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ANALYSIS OF THE INFLUENCE OF THE SLOT INSTALLATION ANGLE ON THE THRUST AND EFFICIENCY OF A UAV SLOTTED PROPELLER

The study examines *the thrust characteristics and efficiency of slotted propellers on an unmanned aerial vehicle (UAV).* ***The object*** *is the slot installation angle of a UAV slotted propeller.* ***The work aims*** *to evaluate the aerodynamic efficiency and thrust of UAV slotted propellers, considering the effect of the installation angle on the slot angle.* ***Task:*** *based on mathematical modeling of the flow, calculate the thrust characteristics of UAV slotted propellers for propellers with different slot installation angles on the propeller blades in a given range of rotational speeds; obtain the dependences of the propeller efficiency on the advance ratio in a given range of rotational speeds, taking into account the effect of the slot installation angle. A study of the flow around slotted propellers was conducted using computational fluid dynamics (CFD). Modeling was based on solving the Reynolds-averaged Navier-Stokes (RANS) equations using the SST turbulence model. The computational domain was discretized using the finite volume* ***method*** *with local mesh refinement near the surfaces of the blades and slotted channels to account for boundary-layer effects.* ***Results.*** *The paper presents the thrust characteristics obtained and the dependence of the coefficient of friction on the advance ratio at rotation speeds of 9000 rpm, 11000 rpm, and 13000 rpm. Three propeller slot installation angle options were considered: 45°, 0°, and -45°. The slot location, length, and width were not varied. The results showed that the slot installation angle significantly affects the propeller's thrust characteristics and efficiency. The use of boundary layer control with slots on propeller blades, with rationally selected slot geometric parameters, including the slot angle, expands the range of propeller operating modes, increasing flight speed by up to 10%. Still, propeller efficiency decreases by 1-8%. It is worth noting that the paper examined the flow and analyzed the performance of slotted propellers using only three slot installation angles.* ***Conclusions.*** *The research results have theoretical and practical significance for substantiating the selection of UAV slot propeller parameters.* ***Future plans*** *include exploring a wider range of slot angles and assessing the impact of slot width on propeller performance and thrust.* ***The scientific novelty of these results*** *lies in providing new data on the impact of the slot installation angle on UAV propeller thrust and efficiency.*

Keywords: *slot, installation angle, propeller, thrust, efficiency, UAV, advance ratio, mathematical modeling.*

Introduction

In the context of increasing demands on energy efficiency and flight performance of unmanned aerial vehicles (UAVs), research into ways to improve aerodynamic, propulsive and acoustic characteristics by optimizing the design parameters of propellers is becoming particularly relevant.

Investigations into boundary layer separation confirm that slot treatments effectively reenergize low-velocity layers by redirecting high-momentum flow from the pressure side to the suction side [1]. Numerical studies of slotted airfoil profiles demonstrate that a slot channel angle of 45° reaches a superior lift-to-drag ratio across various incidence angles, compared to shallower slot configurations of 15° and 30°. Bakhtiari shows that the jet momentum passed via the slot at a 45° angle optimizes the boundary layer interaction, preventing the formation of turbulent separation zones during the high-angle stall regime while maintaining structural flow attachment [1].

Two-dimensional RANS CFD simulations of the S809 airfoil reveal that passive boundary layer control by slots is highly sensitive to the slot's location, width, and internal slope [2]. The maximum lift-to-drag ratio is achieved when the slot is positioned close to the upstream of the flow separation point. Analyses of Belamadi indicate that a converging slot cross-section, which accelerates the exit flow, also provides greater aerodynamic improvement than a uniform slot with an equivalent mass flow rate. Although the slot configuration provokes a drag reduction at low angles of attack, it effectively delays or even eliminates flow separation, significantly enhancing aerodynamic efficiency at moderate to high angles of attack.

A critical analysis of numerical methodologies for small-diameter UAV propellers that operate at low Reynolds numbers from 30,000 to 300,000 indicates that the quality and accuracy of aerodynamic performance predictions are highly dependent on the advance ratio. Low-fidelity Blade Element Momentum Theory (BEMT) models presented by Vargas et al. in [3] demonstrate elevated performance at low advance ratios, where flow patterns are dominated by rotational speed and low Reynolds number effects, including stall mechanisms. Conversely, high-fidelity CFD models, specifically transient Arbitrary Mesh Interface (AMI) approaches, tend to better align with experimental data at higher advance ratios as three-dimensional effects and turbulence become dominant. While computationally heavy, transient CFD methods are necessary to resolve complex flow structures that low-fidelity theories cannot adequately capture under higher operating conditions. The prediction of performance, thrust generation in small-scale UAV propellers is highly dependent on the Reynolds number, with local sectional lift forces playing a dominant role in overall efficiency [4]. Carroll and Marcum in [5] found that analytical comparisons between BEMT and 3D CFD models demonstrate that while BEMT provides acceptable thrust predictions under conditions of attached flow, its accuracy significantly diminishes when the propeller operates in large regions of separated flow at high angles of attack.

CFD evaluations of small-scale propellers demonstrate that the integration of blade slots in propeller design positively impacts thrust generation at low advance ratios [6]. Parametric assessments of varying slot positions along the chord length studied by Seeni indicate that slotted configurations yield thrust coefficient improvements ranging from 0.1% to 4.74% when compared to baseline unslotted geometries under low Reynolds number conditions. Comparative studies of advanced blade configurations provided by Ibrahim [7] indicate that the integration of slots yields superior power performance compared to conventional straight blade designs, and outperforms other passive flow control modifications such as leading-edge tubercles. Furthermore, investigations [8] into slotted profiles confirm that slots can effectively impact and modify boundary layer flow. Performance enhancements are not absolute and remain highly contingent on the precise position and geometric sizing of the slot channels. Numerical investigations into UAV propellers [9] demonstrate that deliberately placed blade slots significantly improve thrust generation. CFD analyses of a slotted propeller over a rotational speed range of 3990 to 6705 rpm show that a slot positioned in the middle section of the blade can yield a thrust force increase of up to 21% compared to a baseline unslotted geometry. The location of the slot is an extremely critical parameter, as positioning the gap too close to the blade root can result in negative aerodynamic effects and reduce overall performance.

Alternative passive aerodynamic modifications, such as leading-edge serrations and protuberances, have also been numerically evaluated by Wei et al. [10] and Nikhade and Joshi [11] for their effect on flow characteristics. These morphological modifications alter the laminar-turbulent transition regime and surface turbulence distribution, resulting in simultaneous acoustic emission reduction and minor thrust improvement under specific operational parameters. Three-dimensional CFD evaluations of slotted propellers across diverse airfoil configurations studied by Wan et al. [12] demonstrate that the aerodynamic efficacy of slot implementation is highly dependent on the base airfoil profile. Incorporating a square slot at 62.5% of the chord length on symmetrical, high-lift airfoils that operate at high Reynolds numbers achieves significant performance enhancements up to a 19.49% increase in thrust and a 53.57% improvement in overall efficiency. Conversely, the integration of slots into low-drag or asymmetrical low-Reynolds-number airfoils usually degrades performance, leading to diminished thrust generation and substantially increased power consumption.

Precise numerical estimation of small-scale propeller aerodynamics by Kutty and Rajendran [13] provided the foundational framework for evaluating slotted configurations. Simulations of an APC Slow Flyer propeller utilizing unstructured meshing and the standard k - ω turbulence model demonstrated high correlation with experimental data at low advance ratios. The implementation of the MRF approach accurately captured rotational flow characteristics and validated the numerical setup for the calculation of thrust and power coefficients prior to geometric modifications. Furthermore, Morgado et al. showed in [14] that comprehensive numerical methodologies for propeller evaluation commonly require robust modelling methods to account for complex flow phenomena, such as high-altitude performance variations and post-stall aerodynamic behaviour. Experimental characterizations of small-scale unmanned aerial vehicle propellers demonstrate substantial aerodynamic performance variations when operating within low Reynolds number regimes (50,000 to 100,000). Wind tunnel assessments across a vast number of propeller geometries [15] indicate that propeller efficiency and thrust coefficients reduce significantly at lower rotational speeds due to Reynolds number effects, emphasizing the necessity of precise baseline performance evaluations prior to the introduction of geometric modifications. Earlier empirical evaluations of small-scale aviation propellers studied by Merchant and Miller in [16] confirm that thrust efficiencies at low Reynolds numbers are noticeably diminished compared to full-scale equivalents. This efficiency degradation underscores the aerodynamic limitations essential to small-diameter baseline rotors and establishes the clear necessity for blade structural optimizations, such as slot implementation, to mitigate flow separation.

Analyses provided by Kutty and Rajendran in [17] evaluated the influence of slot positioning along the chord length of small-scale UAV propellers, indicating a conditional improvement in thrust generation. Specifically, introducing slots between 12.5% and 87.5% of the chord length tends to thrust coefficient improvements ranging from 0.1% to 4.75% at low advance ratios compared to baseline configurations. However, this thrust augmentation is accompanied by a substantial reduction in power consumption, with power coefficients increasing by 10.38% to 44.59%, which finally results in a lower overall aerodynamic efficiency than the unslotted blade design. Numerical evaluations of small-scale propellers [18] demonstrated that the installation angle of the slot significantly dictates aerodynamic performance. Analyses utilized the k-ω turbulence model across slot angles ranging from 90° to 180° reveal that a 170° installation angle yields optimal thrust improvements at low advance ratios, allowing for the generation of up to a 2.71% increase in the thrust coefficient compared to the unslotted baseline. However, introducing slots concurrently stimulates a substantial increase in the power coefficient across most configurations, thereby diminishing overall propeller efficiency. Additionally, static structural assessments provided by Kutty et al. in [18] indicate that slotted blades experience critical stress concentrations near the hub at low operational velocities, necessitating rigid material selection to prevent structural failure. Extensive numerical evaluations of slot geometries [19] show that the specific sizing of the slot channel plays a critical role in determining global aerodynamic performance. The introduction of slots successfully increases the blade's lift-to-drag ratio by manipulating boundary layer separation. The efficiency of the slotted blade remains inversely proportional to the dimensional size of the slot itself. Accurate computational evaluation of propeller performance at low Reynolds numbers [20] requires robust turbulence closures to properly capture complex boundary layer separation and flow phenomena. Comparative numerical analyses of Wang and Walters [20] indicate that incorporating transition-sensitive boundary-layer models into the computational setup significantly improves predictive accuracy for thrust and power coefficients compared to standard *k-ε* or other unmodified RANS turbulence formulations. Accurate prediction of UAV propeller thrust generation and aerodynamic properties can be effectively achieved utilizing Blade Element Theory combined with Glauert Vortex Theory. Aerodynamic optimizations of quadcopter rotors [21] demonstrate a strong correlation between theoretical predictions and experimental wind tunnel data. It establishes a reliable mathematical framework for assessing preliminary propeller performance metrics prior to the introduction of complex geometric modifications.

Therefore, the objective of this work is to evaluate the aerodynamic efficiency and thrust of UAV slotted propellers, taking into account the influence of the slot installation angle.

Tasks of the research:

– Based on mathematical modeling of propeller flow, calculate the thrust characteristics of UAV slotted propellers for propellers with different slot installation angles on the propeller blades over a given rotational speed range.

– Obtain the dependence of propeller efficiency on the advance ratio over a given range of rotational speeds, taking into account the influence of the slot installation angle.

Research problem statement

The object of study is the UAV propeller slot angle (Fig. 1). Three variants of the propeller slot installation angle were considered: 45°, 0°, and -45°. The slot location, length, and width were not varied (Fig. 1).

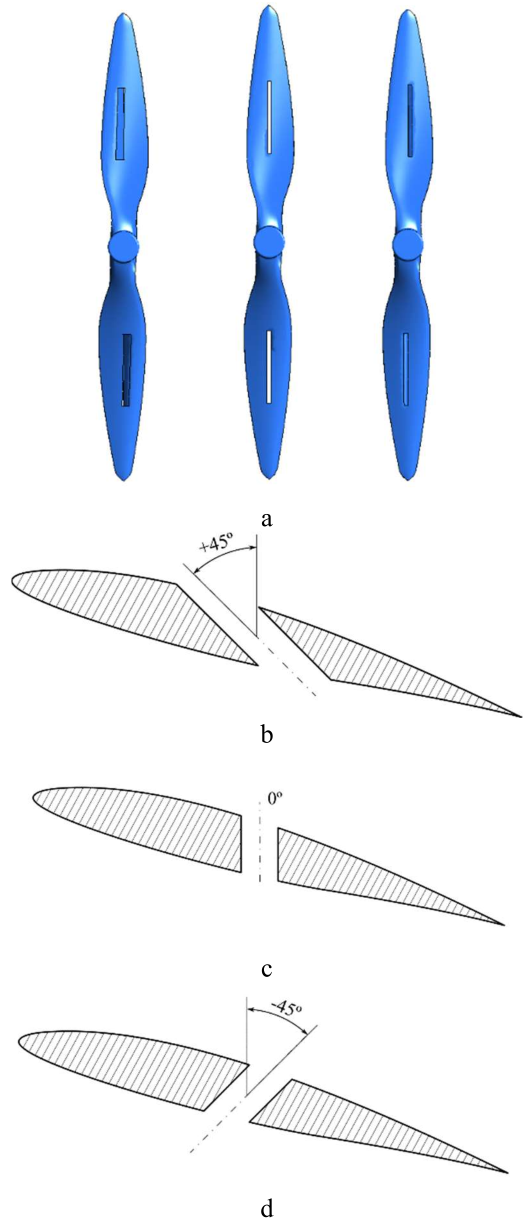

Fig. 1. Slotted propellers
b – section of slot propeller, slot installation angle 45°,
c – section of slot propeller, slot installation angle 0°,
d – section of slot propeller, slot installation angle -45°

Flow parameters around a propeller were determined by solving the Navier-Stokes equations using the Menter SST turbulence model. An unstructured computational mesh with boundary layer adaptation was constructed for the study. The flow simulation results were used to determine propeller thrust, shaft torque, and efficiency.

Propeller efficiency was calculated using the following formula:

$$\eta = \frac{60 \cdot T \cdot V}{2\pi \cdot M \cdot n}, \tag{1}$$

where T is propeller thrust, V is flight velocity, M is shaft torque, n is propeller rotational speed.

For this study, the operating mode was selected at an altitude of 0 km with a propeller rotational speed of 9000 rpm, 11000 rpm, and 13000 rpm. The flight velocity varied in the range from 0 to 22...30 m/s, depending on the propeller rotational speed.

Results

Figures 2-4 show the dependence of thrust on flight velocity for the studied propellers for the basic propeller without slots (Basic) and three variants of a slotted propeller with slot installation angles of -45°, 0°, and 45°.

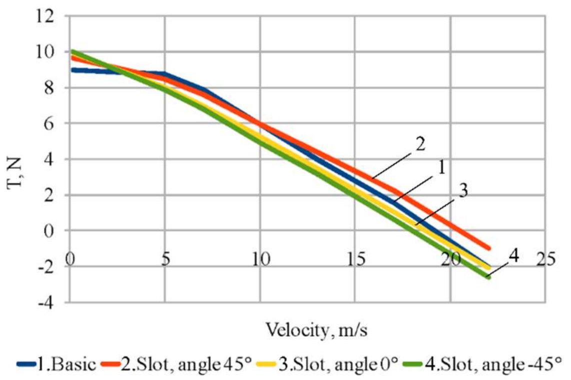

Fig. 2. Propeller thrust dependence on flight velocity at 9000 rpm

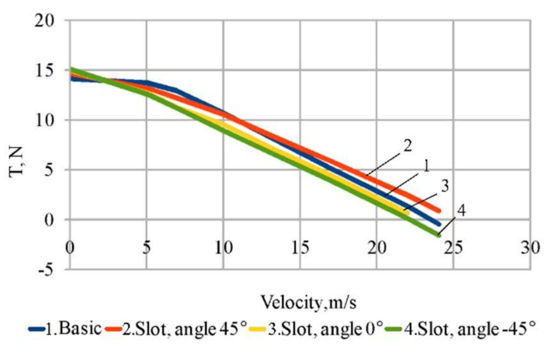

Fig. 3. Propeller thrust dependence on flight velocity at 11000 rpm

All the propeller variants studied showed a consistent decrease in thrust with increasing free-stream speed, due to a decrease in the blade element angle of attack and a reduction in propeller load. At static thrust and low velocities, the differences between the variants under consideration are insignificant for each rotational speed, but all slotted propellers exhibit higher thrust. As flight velocity increases, the differences between the characteristics become more pronounced. As flight velocity increases from 11–12 m/s, the thrust of a slotted propeller with a 45° slot installation angle is higher than that of the basic propeller without slots. This propeller also maintains positive thrust at higher flight velocities, increasing flight velocity by 10%, indicating an expansion of the propeller's operating range. An increase in rotation speed leads to a proportional increase in thrust for all the studied variants, while the nature of the dependencies remains practically unchanged.

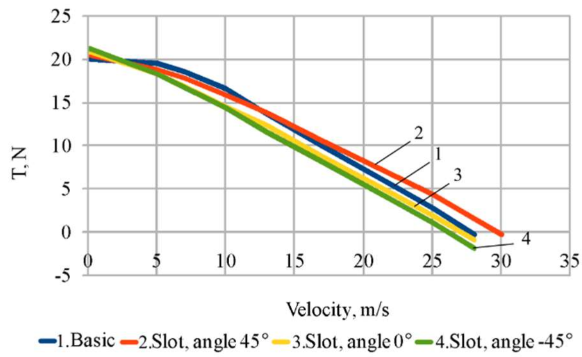

Fig. 4. Propeller thrust dependence on flight velocity at 13000 rpm

Figures 5-7 show the dependence of the propeller efficiency on the propeller pitch at rotation speeds of 9000 RPM, 11000 RPM, and 13000 RPM for a basic propeller without slots (Basic) and three variants of a slotted propeller with slot installation angles of −45°, 0°, and 45°.

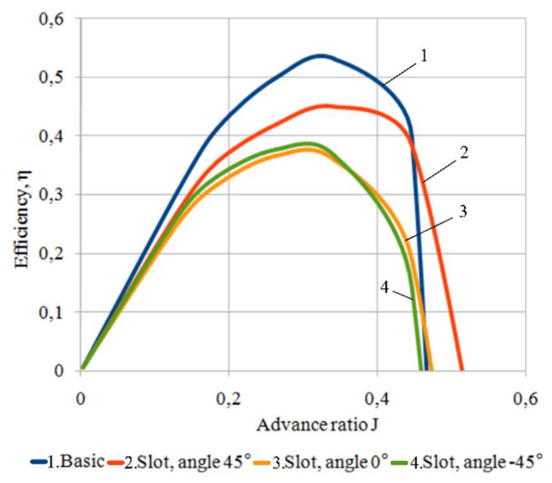

Fig. 5. Dependence of propeller efficiency on the advance ratio at 9000 rpm

An analysis of the results shows that the slot installation angle significantly affects the propeller thrust performance and efficiency. For the studied range of rotational speeds and the investigated modes, the basic propeller demonstrates the highest efficiency values, for which the maximum efficiency reaches 0.53–0.54 at an advance ratio of approximately 0.32–0.35. Modifying the propeller blades by adding slots leads to a decrease in the maximum efficiency.

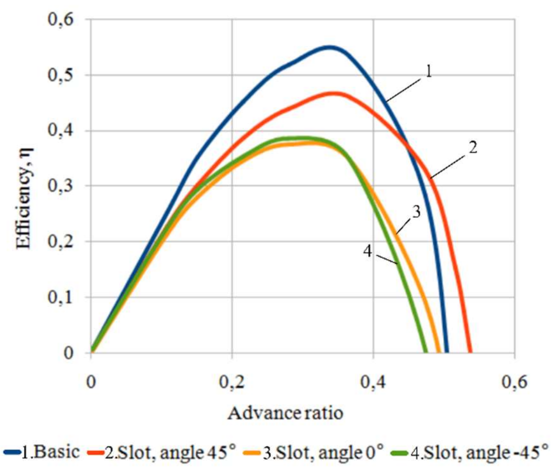

Fig. 6. Dependence of propeller efficiency on the advance ratio at 11000 rpm

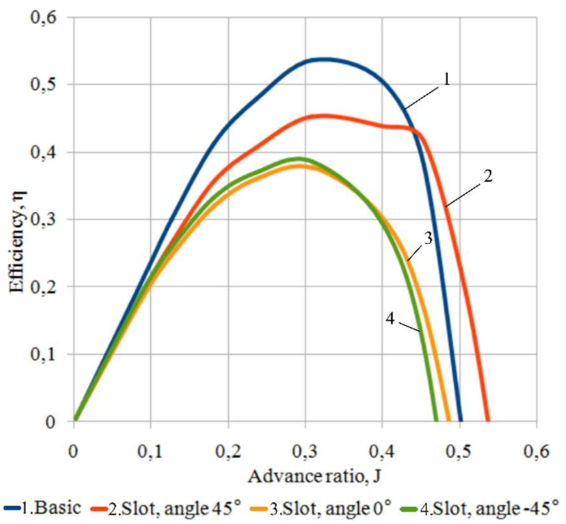

Fig. 7. Dependence of propeller efficiency on the advance ratio at 11000 rpm

For the propeller variant with a slot installation angle of 45°, the efficiency decreases by 1–8%, but a noticeable expansion of the operating range is observed. Among the considered variants of slot installation angles on the propeller blades, the propeller with a slot installation angle of 45° demonstrates the best performance, for which the maximum efficiency is approximately 0.45–0.46, and the effective operating range is maintained up to higher advance ratio values (0.52–0.56), which allows the aircraft to develop higher velocities. Propellers with 0° and -45° slot installation angles have similar characteristics and provide maximum efficiency of 0.37–0.39, but their operating range narrows. At the same time, increasing the rotation speed from 9000 to 13000 rpm practically does not change the nature of the dependence of the efficiency on the advance ratio and the relative position of the curves, which indicates that the influence of the slot geometry on the efficiency of the propeller is preserved in the entire range of modes studied.

The obtained results show that boundary layer control using slots on propeller blades, with appropriately selected geometric slot parameters, including slot installation angle, allows for an expanded range of propeller operating modes, increasing flight velocity of up to 10%.

However, this reduces propeller efficiency by 1-8% depending on flight velocity. It is worth noting that the study examined the flow and performance of slotted propellers with only three slot angle options.

Conclusions

The research results have theoretical and practical significance for substantiating the selection of UAV slot propeller parameters.

Further studies are planned to explore a wider range of slot installation angles and assess the effect of slot width on propeller performance and thrust.

Contributions of authors: problem formulation – **K. Balalaieva, A. Balalaiev, O. Shynkarenko**; introduction and literature review – **O. Shynkarenko**; development of geometry models and mechanics – **K. Balalaieva, A. Balalaiev**; modeling of flow –**K. Balalaieva, A. Balalaiev**; analysis of results – **K. Balalaieva, A. Balalaiev, O. Shynkarenko.**

Conflict of Interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship, or otherwise, that could affect the research and its results presented in this paper.

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The research was conducted without financial support.

Data availability

The manuscript has no associated data.

Use of Artificial Intelligence

The authors confirm that they did not use artificial intelligence methods in obtaining the scientific results of the presented work.

All the authors have read and agreed to the published version of this manuscript.

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АНАЛІЗ ВПЛИВУ КУТА УСТАНОВКИ ЩІЛИНИ НА ТЯГУ ТА ККД ПОВІТРЯНОГО ЩІЛЬОВОГО ГВИНТА БПЛА

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Предмет дослідження – тягові характеристики та ККД щільових повітряних гвинтів безпілотного літального апарату (БПЛА). **Об'єкт** – кут установки щілини щільового повітряного гвинта БПЛА. Метою роботи є оцінка аеродинамічної ефективності та тяги повітряних щілинних гвинтів БПЛА з урахуванням впливу кута установки щілини.Завдання: розрахунок на основі математичного моделювання обтікання тягових характеристик щільових гвинтів БПЛА для гвинтів з різним кутом установки щілини на лопатях гвинта в заданому діапазоні частот обертання; отримання залежностей ККД повітряного гвинта від поступу в заданому діапазоні частот обертання з урахуванням впливу кута установки щілини. Дослідження обтікання щілинних гвинтів проводилося методом обчислювальної гідрогазодинаміки (CFD). Моделювання ґрунтувалося на вирішенні осереднених за Рейнольдсом рівнянь Нав'є-Стокса (RANS) із застосуванням моделі турбулентності SST. Розрахункова область дискретизована методом кінцевих об'ємів з локальним згущенням сітки поблизу поверхні лопатей та щілинних каналів для врахування ефекту примежевого шару. **Результати.** У роботі отримані тягові характеристики та залежності ККД від ходи гвинта для частоти обертання 9000 об/хв, 11000 об/хв, 13000 об/хв. Розглянуто три варіанти кута встановлення щілини повітряного гвинта — 45°, 0° та -45°. Місце розміщення щілини, а також її довжина й ширина не змінювалися. Отримані результати показали, що кут установки щілини суттєво впливає на тягову характеристику та ККД повітряного гвинта. Застосування управління примежевим шаром за допомогою використання щілин на лопатях повітряних гвинтів при раціонально підібраних геометричних параметрах щілин, у тому числі кута установки щілини, дозволяють розширити діапазон експлуатаційних режимів роботи повітряних гвинтів, що дозволяє збільшити швидкість польоту до 10%, проте при цьому ККД гвинта знижується на 1-8%. Варто зазначити, що в роботі досліджено обтікання та проаналізовано роботу щілинних гвинтів лише з трьома варіантами встановлення щілини. **Висновки**. Результати досліджень мають теоретичне та практичне значення для обґрунтування вибору параметрів щілинних гвинтів БПЛА. Надалі планується дослідити ширший діапазон кутів установки щілини, а також оцінити вплив ширини щілини на характеристику та тягу повітряного гвинта. **Наукова новизна одержаних результатів** полягає в тому, що в роботі отримані нові дані щодо впливу кута установки щілини на тягу та ККД щільових повітряних гвинтів БПЛА.

Ключові слова: щілина, кут установки, повітряний гвинт, тяга, ККД, БПЛА, поступ гвинта, математичне моделювання.

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