

AERODYNAMIC DESIGN METHODOLOGY FOR AIR PROPELLERS OF SWARM UAVS UNDER VARIABLE MISSION PAYLOADS

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ABSTRACT

This study presents an aerodynamic design methodology for fixed- and variable-pitch air propellers (APs) for swarm unmanned aerial vehicles (UAVs), based on vortex theory. The methodology integrates design calculations with system analysis, mathematical modeling, and parametric simulations to evaluate aerodynamic and flight characteristics under diverse operational scenarios. The results demonstrate that UAV flight range and endurance are strongly influenced by payload configuration, flight altitude, and velocity, with bomb load having a particularly significant impact. Verification calculations confirm that one of the most critical factors in improving UAV performance is the design of mission-specific propellers. To address this, we propose a modular approach in which UAVs are equipped with sets of interchangeable APs, each optimized for distinct combat tasks and payloads. This approach enables flexible mission adaptation while maintaining efficiency across flight regimes, providing a practical pathway toward enhancing the performance of tactical swarm UAVs.

Keywords

UAV, swarm UAV, air propeller, aerodynamic design, vortex theory, combat load.

1. INTRODUCTION

The versatility and relatively low cost of unmanned aerial vehicles (UAVs) make them effective for carrying out a wide range of tactical and strategic missions. Unmanned aerial systems have become a key element of modern armed conflicts, demonstrating high efficiency in combat operations. In recent years, research in leading countries has increasingly focused on the concept of deploying UAV swarms across entire theaters of military operations. Swarm warfare with UAVs has thus

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emerged as a prominent topic in military research, attracting growing attention from armed forces worldwide [1, 2].

With the changing dynamics of the battlefield and the continuous advancement of UAV autonomy, swarm-based combat operations are expected to become a central mode of employing unmanned systems. The significant advantages of UAVs over manned aircraft have spurred extensive research aimed at optimizing and improving their performance. A particularly pressing scientific and practical challenge is extending the flight range of UAVs under various combat load configurations.

One of the most critical components of a UAV is its power plant (PP), consisting of the engine and AP, which determines the flight envelope. This highlights the importance of refining propeller design methodologies to ensure UAVs can successfully execute diverse combat missions under varying load conditions.

2. LITERATURE REVIEW AND PROBLEM STATEMENT

Recent years have seen extensive research into UAV aerodynamics and propeller design, with numerous studies addressing optimization methods, structural considerations, and efficiency improvements under varying operational conditions. The following review outlines key contributions relevant to the development of UAV PPs and APs.

In [3], the results of a wind tunnel study on the influence of the AP slipstream on UAV aerodynamics are presented. The study shows that aerodynamic effects caused by the AP are more pronounced for small UAVs than for general aviation aircraft, which is attributed to the relatively large ratio of propeller diameter to wingspan.

In [4], a methodology for the aerodynamic design of APs is introduced, using parametric and high-fidelity tools based on the well-known finite element method. Various AP configurations were defined using blade element momentum theory. A baseline airframe and standard operating conditions were selected, and several optimized AP configurations for monitoring tasks were evaluated. The designs obtained through this two-dimensional approach were assessed with the help of numerical modeling, combining aerodynamic loads with structural design through Fluid-Structure Interaction (FSI) analysis in ANSYS 18.

In [5], the early stages of the conceptual design of a high-altitude, long-endurance UAV are explored. The study addresses the selection of the overall configuration, estimation of mass characteristics, calculation of key aerodynamic parameters, and determination of a suitable AP. The findings highlight how the optimal AP blade shape depends on the defined objective functions and design constraints.

In [6], an optimized AP design for a UAV is presented using a Kriging-based optimization approach. The primary objective was to maximize AP efficiency while satisfying a constraint on the thrust-to-torque ratio at a rotational speed of 6500 RPM. The design parameters included blade twist angle and thickness-to-chord

ratio along the entire blade span. To evaluate AP aerodynamics, a comprehensive computational fluid dynamics (CFD) analysis was conducted.

In [7], the flow distribution around a UAV fuselage under various flight regimes, including changes in roll, pitch, and yaw, is investigated. The study identifies key aerodynamic phenomena in the main rotor's operational zone, such as vortex formation, turbulence, flow separation, and tip vortices. A CFD analysis was also carried out to assess thrust at different freestream velocities (3–10 m/s) and rotor speeds (2000–5000 RPM). The influence of dimensionless parameters, particularly the advance ratio and induced flow coefficient, on thrust generation was examined.

In [8], an AP optimization algorithm aimed at reducing aircraft energy consumption is presented. The method combines aerodynamic design with a particle swarm optimization algorithm to determine the optimal AP parameters, including segment-specific airfoil geometry.

In [9], an approach to AP selection and design is described, focusing on the influence of operational and geometric parameters on performance. This enables a deeper understanding of AP operation, which is critical for overall aircraft efficiency and energy use. A validated computational tool is proposed for predicting AP characteristics while accounting for complex physical phenomena. An extensive set of simulations was performed to analyze performance variations under different flight conditions (speed, altitude) and their correlation with geometric features. The study identifies the key factors most affecting AP performance and recommends the most effective geometric configurations for different airfoils.

In [10], an improved methodology for determining the aerodynamic characteristics of fixed-pitch and variable-pitch APs based on vortex theory is introduced. The updated mathematical model for variable-pitch AP operation incorporates the effects of Mach and Reynolds numbers, allowing for accurate design and validation of subsonic APs for both ground and in-flight operation.

In [11], the effect of AP mass on the flight characteristics of small UAVs – particularly flight endurance, maneuverability, and energy efficiency – is analyzed. Although AP mass represents only a small fraction of the total UAV mass, its impact on balance can be significant, especially when mounted at structural extremities. Several empirical models for AP mass were developed using a database of more than 1200 measured AP masses from seven manufacturers, covering diameters from 4 to 27 inches. In addition, actual AP masses were compared with manufacturer specifications.

In [12], a novel technique for enhancing the aerodynamic performance of small-scale APs using surface grooves is explored. The objective was to improve efficiency by increasing thrust and reducing torque – an especially relevant factor for long-endurance UAVs. Numerical modeling was conducted for the Applied Precision Composites 10×7 Slow Flyer AP using CFD methods. Rectangular grooves of 0.1×0.1 mm and 0.1×0.2 mm, positioned at distances of 0.09c, 0.17c, 0.32c, and 0.42c from the leading edge, were evaluated.

In [13], the evolution of UAVs and the development of a PP with large-diameter APs optimized for carrying heavy payloads are examined. To improve aerodynamics and enhance structural durability, a FSI methodology was applied, accounting for the vibrational effects of the AP.

In [14], design requirements for APs intended for tilt-rotor UAVs are presented, along with an analysis model for calculating their aerodynamic characteristics. Based on blade element momentum theory, the aerodynamic forces acting on the blade elements are analyzed. An experimental system was designed and built to test six different AP types. Additionally, software was developed to process test data, generate plots, and calculate key AP parameters such as profile drag power, induced velocity, and efficiency.

In [15], a methodology for numerically modeling vortex structures generated by an AP in flight is proposed. The approach improves the accuracy of predicting AP characteristics. Dependencies of the aerodynamic performance of a low-aspect-ratio wing-AP configuration with counter-rotating propellers on geometric and kinematic parameters – at various aspect ratios and wing tapers – were identified.

In [16], a method for multi-objective optimization and experimental verification of APs for high-altitude airships is investigated. Vortex theory was applied to predict aerodynamic characteristics, and optimization was carried out using the non-dominated sorting genetic algorithm II (NSGA-II), achieving a balance between efficiency and AP mass. Numerical results were validated through wind tunnel testing and full-scale AP experiments.

A critical review of studies [3–16] shows significant progress in UAV propeller research, ranging from aerodynamic modeling and optimization to structural design and material innovations. However, limitations remain in adapting existing methodologies to diverse mission requirements and payload configurations.

3. STUDY OBJECTIVE

To address this gap, the present study seeks to advance the aerodynamic design methodology for UAV PP APs, with the goal of ensuring reliable performance and efficiency in swarm UAV operations. In particular, the research focuses on two key tasks:

- determining the aerodynamic characteristics of the blade airfoil, and
- developing and designing a 3D model of the AP for UAV operation at different flight speeds.

4. RESEARCH METHODS

According to vortex theory, the aerodynamic characteristics of an AP can be determined if its geometric parameters and the aerodynamic characteristics of the blade airfoils are known. A key task is to calculate the circulation, which influences the power output of the AP, and to analyze its distribution along the blade span, since this directly affects the propeller's efficiency coefficient (η). To achieve optimal performance, airfoils and their parameters must be selected so that, at a given radius, the circulation corresponds to the required aerodynamic load [8].

The choice of circulation distribution law along the blade span is critically important, as an inappropriate distribution can significantly reduce propeller efficiency. Both theoretical and experimental studies indicate that the semi-elliptical distribution law provides the most favorable results. However, when applying alternative distribution laws, the underlying calculation methodology remains the same. The average circulation value can be determined with sufficient accuracy, enabling effective optimization of propeller design and aerodynamic performance [8]:

$$\bar{\Gamma}_N = \frac{\frac{2}{\pi^4} \beta}{\frac{\lambda}{\pi \eta_a} (1 - \xi^3) + \frac{2}{3} \mu (1 - \xi^3)},$$

where

$\beta = \frac{75 \cdot N}{\rho n_s^3 D^5}$ is the propeller power coefficient, which must be equal to the engine power coefficient;

N is the propeller power;

ρ is the air density at flight altitude;

n_s is the propeller rotational speed in revolutions per second;

D is the air propeller diameter;

V_0 is the flight speed;

$\xi = \frac{d}{D}$ is the ineffective portion of the blade;

d is the ineffective portion of the blade diameter;

$\lambda = \frac{V_0}{n_s D}$ is the advance ratio;

μ is the inverse of the airfoil's lift-to-drag ratio; and

$\eta_a = \frac{2}{1 + \sqrt{1 + \frac{4\pi^2 \bar{\Gamma}_N}{\lambda^2}}}$ is the axial efficiency coefficient.

Thus, there are two equations with two unknowns: the average circulation $\bar{\Gamma}_N$ and the axial efficiency coefficient η_a . These equations are solved by the method of successive approximations. The obtained average circulation is distributed along the blade according to the selected law (Fig. 1).

The axial velocity in the propeller plane $\bar{V}_1$ is determined from the equation:

$$\bar{V}_1 = \frac{\bar{V}_0}{2} + \sqrt{\frac{\bar{V}_0^2}{4} + \bar{\Gamma}}.$$

The rotational velocity in the propeller plane $\bar{U}_1$ is determined from the equation:

$$\bar{U}_1 = \bar{\tau}_1 - \bar{u}_1,$$

where $\bar{u}_1 = \frac{\bar{\Gamma}}{\bar{r}_1}$ is the rotational induced velocity in the propeller plane.

The results of the AP design are presented in Figs. 1–10 (all of them based on the present authors' own calculations).

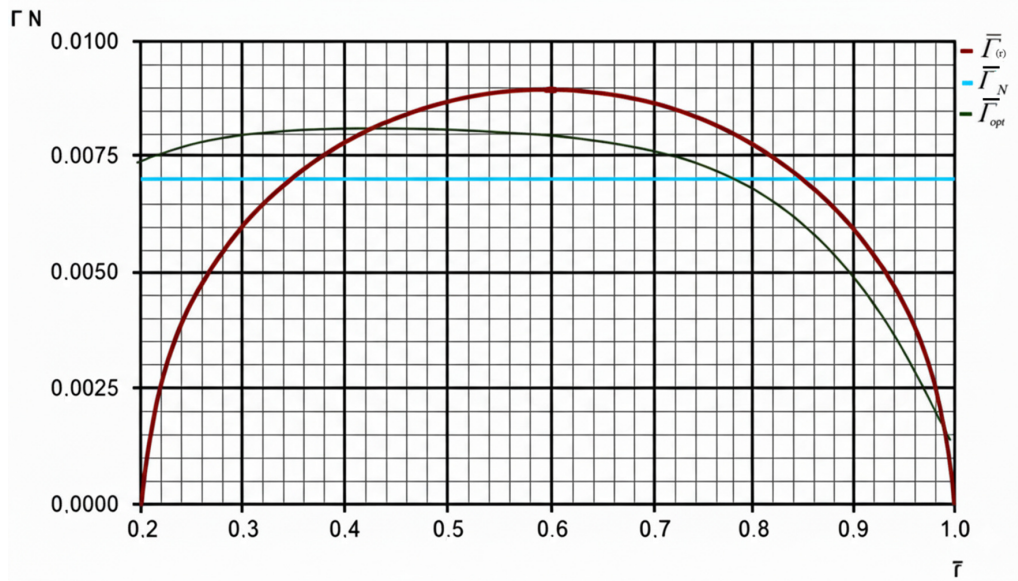


Fig. 1. Circulation distribution along the AP blade.

The relative velocity $\bar{w}_1$ is determined from the known value $\bar{V}_1$ and the inflow angle β_1 [10]:

$$\bar{w}_1 = \frac{\bar{V}_1}{\sin \beta_1}.$$

The inflow angle β_1 is found from its tangent $\beta_1 = \arctg \frac{\bar{V}_1}{\bar{U}_1}$.

The circulation $\bar{\Gamma}$, relative velocity $\bar{w}_1$ and inflow angle β_1 at each cross-section determine the required C_{ya} and after the airfoil is specified, the required angle of attack α . The angle of attack and the inflow angle determine the blade setting angle φ at the given cross-section.

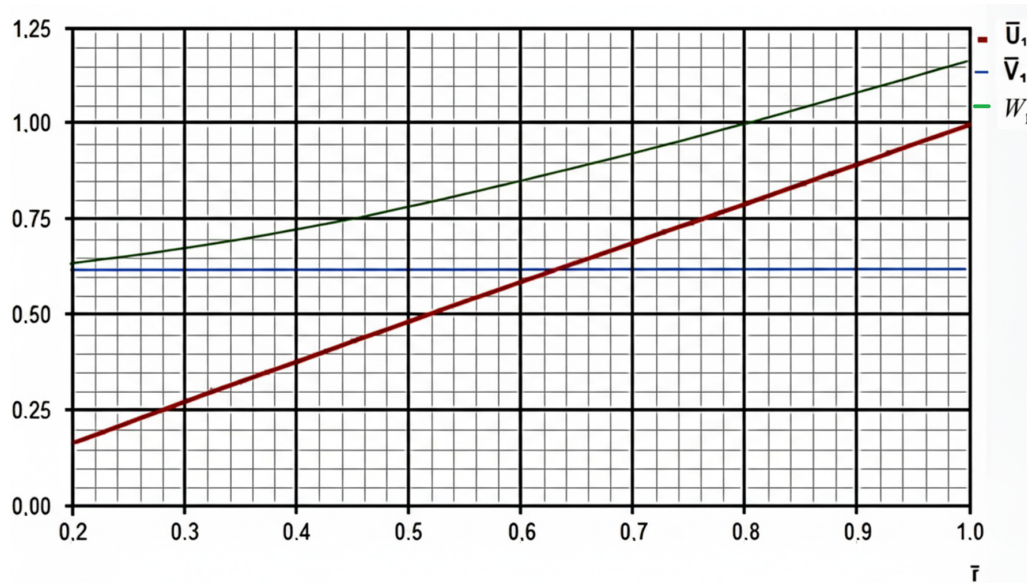


Fig. 2. Velocity distribution along the AP blade.

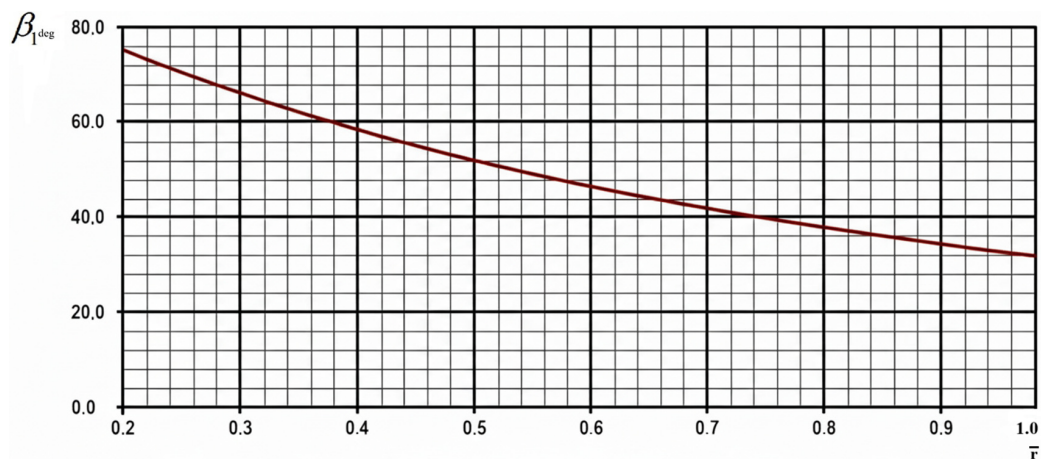


Fig. 3. Inflow angle distribution along the AP blade.

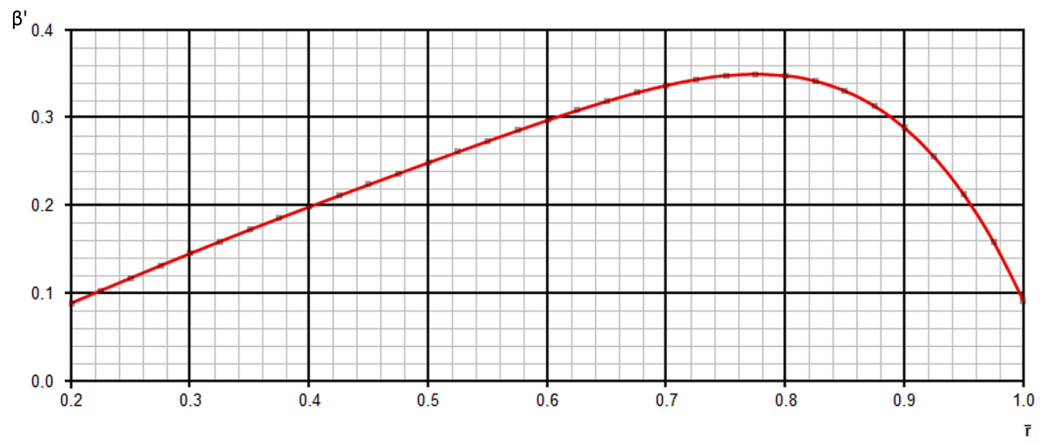


Fig. 4. Distribution of the power coefficient derivative β' along the relative radius of the AP blade.

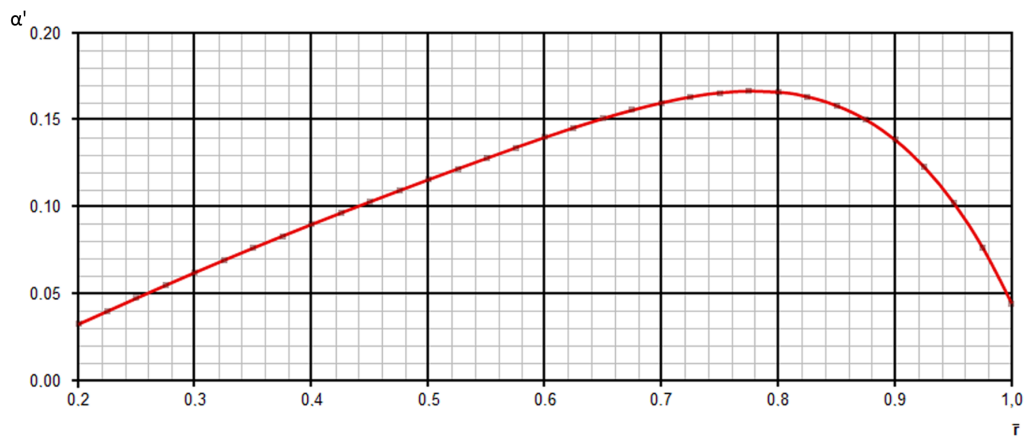


Fig. 5. Distribution of the thrust coefficient derivative α' along the relative radius of the AP blade.

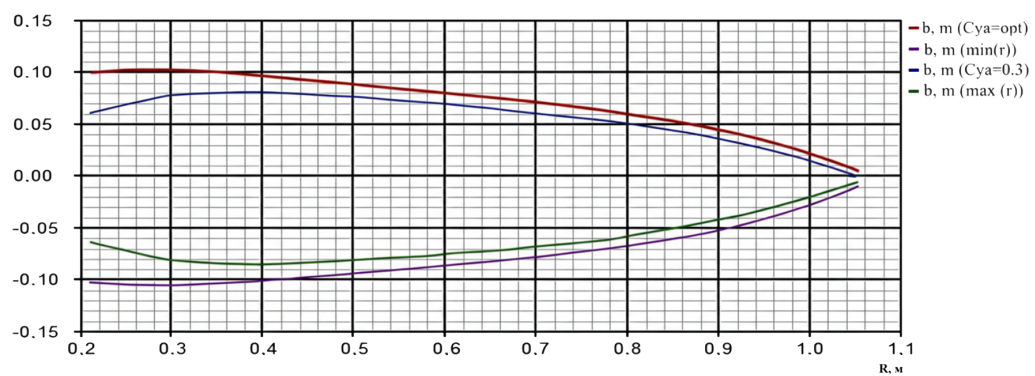


Fig. 6. Blade thickness distribution along the AP radius.

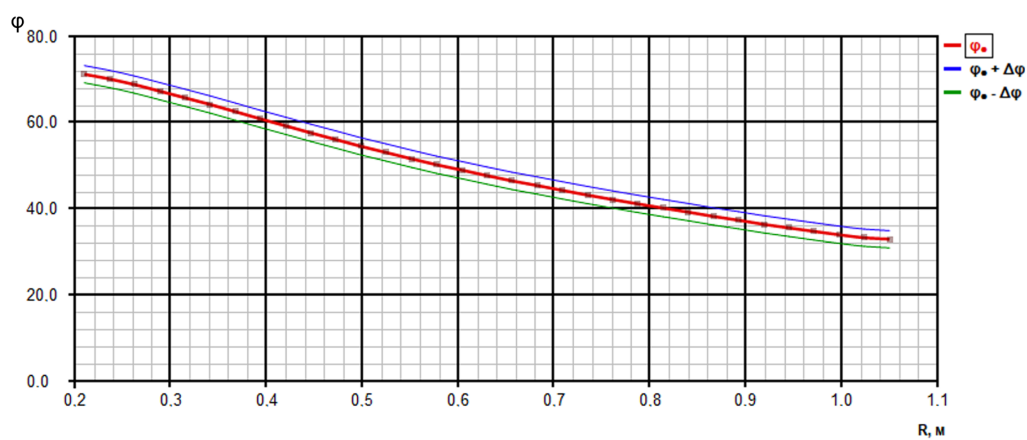


Fig. 7. Distribution of the cross-section setting angle along the AP blade radius.

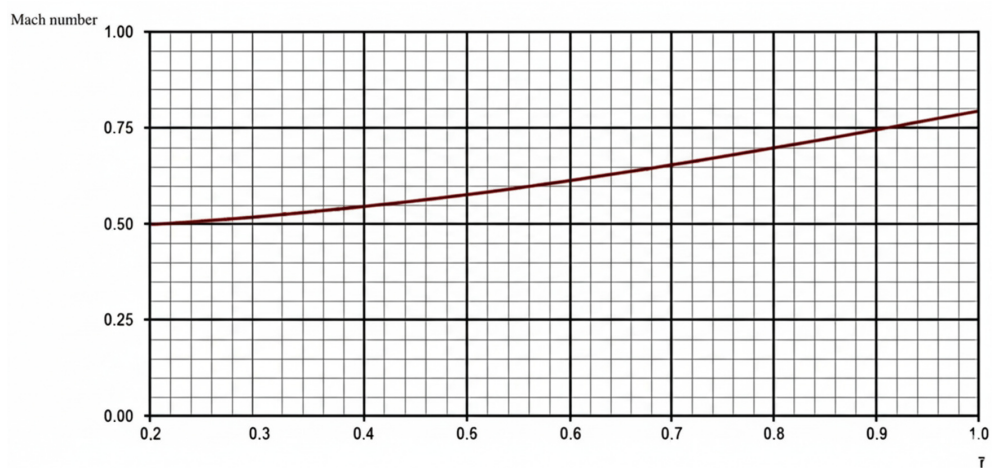


Fig. 8. Mach number distribution along the AP blade radius.

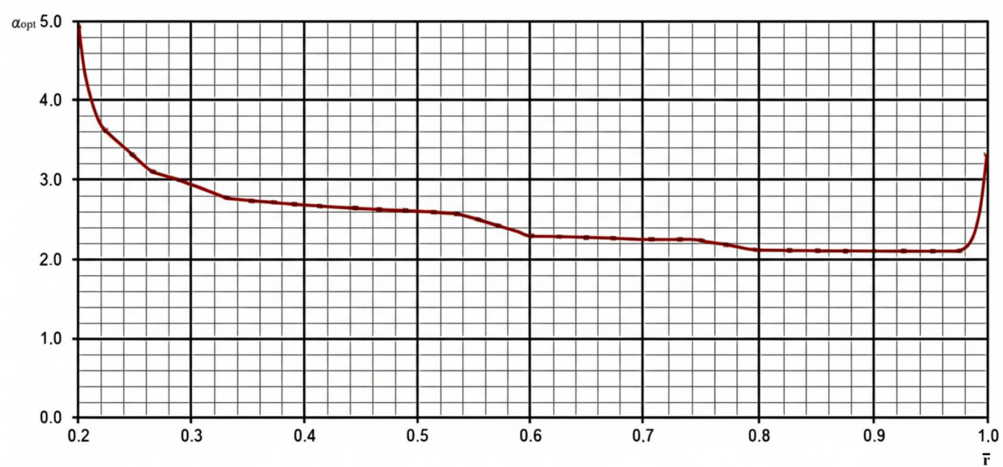


Fig. 9. Distribution of the optimal angles of attack along the AP blade radius.

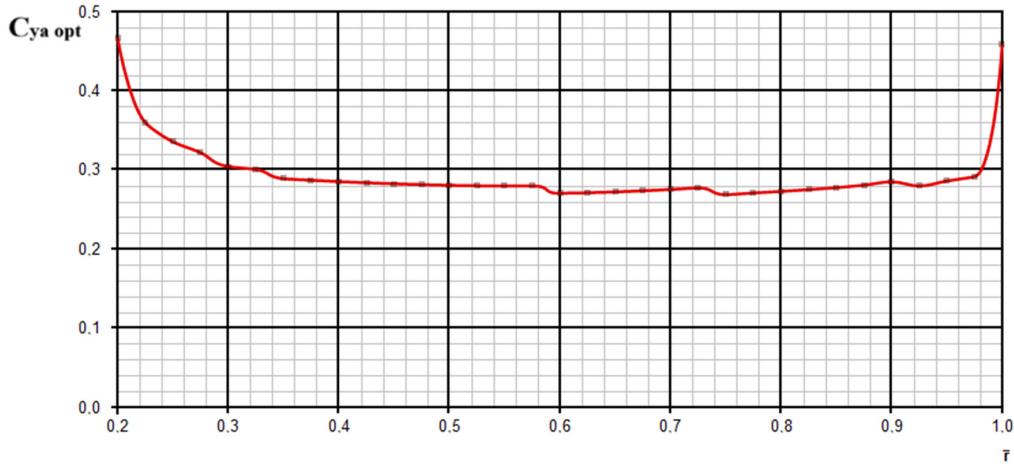


Fig. 10. Distribution of the optimal lift coefficients along the AP blade radius.

The aerodynamic characteristics of the blade airfoil are determined by decomposing the total aerodynamic force into lift, profile drag, and induced drag. Drag itself is formed by two components: tangential forces, which arise from air viscosity and produce skin-friction drag, and normal forces, which result from changes in pressure distribution and define pressure drag. In subsonic flow, profile drag consists of both skin-friction and pressure drag, each generated within the boundary layer. Since lift production generates a three-dimensional vortex wake, it also produces induced drag. Thus, the total drag of the airfoil is the sum of profile drag and induced drag [11]. Experimental studies indicate that, under attached flow, profile drag remains nearly constant across a wide range of angles of attack. This assumption is valid because the Reynolds number for the designed air propellers exceeds $Re_{0.7} > 230,000$, while the region with unfavorable characteristics (abrupt changes in aerodynamic performance) is located at $Re < 150,000$.

A slight increase in drag is observed only near the critical angle of attack, associated with boundary-layer thickening and the onset of flow separation zones. Similarly, drag caused by local disturbances and interference effects is not dependent on angle of attack. Therefore, within acceptable flow regimes, the drag coefficient remains relatively stable, showing significant growth only when transitioning into separated flow regimes:

$$C_{xa} = C_{x0} + C_{xi},$$

where C_{x0} is the zero-lift drag coefficient; C_{xi} the induced drag coefficient.

In subsonic flow:

$$C_{x0} = C_{xp} + C_{xv},$$

where C_{xp} is the profile drag coefficient; C_{xv} the wave drag.

The profile drag is determined by the following formula [11]:

$$C_{xp} = 2 C_f \eta_c \eta_M,$$

where C_f is the skin friction coefficient of a flat plate in an incompressible fluid flow at the given Reynolds number and position of the laminar-to-turbulent flow transition point; the doubled value accounts for friction on the lower and upper surfaces; η_c is the coefficient that accounts for the contribution of pressure drag to the profile drag; η_M is the coefficient that accounts for the effect of compressibility.

The skin friction coefficient of a thin plate is calculated using the following dependence [11]:

$$C_f = \frac{0.087}{(\lg Re - 1.6)^2} (1 - \bar{x}_B) + \frac{1.33}{\sqrt{Re}} \sqrt{\bar{x}_B},$$

where $\bar{x}_B$ is the relative coordinate of the transition point position and Re is the Reynolds number, which is calculated based on the characteristic length (the blade section chord) and for specific flight conditions.

The position of the transition point depends on many factors, the main ones are the Reynolds numbers Re and Mach M , the shape and condition of the surface, the pressure gradient, and the initial turbulence level of the flow. The transition point for a smooth surface is calculated using the following formula [11]:

$$\bar{x}_B = \bar{x}_B^0 k_M,$$

where $k_M = 1 + 0.35 \cdot \sqrt{M}$; M – is the Mach number of the freestream flow.

$$\bar{x}_B^0 = \frac{\bar{c} \cdot \bar{x}_c}{\bar{c} + 0.02} + \frac{0.95}{10^{-6} \cdot Re + 2.4},$$

where $\bar{c}$ is the relative thickness of the airfoil at the mean aerodynamic chord section, $\bar{x}$ is the relative coordinate of the maximum airfoil thickness.

The coefficients η_c and η_M are calculated using the following formulas:

$$\eta_c = 1 + 2 \cdot \bar{c} \cdot e^{-2.4 \cdot \bar{x}_B} + 9 \cdot \bar{c}^2 \cdot e^{-4 \cdot \bar{x}_B},$$

$$\eta_M = \left(\frac{1}{\sqrt{1 + 0.2 \cdot M^2}} + 0.055 \cdot \bar{x}_B^2 \cdot M \right) (1 + \bar{c} \cdot M).$$

The main-stream flow Mach number M is determined by taking into account the Mach number of the undisturbed flow M_∞ and the flow deceleration coefficient k_d .

When calculating the blade profile drag, it is necessary to account for both the presence and the placement of turbulators, ensuring they are aligned with the transition point. If required, the transition point should be shifted to coincide with the turbulator location.

In the range of operational angles of attack, excluding the region near maximum lift, the lift coefficient C_{ya} :

$$C_{ya} = C_{ya}^{\alpha}(\alpha - \alpha_0) + \Delta C_{ya},$$

where C_{ya}^{α} is the derivative of the lift coefficient with respect to the angle of attack; α , α_0 are the specified and zero angles of attack, respectively; ΔC_{ya} is the non-linear increment of the lift coefficient.

According to both theoretical and experimental data, the value of the derivative C_{ya}^{α} depends on the relative thickness of the airfoil $\bar{c}$ and the flight Mach number M , the formula for determining C_{ya}^{α} being as follows [11]:

$$C_{ya}^{\alpha} = \frac{2\pi(1 - 0.27 \cdot \sqrt[4]{\bar{c}})}{E + 2(1 - 0.27 \cdot \sqrt[4]{\bar{c}})} - \lambda,$$

where the parameter E considering the correction for compressibility, is equal to $E = \lambda \sqrt{1 - M^2} + 1$.

Induced drag is associated with the formation of a vortex sheet behind the body in the presence of lift. In the general case, the drag polar is as follows:

$$C_{xa} = C_{x0} + A \times C_{ya}^{\alpha},$$

where A is the drag-due-to-lift coefficient.

At subsonic speed, A is found from the following expression:

$$A = \frac{1 + \delta}{\pi \cdot \lambda},$$

where λ is the effective aspect ratio of the wing;

$$\delta_1 = m(1 + 0.225 \cdot m), \delta_1 = 0.3529, m = \frac{z_1}{a_{\infty}}, a_{\infty} = 2\pi(1 - 0.27 \sqrt[4]{\bar{c}}), z_1 = \lambda \sqrt{1 - M^2}.$$

When determining the drag polar at subsonic speeds, it is necessary to account for additional drag components, which are caused by the influence of the angle of attack on the profile drag and the onset of the wave crisis.

As a result of the design and verification calculations, the characteristics of the 3 SMV-1 air propeller were obtained, as presented in [20] and summarized in Table 1. The blade setting angle at the $\bar{c} = 0.75$ section is 34° , corresponding to the design operating point of this propeller.

Table 1. Experimental and Calculated Characteristics of the 3 SMV-1 Air Propeller.

Parameter	Parameter value						
λ	0.90	1.00	1.10	1.20	1.30	1.40	1.50
α (experiment)	0.13617	0.1256	0.11096	0.09399	0.07591	0.05765	0.03997
α (calculation)	0.13523	0.11709	0.09832	0.07893	0.05896	0.03843	0.01735
β (experiment)	0.16649	0.157	0.14639	0.13402	0.11925	0.10144	0.07994
β (calculation)	0.14602	0.13547	0.12161	0.10428	0.08331	0.05856	0.02985
η (model experiment)	0.73614	0.8000	0.83378	0.84159	0.82751	0.79563	0.75006
η (calculation)	0.83347	0.86433	0.88931	0.90833	0.91999	0.91871	0.87224
Flight speed, km/h	285.1	316.8	348.5	380.2	411.8	443.5	475.2
Propeller thrust, kg (experiment)	1001.2	923.5	815.8	691.0	558.1	423.8	294.0
Propeller thrust, kg (calculation)	994.3	860.9	722.9	580.3	433.5	282.5	127.6
Power consumption, h.p. (experiment)	1436.3	1354.4	1262.9	1156.2	1028.7	875.1	689.6
Power consumption, h.p. (calculation)	1259.7	1168.7	1049.1	899.6	718.7	505.2	257.5

As a result of the verification calculation, the characteristics of the MTV-5-1/210 air propeller were obtained, and are presented in Tables 2-7.

Table 2. Known and Calculated Characteristics of the MTV-5-1/210 Air Propeller at $\varphi_{0.75} = 15^\circ$.

Parameter	Parameter value			
λ	0.3	0.4	0.5	0.6
α	0.116	0.097	0.065	0.020
α (calculation)	0.123	0.091	0.069	0.044
β	0.074	0.064	0.050	0.033
β (calculation)	0.074	0.064	0.052	0.037
η	0.531	0.604	0.704	0.758
η (calculation)	0.480	0.604	0.650	0.620

Table 3. Known and Calculated Characteristics of the Air Propeller MTV-5-1/210 at $\varphi_{0.75} = 20^\circ$.

Parameter	Parameter value					
λ	0.3	0.4	0.5	0.6	0.7	0.8
α	0.195	0.171	0.143	0.111	0.074	0.033
α (calculation)	0.179	0.154	0.132	0.107	0.080	0.050
β	0.135	0.123	0.108	0.090	0.067	0.042
β (calculation)	0.138	0.128	0.115	0.099	0.079	0.054
η	0.417	0.517	0.614	0.697	0.760	0.789
η (calculation)	0.445	0.569	0.660	0.717	0.741	0.731

Table 4. Known and Calculated Characteristics of the Air Propeller MTV-5-1/210 at $\varphi_{0.75} = 25^\circ$.

Parameter	Parameter value								
λ	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1
α	0.269	0.252	0.229	0.201	0.169	0.131	0.089	0.042	-0.010
α (calculation)	0.232	0.215	0.196	0.175	0.151	0.124	0.096	0.065	0.031
β	0.209	0.204	0.194	0.178	0.156	0.129	0.097	0.059	0.016
β (calculation)	0.213	0.205	0.194	0.180	0.163	0.141	0.115	0.083	0.047
η	0.351	0.449	0.540	0.621	0.692	0.753	0.802	0.831	0.792
η (calculation)	0.417	0.528	0.600	0.666	0.736	0.799	0.819	0.740	0.480

Table 5. Known and Calculated Characteristics of the Air Propeller MTV-5-1/210 at $\varphi_{0.75} = 30^\circ$.

Parameter	Parameter value									
λ	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3
α	0.298	0.292	0.276	0.254	0.226	0.192	0.155	0.116	0.075	0.035
α (calculation)	0.270	0.255	0.238	0.218	0.196	0.172	0.145	0.117	0.087	0.055
β	0.285	0.289	0.283	0.268	0.247	0.221	0.189	0.152	0.108	0.056
β (calculation)	0.293	0.288	0.278	0.265	0.248	0.226	0.199	0.168	0.131	0.089
η	0.394	0.474	0.548	0.616	0.677	0.731	0.779	0.821	0.848	0.855
η (calculation)	0.448	0.530	0.603	0.669	0.729	0.780	0.820	0.843	0.842	0.809

Table 6. Known and Calculated Characteristics of the Air Propeller MTV-5-1/210 at $\varphi_{0.75} = 35^\circ$.

Parameter	Parameter value									
λ	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5
α	0.336	0.327	0.310	0.286	0.256	0.223	0.188	0.151	0.111	0.067
α (calculation)	0.293	0.278	0.260	0.241	0.219	0.196	0.171	0.144	0.116	0.086
β	0.360	0.374	0.377	0.369	0.348	0.316	0.274	0.224	0.170	0.117
β (calculation)	0.384	0.378	0.367	0.352	0.333	0.309	0.279	0.245	0.205	0.159
η	0.489	0.550	0.606	0.658	0.705	0.749	0.786	0.820	0.847	0.865
η (calculation)	0.556	0.607	0.654	0.699	0.745	0.788	0.827	0.856	0.870	0.859

Table 7. Known and Calculated Characteristics of the Air Propeller MTV-5-1/210 at $\varphi_{0.75} = 40^\circ$.

Parameter	Parameter value					
λ	1.5	1.6	1.7	1.8	1.9	2.0
α	0.196	0.160	0.122	0.081	0.037	-0.009
α (calculation)	0.178	0.152	0.125	0.097	0.068	0.037
β	0.347	0.294	0.235	0.169	0.096	0.017
β (calculation)	0.353	0.312	0.267	0.216	0.159	0.097
η	0.809	0.834	0.853	0.856	0.863	0.818
η (calculation)	0.845	0.898	0.899	0.848	0.744	0.588

In [21], an example is provided for determining the thrust and efficiency of the AV-68 air propeller used on the An-12 aircraft at the moment of liftoff from the runway. The engine's propeller power is specified as $N_v = 3720$ h.p., the liftoff speed is $V_{lift} = 215$ km/h, and the propeller rotational speed is 1075 rpm. In this example, the airfield is assumed to be at sea level under standard atmospheric conditions: $P_a = 760$ mm Hg, $t = 15^\circ\text{C}$. This example is significant because the results are presented as specific and reliable figures rather than in graphical form.

Based on the calculations reported in [21], the propeller's advance ratio $\lambda = 0.742$, the power coefficient $\beta = 0.2108$, $\varphi_{0.75} = 28.4^\circ$, and the thrust coefficient $\alpha = 0.186$. Consequently, the propeller thrust is $P = 3070$ kg and the efficiency is $\eta = 0.655$. The verification results obtained using the developed methodology are summarized in Table 8.

Table 8. Results of the Verification Calculation for the AV-68 Air Propeller.

Parameter Name	Value of Calculated Parameters		Experiment
Advance ratio λ	0.7	0.8	0.742
Thrust coefficient α	0.1973	0.1746	0.186
Power coefficient α	0.2182	0.2022	0.2108
KPD η	0.6331	0.6907	0.655
Propeller thrust, kg	3240.5	2866.7	3070
Consumed power, h.p.	3848.3	3566.3	3720
Flight speed, km/h	203.0	232.0	215

Thus, for a liftoff speed $V_{lift} = 215$ km/h, the averaged calculated propeller thrust $P \approx 3085$ kg, and the efficiency $\eta \approx 0.66$.

The satisfactory agreement between the calculated and experimental data confirms that the proposed methodology is applicable for the design and verification of air propeller blades. However, the results are strongly influenced by factors such as the geometric and aerodynamic twist of the blade (via the zero-lift angle) and the setting angle of the characteristic section. These parameters not only vary in full-scale experiments due to blade flexibility but are also difficult to measure accurately. The outcomes further depend on potential errors in representing linear dimensions (chord and airfoil thickness) and on the treatment of flow separation in blade sections. Consequently, reliable geometric data – particularly angular parameters – are essential for conducting verification and parametric studies of designed air propellers.

5. RESEARCH RESULTS

As part of the study of the UAV's aerodynamic characteristics, several air propeller (AP) designs optimized for the specified flight regimes were developed and modeled for flight speeds of 50 km/h (Fig. 11) and 120 km/h (Fig. 12). The proposed APs differ in airfoil geometry, blade shape, and mass distribution. Using the software packages "Air Propeller 2019" and "Integration 2.1" [17, 18], comprehensive parametric studies were carried out for an attack UAV. The results of these simulations are presented in Figs. 13–15 (all of which are the work of the present authors).

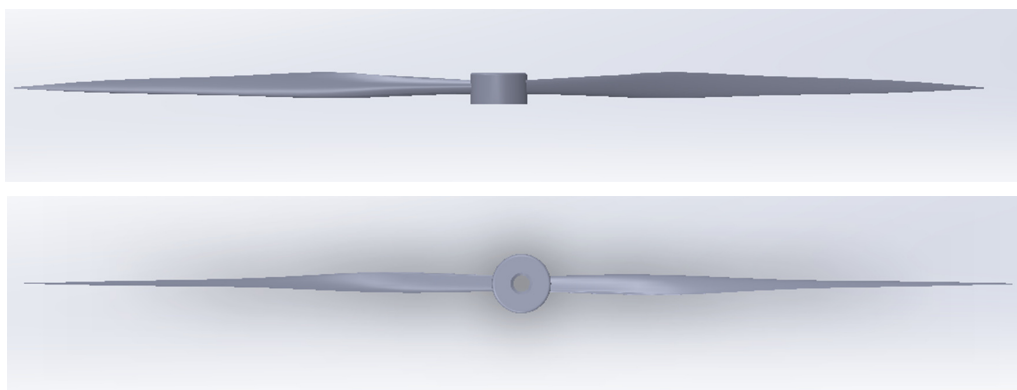


Fig. 11. A 3D model of the AP designed for a flight speed of 50 km/h ($D=0.38$ m; $N=0.4$ h.p.; 83,333 rps).

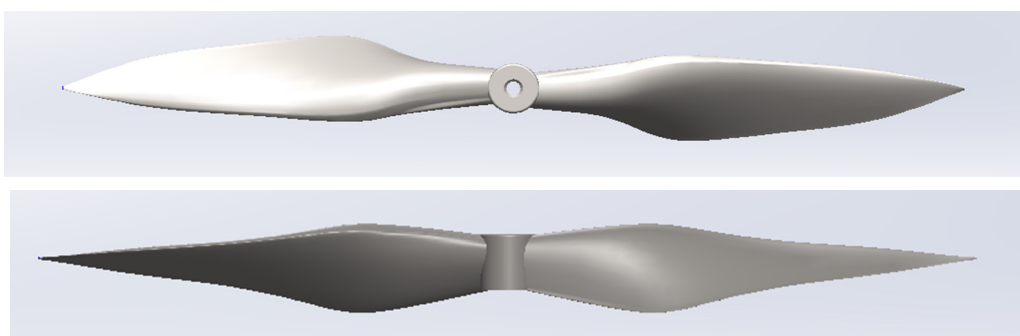


Fig. 12. A 3D model of the AP designed for a flight speed of 120 km/h ($D=0.38$ m; $N=0.6$ h.p.; 100 rps).

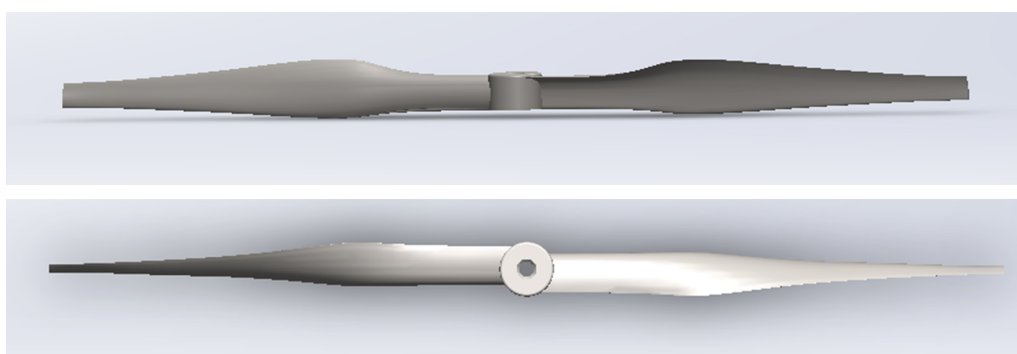


Fig. 13. A 3D model of the AP with a reduced blade chord.

The results of the air propeller design calculation have demonstrated the necessity of designing an AP for a specific combat mission with varying combat loads, as presented in Figs. 14–15.

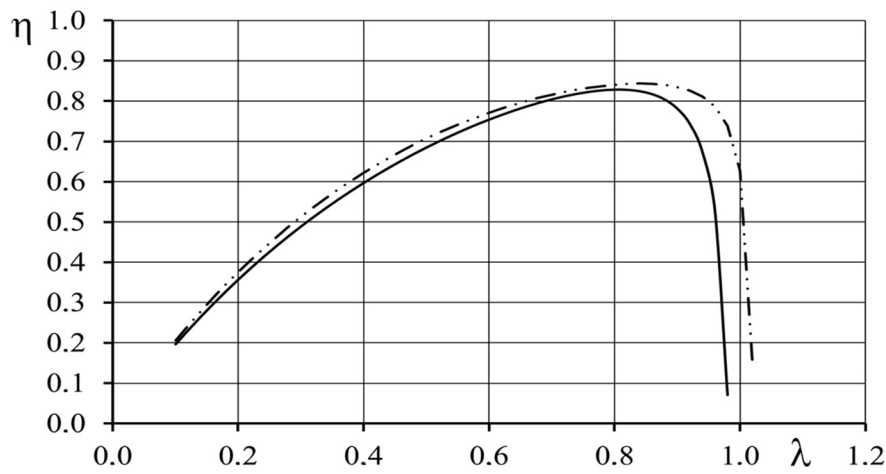


Fig. 14. Dependence of the AP efficiency on the relative flight speed:
 - · - · - characteristic of the propeller with a reduced blade chord width;
 — characteristic of the propeller with an increased blade chord width.

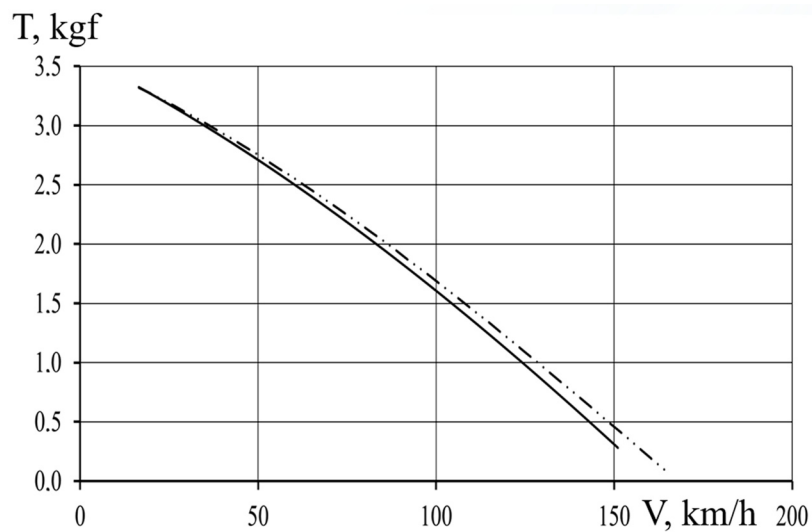


Fig. 15. Dependence of the propeller thrust on the flight speed:
 - · - · - characteristic of the AP with a reduced blade chord width;
 — characteristic of the AP with an increased blade chord width.

Source: Developed by the author.

The analysis of the results indicates that a primary factor in improving the flight performance of the UAV studied is the design of an optimal air propeller (AP) tailored to specific combat missions and varying payloads. We therefore propose implementing the optimal-AP concept as a modular set of propellers, which can be selected and fitted to the UAV depending on the mission requirements.

6. DISCUSSION OF THE RESULTS

The results of the AP design demonstrate that selecting the optimal diameter and pitch, along with calculating thrust and efficiency for a given aircraft, is essential. Key factors influencing performance include the blade installation angle, streamline shape, and choice of material. The design process often requires testing different propeller configurations and employing specialized computational tools to optimize aerodynamic characteristics.

A comparison of the results shown in Figs. 11–13 indicates that different propeller geometries are required for vertical take-off and for cruise flight. Specifically, these modes demand blades with distinct twist distributions, planform shapes, and even blade numbers. However, only one AP can be installed on the UAV. If a propeller optimized for take-off is also used during cruise, its efficiency in cruise mode decreases significantly. Verification calculations confirmed this limitation. Conversely, a propeller optimized for cruise mode cannot operate effectively in take-off conditions due to insufficient blade area.

A compromise propeller, with blade geometry intermediate between those required for take-off and cruise, would increase efficiency during cruise but also raise the power requirement during take-off. Since take-off requires the highest power across the entire flight profile, this would dictate the need for a heavier and more powerful engine, ultimately degrading overall aircraft performance. Thus, the most practical solution is to employ a propeller designed specifically for take-off and to use it across all flight modes, despite the resulting efficiency trade-off.

Another open issue concerns material selection for blades subjected to high aerodynamic loads. Additive manufacturing and advanced composites such as carbon fiber offer potential advantages, including reduced structural weight and the ability to produce complex geometries with high precision [19]. However, these methods require further detailed investigation in the context of specific combat applications, which will be addressed in future research.

7. CONCLUSIONS

The improvement of UAV performance underscores the scientific and practical challenge of extending flight range. A critical review of the literature on UAV flight performance highlighted the need for refined methodologies in the design of APs capable of adapting UAVs to diverse mission payloads.

This study presented a methodology for the aerodynamic design of fixed- and variable-pitch APs for aircraft-type UAVs, based on vortex theory. The design calculations provided input data for determining both the aerodynamic and flight characteristics of the UAV. The methodology was implemented in the Air Propeller 2019 software package and, while grounded in conventional vortex theory, introduces

modifications to the circulation distribution laws along the blade span to reflect the manufacturing specifics of small-scale APs for tactical UAVs. Additional differences include the reduced hub radius typical of electric motor APs and the specialized profiling of blade roots for piston engine cooling. Together, these account for the unique design requirements of tactical-level UAVs. The use of Air Propeller 2019 and Integration 2.1 [17, 18] enabled comprehensive parametric studies of APs designed for UAV applications.

The results confirm that one of the most critical factors in enhancing UAV flight performance is the design of an optimal AP tailored to specific mission profiles and varying payloads. We propose implementing this concept in the form of a modular set of interchangeable propellers, each optimized for a particular mission scenario. Based on the improved AP design methodology, several such propeller designs have been successfully developed.

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