynold’s method considering additional stresses caused by turbulent fluctuations [28]. The resulting unclosed system of the equations is closed using additional transport equations for the turbulent kinetic energy (k) and the turbulent energy dissipation rate ε in accordance with the well-known k - ε turbulence model [29].

It should be noted that a Low-Reynolds number (Low-Re) k - ε turbulence model was selected for the computational modelling of the aerodynamic characteristics of the flying wing configuration. The choice of this turbulence model is determined by the specific features of the considered airflow, which is characterised by relatively Low-Re numbers ($Re \approx 10^5$ – 10^6), where boundary-layer effects play a significant role, including laminar-to-turbulent transition and possible airflow separation [30], [31].

Unlike the standard k - ε model, the Low-Re modification considers the effects of viscosity in the near-wall region and

makes it possible to resolve the boundary layer directly without the use of approximate wall functions [35]. This is especially important for external airflow problems involving wing profiles and wings, where an accurate description of the velocity and stress distributions in the near-wall region has a significant influence on the prediction of lift and drag forces [30], [32]. The application of the Low-Re k - ε model requires the use of a sufficiently fine computational mesh near the surface to correctly resolve the boundary-layer structure.

Additional advantage of this model is its ability to provide a more accurate description of the initial stages of turbulence, regions with strong velocity gradients, and airflow separation processes at moderate AOA.

Thus, the use of the Low-Re k - ε model is well justified for the considered problem and makes it possible to improve the reliability of the numerical simulation of the aerodynamic characteristics of the flying wing configuration.

The formulated system of differential and/or integral equations is nonlinear and, in the general case, does not have an analytical solution. Therefore, it is solved numerically. For this purpose, the differential (or integral) equations are transformed into their finite-difference equivalents. As a result, the mathematical problem of solving a system of differential (integral) equations is reduced to the problem of solving a system of algebraic, usually nonlinear, equations. A discrete set of numerical values is obtained at specific points (or cells) in space and for specific moments in time instead of a continuous solution.

The model is placed inside a computational domain representing a bounded volume of the surrounding air environment for the computational modelling of the aerodynamic characteristics of the flying wing.

The dimensions of the computational domain are selected in a way to eliminate the influence of the boundary conditions at the domain walls on the airflow structure near the wing model. In particular, the domain boundaries are positioned at the

2.3. Initial and Boundary Conditions

The airflow conditions were defined using the dimensionless Reynolds number (Re) at the inlet boundary of the computational domain, which characterises the ratio between inertial forces and viscous friction forces in the incoming airflow equation:

$$Re = \frac{\rho \cdot V \cdot b_{sr}}{\mu},$$

where ρ (kg/m³) is the air density, μ (Pa·s) is

the dynamic viscosity of air at 20 °C, b_{sr} (m) is the mean geometric chord of the wing, and V (m/s) is the characteristic (mean) velocity of the incoming airflow.

The considered Reynolds number range was $Re = 9.66 \times 10^4 - 1.29 \times 10^6$, corresponding to the airflow velocities of $V = 3 - 40$ m/s and covering laminar, transitional, and turbulent airflow regimes (Table 1).

Table 2. The Airflow Conditions

Regime	Laminar		Transitional					Turbulent
V (m/c)	3	5	10	15	20	25	30	40
Re	$9.66 \cdot 10^4$	$1.61 \cdot 10^5$	$3.22 \cdot 10^5$	$4.83 \cdot 10^5$	$6.44 \cdot 10^5$	$8.05 \cdot 10^5$	$9.66 \cdot 10^5$	$1.29 \cdot 10^6$

The simulations were carried out under standard atmospheric conditions: atmospheric pressure ($P = 101325$) Pa, air density $\rho = 1.225$ kg/m³, and dynamic viscosity $\mu = 1.81 \times 10^{-5}$ Pa·s.

The flying wing was treated as a rigid stationary body with zero velocity components specified as ($V_x = V_y = V_z = 0$) within the computational modelling. Thus, the

problem was formulated as the airflow around a fixed solid body exposed to an incoming airflow.

The effect of mass forces due to gravity was also included in the simulation. Gravity was directed along the Y -axis, and the gravitational acceleration was set to $g = -9.81$ (m/s²).

2.4. Computational Mesh Generation Features

Continuous unsteady mathematical model of the physical processes was discretized in both space and time to obtain the numerical solution of the problem.

The computational mesh was generated using the base Cartesian grid formed by dividing the computational domain with planes parallel to the coordinate planes [26]. Local mesh refinement was applied to improve the accuracy of the numerical solu-

tion in regions with high flow parameter gradients, especially near the flying wing model [26], [33]. It should be noted that reducing the size of local cells improves the accuracy of the calculated aerodynamic characteristics, however, at the same time increases the number of mesh elements and the computational costs [26], [27]. Excessive mesh refinement may also lead to the accumulation of numerical round-off errors

and increased computation time [26], [34].

Grid independence study was carried out to evaluate the reliability of the results as the obtained discrete solution depends on the mesh parameters. This was achieved by performing a series of calculations using meshes with different levels of refinement [26], [35]. An example of the computational mesh is shown in Fig. 3.

The convergence analysis was performed through successive refinement of the computational mesh by increasing the total number of cells and comparing the key aerodynamic characteristics of the model, including the lift and drag coefficients, as

well as the velocity and pressure distributions within the computational domain.

The analysis showed that when a mesh containing approximately (1.9×10^6) cells was used, further mesh refinement resulted only in minor changes in the calculated results, remaining within the engineering error range not exceeding 5–10 %. This indicates that grid convergence of the solution was achieved.

Thus, the selected computational mesh provides sufficient simulation accuracy with moderate computational cost and can effectively be used for further investigations of the flow around the flying wing model.

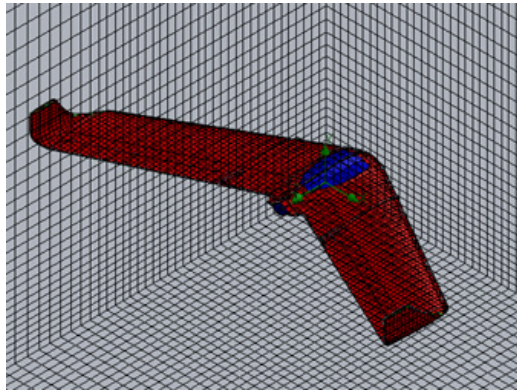


Fig. 3. Example of the computational mesh. Finite volume method.

The numerical simulations were performed in an unsteady formulation using a variable time step. The time step value Δt was automatically adapted during the computation and remained within the range of approximately $4 \times 10^{-4} - 1.3 \times 10^{-3}$ s. The use of an adaptive time step made it possible to ensure numerical stability during the initial stage of the simulation, which was characterised by significant unsteady effects, while also improving computational efficiency.

The selected time-step range provided an adequate resolution of unsteady airflow processes and did not have any significant influence on the final aerodynamic characteristics of the model.

The primary convergence criterion for terminating the simulation was the stabilization of the monitored parameters over time.

The reliability of the obtained results is confirmed by their qualitative agreement with the classical aerodynamic theory of finite wings, as well as by consistency with previously published numerical and experimental studies in this field.

The applied approach allows numerical simulation to be considered not only as an analysis tool, but also as an element of digital engineering design, supporting the selection of geometric parameters and operating conditions during the product development stage.

2.5. Experimental Data Processing

To calculate the lift, drag, and pitching moment coefficients, the following parameters were determined during the simulations: total, static, and dynamic pressure; velocity and its components; aerodynamic forces and moments; force and moment components; as well as flow vorticity.

The lift force of the wing results from pressure-induced normal forces. In an absolute coordinate system, the pressure difference between the lower and upper

wing surfaces determines key aerodynamic parameters. These include the lift coefficient (C_L), the drag coefficient (C_D) both with and without ground effect, as well as the rolling (C_{l_a}) and pitching (C_{m_a}) moment coefficients. This pressure differential also dictates the aerodynamic efficiency (K), the energy efficiency criterion (K_{eff}), and the flow vorticity, which measures the local rotational motion of fluid or gas particles [22], [24].

3. RESULTS AND DISCUSSION

Computational modelling results showed that at small AOAs, $\alpha = -4^\circ - 14^\circ$, the lift coefficient C_L linearly depends on α , which corresponds to a flow regime without separation over the wing surface. This can be explained by the fact that under smooth airflow conditions the airflow is deflected by an angle α , while the change in momentum is proportional to $V_\infty \sin(\alpha)$ or for small AOAs, to $V_\infty \alpha$. Consequently, the impulse of the aerodynamic forces (the normal force in this case) is directly proportional to the AOA α .

The zero-lift condition observed at $\alpha \approx -1^\circ$ indicates the asymmetry of the wing profile. Aerodynamic drag is generated mainly by friction and pressure forces in the absence of lift. Suction force directed forward along the chord appears due to the low-pressure region formed near the leading edge during wing flow at $C_L \neq 0$ ($\alpha \neq 0$). Streamlines over the upper surface become compressed, the flow accelerates, and the pressure decreases with AOA increase. The streamlines expand on the lower surface, the flow decelerates, and the pressure

increases at the same time. The lift coefficient increases as a result.

The lift coefficient $C_L(\alpha)$ dependence on AOA within the investigated range $\alpha = -4^\circ - 14^\circ$, demonstrates a linear behaviour, as shown in Fig. 4.

The dependence of the drag coefficient $C_D(\alpha)$, shown in Fig. 5, demonstrates a nonlinear, approximately parabolic behaviour. The minimum drag coefficient values, $C_{Dmin} \approx 0.025 - 0.03$, are achieved at AOA close to ($\alpha \approx 0^\circ$). The increase in the AOA leads to the increase in induced drag and, consequently, to higher overall aerodynamic drag.

Figures 4 and 5 also show that the Reynolds number range $Re = 9.66 \times 10^4 - 1.29 \times 10^6$, corresponding to flow velocities of 3–40 m/s (Table 1), has only a minor influence on the drag coefficient C_D . The calculated data for the corresponding airflow velocities almost coincide with only slight dispersion. This indicates a weak dependence on the Reynolds number and confirms the stability of the aerodynamic characteristics within the investigated range.

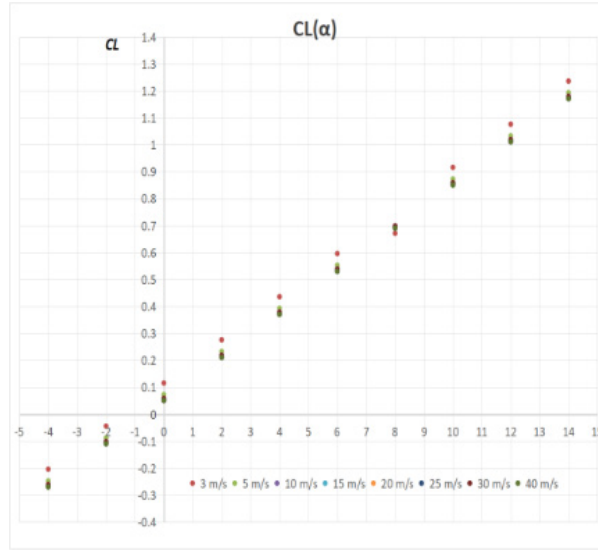


Fig. 4. Dependence of the lift coefficient C_L on the AOA α .

A comparison of the $C_L(\alpha)$ and $C_D(\alpha)$ curves shows that aerodynamic drag increases more rapidly than lift with increasing AOA. The obtained results provide

the basis for further analysis of the aerodynamic polar, aerodynamic efficiency, and determination of optimal operating conditions for the UAV.

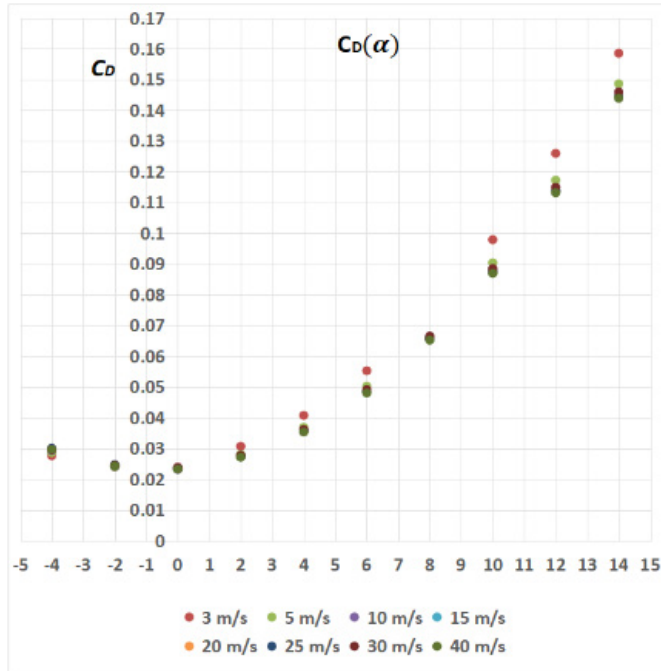


Fig. 5. Dependence of the drag coefficient C_D on the AOA α .

Aerodynamic efficiency K is one of the main indicators of the flying vehicle performance. This parameter characterises how effectively the considered model generates lift while minimising aerodynamic drag losses. The higher the value of K , the greater the flight range and energy efficiency.

The calculations showed that for the investigated flying wing model, the maximum aerodynamic efficiency $K_{max} \approx 11$ was achieved at AOA of approximately $\alpha \approx 4^\circ\text{--}6^\circ$ (Fig. 6). Thus, the maximum aerodynamic efficiency increases as the coefficients C_{D0} and AOA α (Fig. 7).

According to the published studies [36–39], UAVs based on the flying wing configuration typically demonstrate ($K_{max} \approx 8\text{--}14$), with the optimal aerodynamic effi-

ciency achieved at relatively small AOAs ($\alpha_{opt} \approx 4^\circ\text{--}8^\circ$).

The obtained aerodynamic efficiency values ($K \approx 11$) are consistent with those reported in the literature for the flying wing UAV configurations, confirming the validity of the selected geometric layout and numerical approach. The weak dependence of the aerodynamic characteristics on the Reynolds number is also in agreement with previously published results for the wings with similar aspect ratios.

The obtained relationships make it possible to use aerodynamic efficiency as a criterion for selecting wing geometry and operating conditions during the design process of UAVs from the engineering perspective.

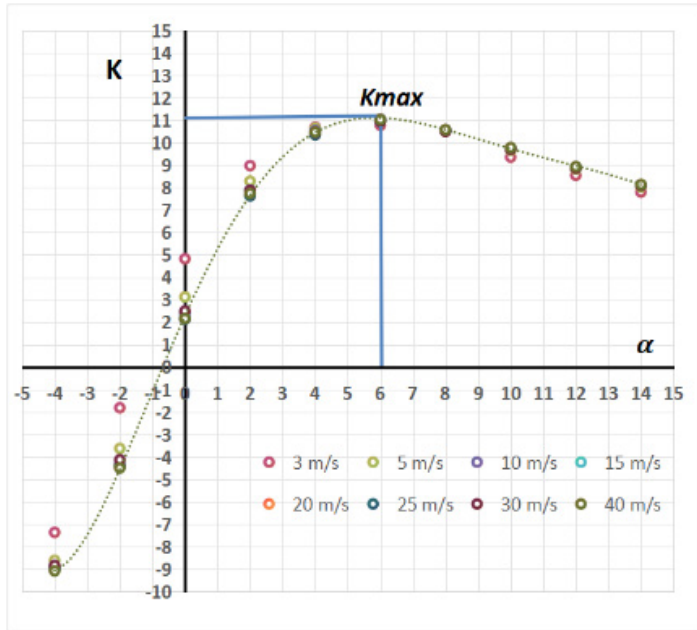


Fig. 6. Dependence of the aerodynamic efficiency K on AOA α .

The aerodynamic polar represents the relationship between the lift coefficient C_L and the drag coefficient (C_D) for the considered VTOL flying wing UAV configuration. It is one of the key characteristics describ-

ing the aerodynamic efficiency of the aircraft in horizontal flight conditions (Fig. 7).

The main feature of the obtained aerodynamic polar is that the zero-lift drag component C_{D0} is shifted along the C_D axis. This

characterises the drag associated with the structural elements of the flying wing configuration in the considered case. The quadratic growth region of the drag coefficient reflects the increase in the induced drag and depends on the wing aspect ratio and lift distribution.

A tangent line drawn from the origin to the polar curve is used to determine the maximum aerodynamic efficiency (Fig. 7).

The tangency point between the straight line and the parabola corresponds to the optimal flight regime. Optimal AOA $\alpha_{opt} \approx 6^\circ$ in the present study. The corresponding values are $C_{Dopt} \approx 0.05 - 0.06$ and $C_{Lopt} \approx 0.5 - 0.55$.

At these conditions, the maximum lift-to-drag ratio is achieved, corresponding to the most energy-efficient cruise flight regime for the considered flying wing configuration.

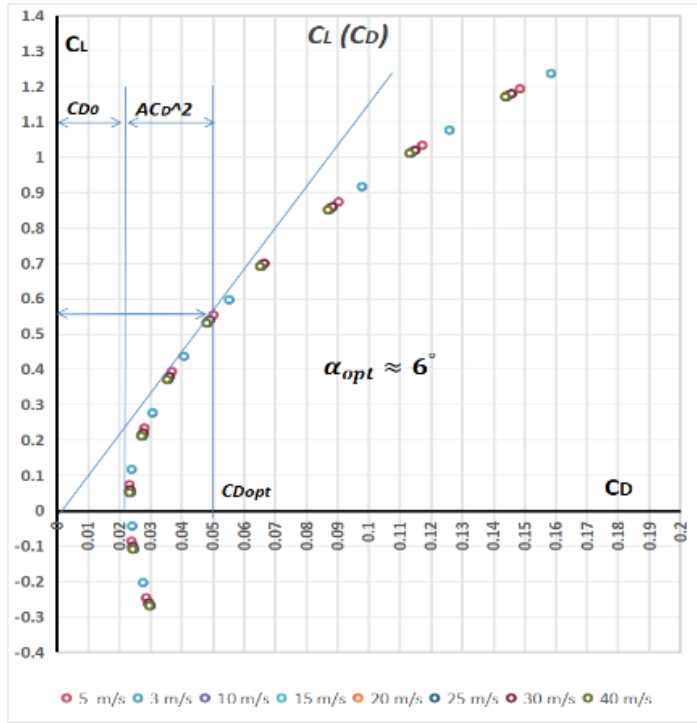


Fig. 7. Dependence of the lift coefficient on the drag coefficient, ($C_L(C_D)$).

The energy efficiency criterion K_{eff} plays a critical role during the transition from vertical hovering to horizontal flight, as well as during long-endurance loitering conditions for the flying wing type VTOL UAVs. The K_{eff} parameter characterises how effectively the UAV can maintain altitude at low flight speeds when the lift generated by the wing only begins to replace the thrust produced by the propellers.

Maximization of this criterion allows the UAV to transition to horizontal flight at lower velocities. The higher the value of K_{eff} , the lower the motor power is required to maintain altitude during the stage when the wing has not yet reached cruise flight conditions.

Figure 8 shows the relationship between the energy efficiency criterion K_{eff} and the aerodynamic efficiency K . As shown in Fig. 8, the value $K_{eff} \approx 80$ is achieved at $K \approx 10$.

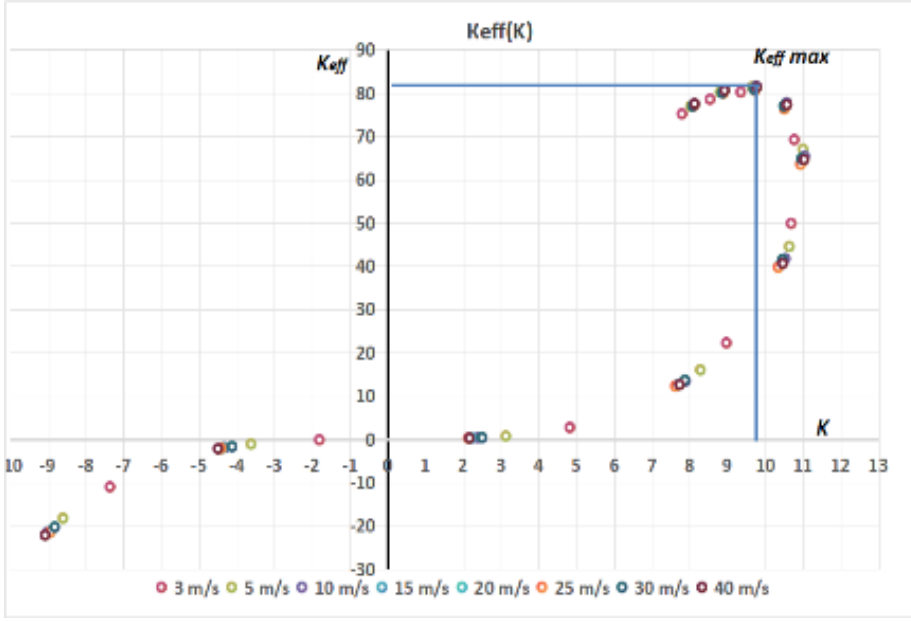


Fig. 8. Dependence of the energy efficiency criterion K_{eff} on the aerodynamic efficiency K .

The analysis of the pitching moment coefficient C_m and the lift coefficient C_L as functions of the AOA α is presented in Fig. 9.

- The lift coefficient C_L increases linearly with increase of AOA, which corresponds to classical aerodynamic behaviour. At AOA $\alpha \approx 0^\circ$, a positive lift coefficient $C_L \approx 0.1$ is observed. This indicates that the wing profile generates lift and confirms the aerodynamic camber of the wing profile.
- The dependence of the pitching moment coefficient $C_m(\alpha)$ has a negative slope, which indicates static longitudinal stability. The trim angle of attack is located within the range of $\alpha \approx 0^\circ - 2^\circ$. An increase in lift is accompanied by the appearance of a nose-down pitching moment, which provides self-stabilization of the model.
- The analysis of the lift and pitching moment coefficients as functions of AOA showed that the considered UAV possessed linear aerodynamic charac-

teristics and static longitudinal stability. The negative slope of the pitching moment dependence on the AOA indicates the stabilizing nature of the aerodynamic forces. The obtained results confirm the validity of the selected aerodynamic configuration and demonstrate the possibility of stable and controllable flight of the UAV.

The dependence of the pitching moment coefficient on the lift coefficient $C_m(C_L)$, shown in Fig. 10, exhibits a linear behaviour with a negative slope, which indicates static longitudinal stability of the flying vehicle. Based on the slope of the curve, it was determined that the centre of gravity was located ahead of the aerodynamic centre by approximately 5 % of the mean aerodynamic chord. The obtained results confirm the correctness of the aircraft trim and provide stable and controllable flight characteristics for the UAV.

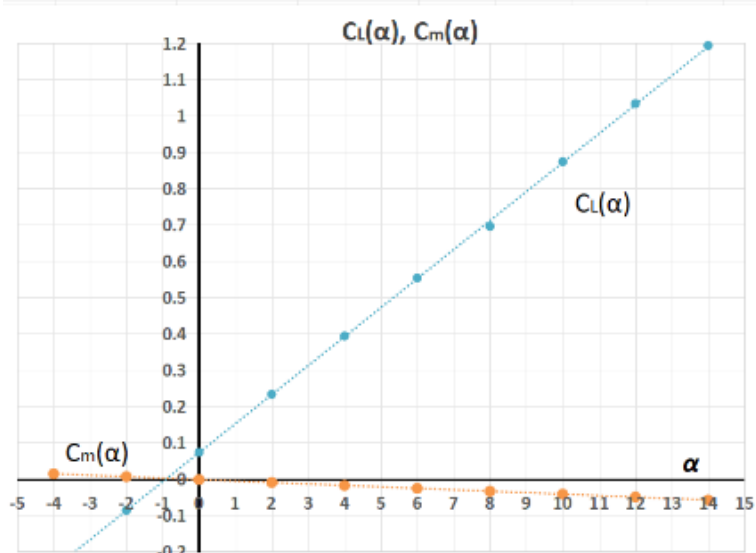


Fig. 9. Dependence of the pitching moment coefficient C_m and the lift coefficient (C_L) on the AOA (α).

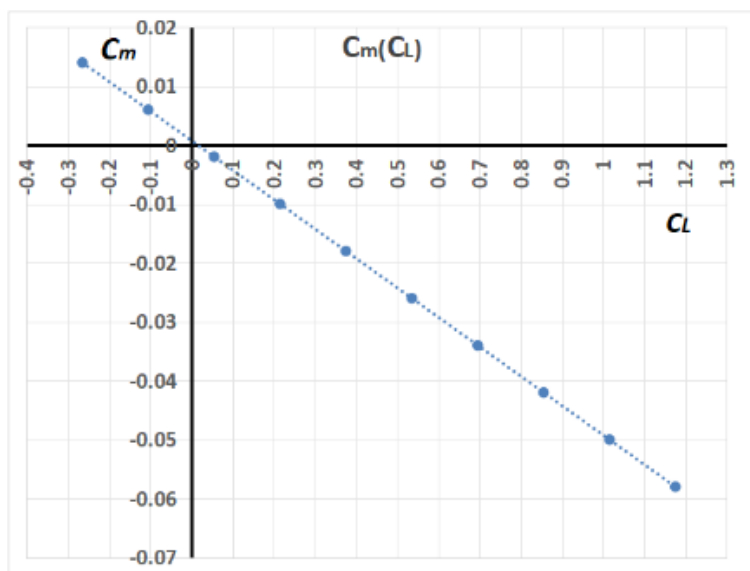


Fig. 10. Dependence of the pitching moment coefficient on the lift coefficient $C_m(C_L)$.

The stall speed V_s , at which the considered model is capable of maintaining steady horizontal flight by generating lift equal to its weight, was determined to be $V_s = 8.5$ m/s. When the flight speed decreases below this value, the wing is no longer able to

generate sufficient lift due to airflow separation, which leads to a rapid loss of altitude, reduced controllability, and aerodynamic stall (nosedive or unstable descent).

The stall speed of the considered flying wing model is determined from the condi-

tion that the lift force is equal to the weight of the model, Eq. (1).

$$V_s = \sqrt{\frac{2 \cdot W}{\rho \cdot S \cdot C_{Lmax}}} = 8.5 \text{ m/s}, \quad (1)$$

where V_s (m/s) is the stall speed; $W = mg$ (N) is the UAV weight; ρ (kg/m³) is the air density; S (m²) is the wing area; and C_{Lmax} is the maximum lift coefficient of the wing profile.

The stall speed determined from the maximum lift coefficient is $V_s \approx 8.5$ m/s. Considering an operational safety margin, the safe flight speed should not be lower than $V_{seff} \approx 1.2 - 1.3 \times V_s$, which corresponds to $C_L \approx 1.2-1.3$ at $\alpha \approx 12^\circ-14^\circ$ (see Fig. 4).

The obtained value is consistent with the aerodynamic characteristics of the aircraft and should be considered when evaluating the transition regime and selecting UAV operating conditions.

The transition speed to horizontal flight V_{trans} for the considered model represents a critical operating condition at which the wing-generated lift begins to support the flying vehicle, Eq. (2):

$$V_{trans} = \sqrt{\frac{2 \cdot k \cdot m \cdot g}{\rho \cdot S \cdot C_L}} \approx 11 \text{ m/s}. \quad (2)$$

$V_{trans} \approx 1.2-1.3 \cdot V_s \approx 10.6$ m/s, where $k = 0.7-0.8$ is the fraction of the aircraft weight supported by the wing, and C_L in the transition regime at $\alpha \approx 5^\circ-6^\circ$ is $C_L \approx 0.5-0.6$ (see Fig. 7).

The calculations showed that the transition speed from vertical to horizontal flight for the considered UAV is $V_{trans} \approx 11$ m/s. This value corresponds to the condition at which the wing generates about 70–80 % of the lift required to balance the flying vehicle weight. The obtained result is consistent with the stall speed value, $V_s \approx 10.6$ m/s, which confirms the validity of the selected transition regime.

It is recommended to perform the transition at the velocities of at least approximately 11 m/s and at AOA $\alpha \approx 5^\circ-6^\circ$ to ensure stable and safe flight conditions. These results can be applied in the development of transition control algorithms and in the selection of propulsion system parameters during the UAV design process.

Consideration of the ground effect is important when designing control systems and selecting operating conditions, especially for aircraft operating in the confined environments. The ground effect occurs when the wing flies at a height $h \leq L$ (h is the height above the ground and L is the wing span). The lift coefficient (C_L) increases, the induced drag coefficient (C_D) decreases, and the pitching moment (C_m) changes under these conditions.

Figure 11 shows the dependence of the lift coefficient C_L on the relative flight height near the ground h/L . Figure 12 demonstrates the dependence of the induced drag coefficient C_{Di} on the relative flight height near the ground h/L .

The pitching moment changes due to the forward shift of the pressure centre near the ground surface, which can be expressed as $C_m(h) = C_m(\infty) + \Delta C_m(h)$.

The ground effect leads to a significant increase in lift and a reduction in the induced drag of the wing. The calculations showed that at a relative height of $h/L \approx 0.1$, the lift coefficient increases almost by a factor of two, which reduces the transition speed from 11.7 m/s to approximately 8.5–9 m/s. At the same time, the pressure centre shifts forward, producing an additional nose-down pitching moment of about $\Delta C_m \approx -0.04-0.05$.

These effects disappear when the aircraft leaves the ground-effect region, resulting in a decrease in lift and an increase in drag, which may lead to a temporary loss of altitude. The transition from the vertical to

horizontal flight should be performed with an adequate speed margin based on out-of-ground-effect flight conditions for this rea-

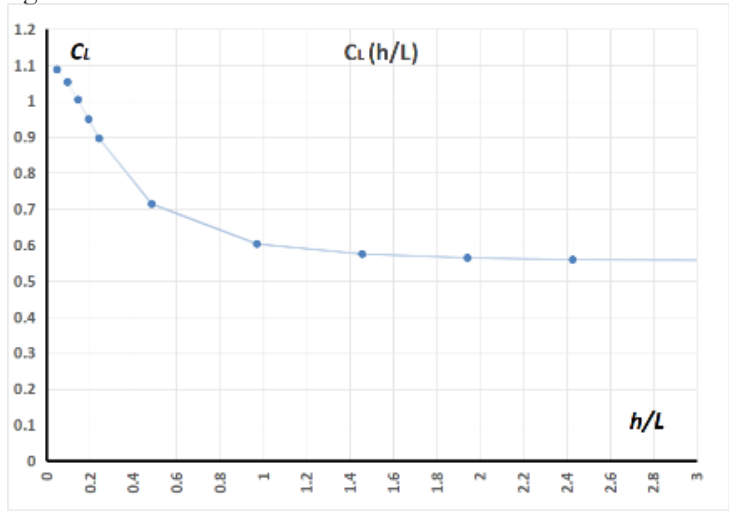


Fig. 11. Influence of the ground proximity on the lift coefficient C_L .

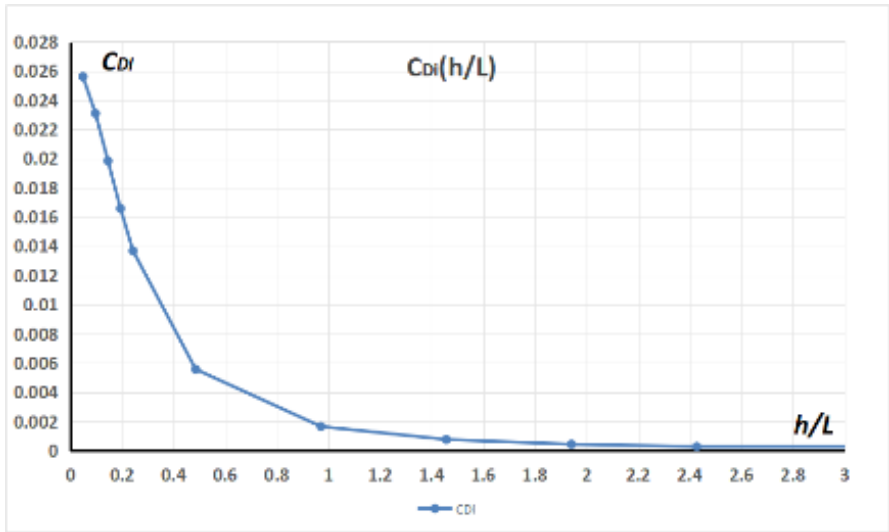


Fig. 12. Influence of ground proximity on the induced drag coefficient C_{Di} .

Flying wing aerodynamic configurations are characterised by a complex 3D distribution of the flow vorticity caused by the absence of a tail assembly, the large lifting surface area, variations in local AOAs along the wingspan, and the interaction

between the wing, the central fuselage, and the winglets. As a result, the vorticity distribution over the wing surface is nonuniform.

The analysis of the airflow structure in the nose region of the model revealed the formation of the local vortex zone

accompanied by 3D airflow redistribution. In the lower part of the airflow field, the airflow shifts toward the right-wing panel, while in the upper part the airflow is redirected toward the left-wing panel. This effect is caused by the 3D nature of the airflow and the formation of a longitudinal vortex structure (Fig. 13).

The observed airflow redistribution indicates the formation of a spatial vortex structure in the nose region of the flying vehicle. The resulting longitudinal vortex redistributes the airflow between the wing panels and affects the pressure distribution and lift generation.

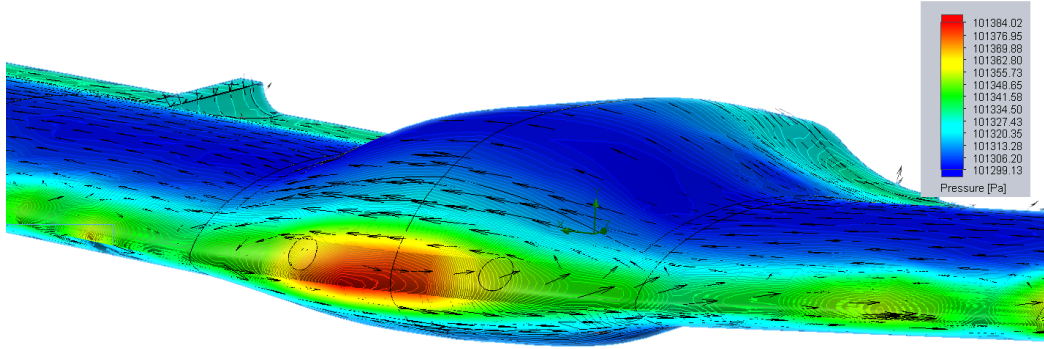


Fig. 13. Pressure distribution and flow structure in the nose region of the flying wing model.

The analysis of the vorticity field showed that opposite wing panels exhibited vorticity values of different signs with the respect to the longitudinal and vertical coordinate axes (Fig. 15). This effect is caused by the formation of paired wingtip vortices

rotating in the opposite directions (Fig. 14). The symmetric distribution of the positive and negative vorticities confirms the correctness of the calculations and indicates a stable flow regime around the model.

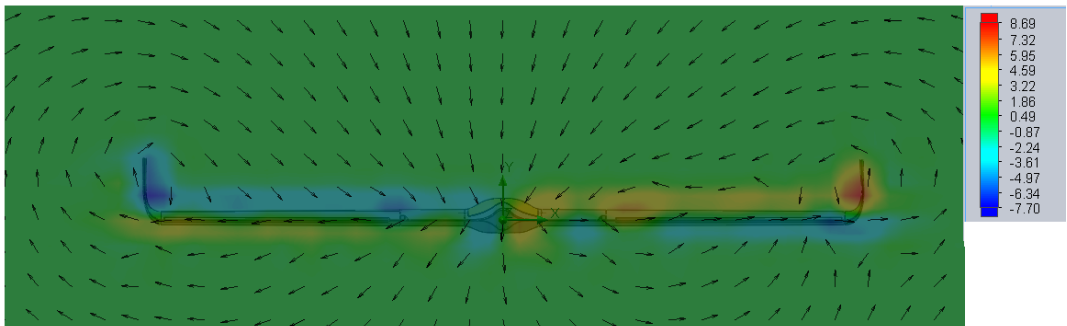


Fig. 14. Flow vorticity relative to the longitudinal Z-axis at the distance of 1 meter downstream of the flying wing model.

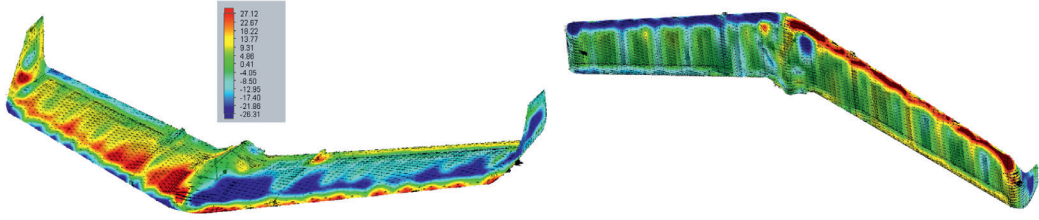


Fig. 15. Flow vorticity relative to the longitudinal Z-axis on the surface of the flying wing model.

4. CONCLUSIONS

Comprehensive analysis of the aerodynamic characteristics of a VTOL flying wing UAV have been carried out. Special attention has been devoted to the investigation of the lift coefficient C_L and drag coefficient C_D as functions of the AOA α , the construction of the aerodynamic polar, and the evaluation of aerodynamic efficiency K and energy efficiency K_{eff} .

The analysis has shown that the dependence of the lift coefficient C_L on the AOA α is linear within the investigated operating range $\alpha = -4^\circ$ – 14° , while the drag coefficient C_D follows a quadratic dependence. These results are consistent with the classical aerodynamic theory and confirm the validity of the obtained computational modelling results.

The constructed aerodynamic polar $C_L(C_D)$ has made it possible to determine the optimal flight regime corresponding to the maximum aerodynamic efficiency. It has been established that the maximum aerodynamic efficiency is $K_{max} \approx 11$ and is achieved at AOA close to $\alpha \approx 6^\circ$. This regime provides the best lift-to-drag ratio and can therefore be considered optimal for cruise flight with maximum range.

Additional analysis of aerodynamic performance has been carried out using

energy-based criteria such as K_{eff} . It has been shown that the maximum energy efficiency is achieved at aerodynamic efficiency values of $K \approx 9.5$ – 10), which differs only slightly from the regime of maximum aerodynamic quality. Thus, it has been established that the maximum-range regime and the maximum-endurance regime do not fully coincide, which should be considered when selecting the wing profile for UAV applications.

The analysis of the velocity effects has demonstrated weak dependence of the aerodynamic characteristics on the Reynolds number within the investigated range, indicating stable aerodynamic behaviour of the considered configuration. This is an important factor for ensuring reliable and predictable aircraft performance under different flight conditions.

Special attention has been devoted to the application of the obtained results to VTOL UAVs. It has been established that in the vertical flight regime, aerodynamic efficiency has no significant effect, whereas in the transition regime it becomes a determining factor. The analysis has shown that the optimal transition conditions correspond to AOAs of $\alpha \approx 5^\circ$ – 7° , which provide a smooth increase in lift with minimal energy consumption.

The flying vehicle has been found to possess static longitudinal stability, confirmed by the negative slope of the pitching moment dependence on both the AOA and the lift coefficient. It has been determined that the centre of gravity is located approximately 5 % of the mean aerodynamic chord ahead of the aerodynamic centre, providing the required stability margin.

The stall speed, determined from the maximum lift coefficient is $V_s \approx 8.5$ m/s. Considering the operational safety margin, the safe flight speed should be at least $V_{seff} \approx 1.0\text{--}1.2 \times$ m/s, which corresponds to $C_L \approx 1.2\text{--}1.3$ at $\alpha \approx 12^\circ\text{--}14^\circ$ (see Fig. 5). The obtained value is consistent with the aerodynamic characteristics of the flying vehicle and should be considered when evaluating the transition regime and selecting UAV operating conditions.

The performed analysis of the lift coefficient, induced drag, and pitching moment as functions of the relative flight height has shown a pronounced ground effect in the vicinity of the surface. It has been established that at small values of $h/L < 0.3$, the lift force increases by up to two times, while the induced drag decreases significantly, leading to improved aerodynamic efficiency of the flying vehicle. At the same time, the longitudinal trim changes due to the appearance of the additional nose-down pitching moment caused by the forward shift of the pressure centre. As the flight altitude increases, these effects rapidly weaken, resulting in reduced lift, increased drag, and changes in the pitching moment.

Thus, despite the improvement of aerodynamic characteristics near the ground, the transition regime should be performed considering out-of-ground-effect conditions and an adequate speed margin to prevent aircraft sink.

The analysis of the flow vorticity has revealed that the most intensive vortex structures are concentrated in the centre-section region and at the wing-fuselage junction, where redistribution of velocity and pressure occurs. The wingtip vortices exhibit limited intensity, indicating a moderate level of induced drag and good aerodynamic efficiency of the configuration. The obtained results confirm the effectiveness of the selected flying wing aerodynamic layout and demonstrate the possibility of its application in VTOL UAV systems.

The obtained results make it possible to provide recommendations for selecting optimal flight regimes, improving energy efficiency, and ensuring UAV stability. The practical significance of the work lies in the possibility of applying the obtained relationships in the design, numerical simulation, and development of control algorithms for VTOL UAVs.

The practical value of the study is associated with the application of the obtained dependencies in engineering practice for UAV design, aerodynamic configuration optimisation, and control algorithm development. The proposed approach makes it possible to reduce the amount of full-scale testing, decrease development costs, and shorten the aircraft development cycle.

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