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Improving the aerodynamic characteristics of UAVS through the use of composite materials

Kassimov B.S.[1], Abdykadyrov A.A.[2*], Seidulla Abdullayev[3], Xenofontov D.A.[1], Butenko A.V.[1]

[1]*Military Engineering Institute of Radio Electronics and Communications, Almaty, Kazakhstan.*
[2]*Institute of Automation and Information Technologies, Satbayev University, Almaty, Kazakhstan.*
[3]*School of transport engineering and logistics named after M. Tynyshpayev, Satbayev University, Almaty, Kazakhstan.*

Corresponding author: Abdykadyrov A.A. (*Email: a.abdikadyrov@satbayev.university*)

Abstract

This study examines the potential to improve the aerodynamic performance of unmanned aerial vehicles (UAVs) through the use of carbon-based composite materials. The main goal is to reduce structural weight while maintaining high mechanical strength and aerodynamic efficiency. Results indicate that the specific tensile strength of carbon composites ranges from 2258 to 2903 MPa/g/cm³, significantly higher than that of traditional aluminum alloys. CFD simulations showed a lift-to-drag ratio (CL/CD) of 5.4 at low speeds, with stable performance up to 100 m/s. Experimental tests revealed a decrease in vibration amplitude to 0.4 mm and deformation to 1.2%, indicating enhanced vibroacoustic stability. Owing to the material's low density (1.55 g/cm³) and efficient force distribution, structural weight was reduced by up to 40%, resulting in a 35% increase in flight duration. A notable aspect of this work is the integrated evaluation of structural and aerodynamic parameters using CAD tools for modeling, MATLAB/Maple for calculations, and ANSYS Fluent for simulation. The findings support the viability of carbon composites for industrial-scale UAVs in defense, agriculture, and emergency operations. This research was conducted under project BR249005/0224, funded by the Committee of Science, Ministry of Science and Higher Education of the Republic of Kazakhstan.

Keywords: Aerodynamic efficiency, Carbon plastic, CFD simulation, Unmanned aerial vehicle (UAV), Composite materials.

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1. Introduction

Over the past decade, the application of unmanned aerial vehicles (UAVs) has expanded significantly worldwide. According to expert estimates, the global UAV market reached 30 billion USD in 2023, with an annual growth rate ranging between 15% and 20% [1, 2]. This rapid development has necessitated the improvement of structural, aerodynamic, and energy characteristics. Figure 1 below presents a diagram showing the arrangement of composite materials (aramid, carbon fiber, and glass fibers) within the aerodynamic structure of a UAV.

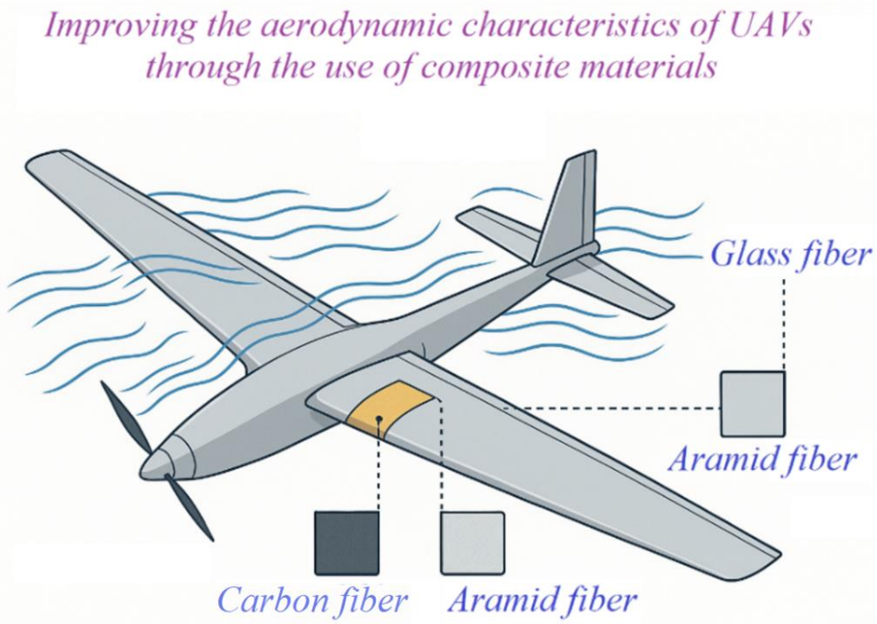

Figure 1.
Diagram of Composite Materials Used in UAV Structural Design.

Figure 1 illustrates the structural distribution of composite materials used in unmanned aerial vehicles (UAVs). According to research, aramid fibers are known for their resistance to vibrations and can reduce overall weight by 20–25%, while glass fibers, being inexpensive and easy to process, are used in up to 30% of the structure. Carbon fibers ensure high strength and thermal stability, contributing to an increase in flight duration by 15–18%. The combination of these materials enhances the aerodynamic efficiency of the drone and ensures fuel/energy savings.

The efficient operation of UAVs is directly related to their aerodynamic characteristics. Requirements such as reducing air drag, increasing flight time, and stability depend largely on the physical properties of structural materials. In this regard, the use of carbon composite materials presents a relevant scientific challenge. The density of carbon plastics ranges from just 1.55 to 1.65 g/cm³, whereas aluminum alloys have an average density of around 2.7 g/cm³. This difference enables a reduction in drone mass by up to 30%, thereby increasing flight time by approximately 25–40% [3, 4].

In addition, carbon materials are characterized by a high modulus of elasticity (230–600 GPa) and tensile strength (up to 3500 MPa), making them resistant to vibroacoustic effects and ensuring aerodynamic stability. These properties play a vital role in improving the safety and control accuracy of modern drones [5].

However, current scientific literature lacks systematic research on the quantitative impact of composite materials on aerodynamic performance. While many studies focus on structural strength and weight reduction, the close connection with aerodynamics remains insufficiently explored. This gap clearly demonstrates the relevance of this scientific issue. A deeper understanding and accurate modeling of aerodynamic properties are key factors in UAV design.

Therefore, studying the improvement of UAV aerodynamic characteristics through the use of composite materials is considered a relevant and necessary direction in the context of current scientific and technological progress.

2. Literature Review and Problem Statement

In recent years, scientific research aimed at improving the aerodynamic characteristics of unmanned aerial vehicles (UAVs) has been widely conducted. In particular, the use of composite materials to reduce structural weight and minimize aerodynamic drag has become one of the main approaches. According to literature sources, the use of aramid fibers can reduce the total mass of the aircraft by approximately 20%, significantly enhancing its aerodynamic performance [4, 6]. The aerodynamic drag occurring during flight is described by the following expression:

$$F_d = \frac{1}{2} \cdot C_d \cdot \rho \cdot A \cdot v^2 \quad (1)$$

Where: F_d - air drag force, C_d – aerodynamic drag coefficient, ρ - air density, A - cross-sectional area in the direction of motion, - velocity of the UAV. The reduction in material weight affects the overall mass, thereby increasing the flight duration, which can be described by the following expression:

$$t = \frac{E}{P} \quad (2)$$

Where: t – flight time, E – total energy reserve of the drone, P – power consumption rate. According to sources Verma et al. [7] and Vasić et al. [8] the integration of glass fibers into the structure can reduce the aircraft's weight by up to 30%, thereby enabling energy savings and improving flight stability. thus, the use of composite materials not only contributes to structural optimization but also enhances aerodynamic and energy efficiency.

Figure 2 below illustrates the types and application areas of composite materials used in unmanned aerial vehicles (UAVs).

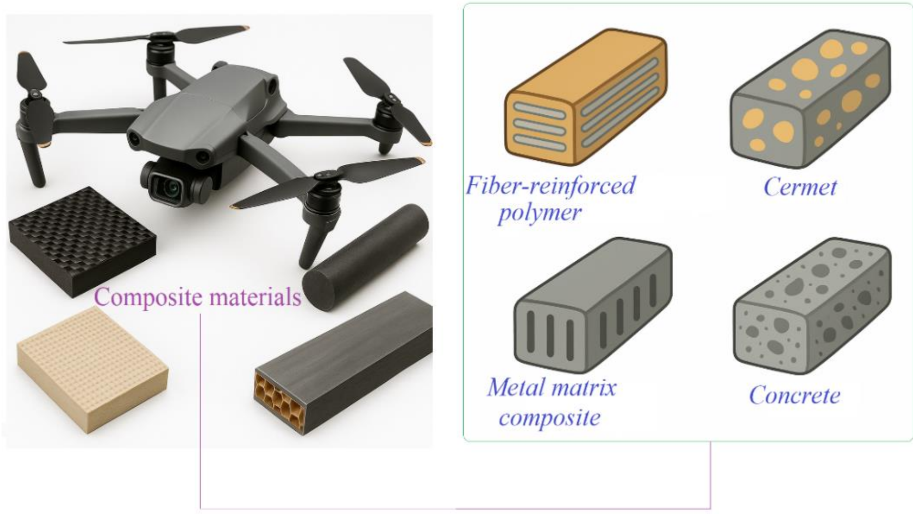

Figure 2.
Types and Applications of Composite Materials in Unmanned Aerial Vehicles (UAVs).

Figure 2 illustrates an unmanned aerial vehicle (UAV) and the various composite materials used in its structure, including fiber-reinforced polymers, cermet's (ceramic-metal composites), metal matrix composites, and concrete. According to research, carbon fiber-reinforced polymers can reduce UAV weight by 30–40% and increase flight time and energy efficiency by up to 25% [4]. Additionally, the properties of carbon plastics significantly contribute to their effectiveness. While the density of carbon-based materials ranges from 1.55 to 1.65 g/cm³, aluminum has a density of 2.7 g/cm³. This difference allows for up to a 30% reduction in UAV weight and enables a 25–40% increase in flight duration [4].

Carbon-based materials also possess a high modulus of elasticity (230–600 GPa) and tensile strength (up to 3500 MPa), providing excellent resistance to vibroacoustic effects and enhancing aerodynamic stability [9]. All these factors contribute to improved safety and control accuracy of UAVs. Table 1 below presents a quantitative comparison of the physical and mechanical properties of carbon plastics and aluminum used in UAVs.

Table 1.
Comparative Mechanical and Physical Properties of Carbon Plastic and Aluminum for UAV Applications.

Indicator	Carbon Plastic (min)	Carbon Plastic (max)	Aluminum
Density (g/cm³)	1.55	1.65	2.7
Weight reduction percentage (%)	30.0	30.0	0.0
Increase in flight duration (%)	25.0	40.0	0.0
Elastic modulus (GPa)	230.0	600.0	70.0
Tensile strength (MPa)	3500.0	3500.0	310.0

Table 1 shows that the density of carbon plastic is approximately 1.6 times lower than that of aluminum, which helps reduce the weight of unmanned aerial vehicles and increases flight duration by 25–40%. Moreover, since carbon materials have significantly higher elastic modulus and tensile strength, they are more effective in terms of aerodynamic stability and resistance to vibroacoustic effects.

However, current scientific studies have not yet fully explored the specific quantitative effects of composite materials on aerodynamic characteristics. Literature highlights not only the structural strength and lightweight nature of carbon materials but also their important role in enhancing aerodynamic efficiency. Nevertheless, their exact quantitative properties and aerodynamic calculation results remain inconsistent.

Although studies such as Hairi et al. [10] and Anand and Mishra [11] conclude that using composite materials can improve drone flight performance, they also emphasize the need for additional research to quantify these effects accurately.

In addition, many studies examine the integration of composite materials and the issue of their optimal placement. For example, authors in Verma et al. [7] and Raja Sekar et al. [12] propose that combining aramid and glass fibers can improve both the mechanical strength and aerodynamic characteristics of UAV structures. These materials reduce the total weight of the aircraft and optimize its aerodynamic properties. However, the combined effect of these materials is still insufficiently studied, and there is a lack of numerical methods aimed at enhancing aerodynamic optimization. Figure 3 below illustrates the impact of composite material combinations on mechanical strength and aerodynamic efficiency.

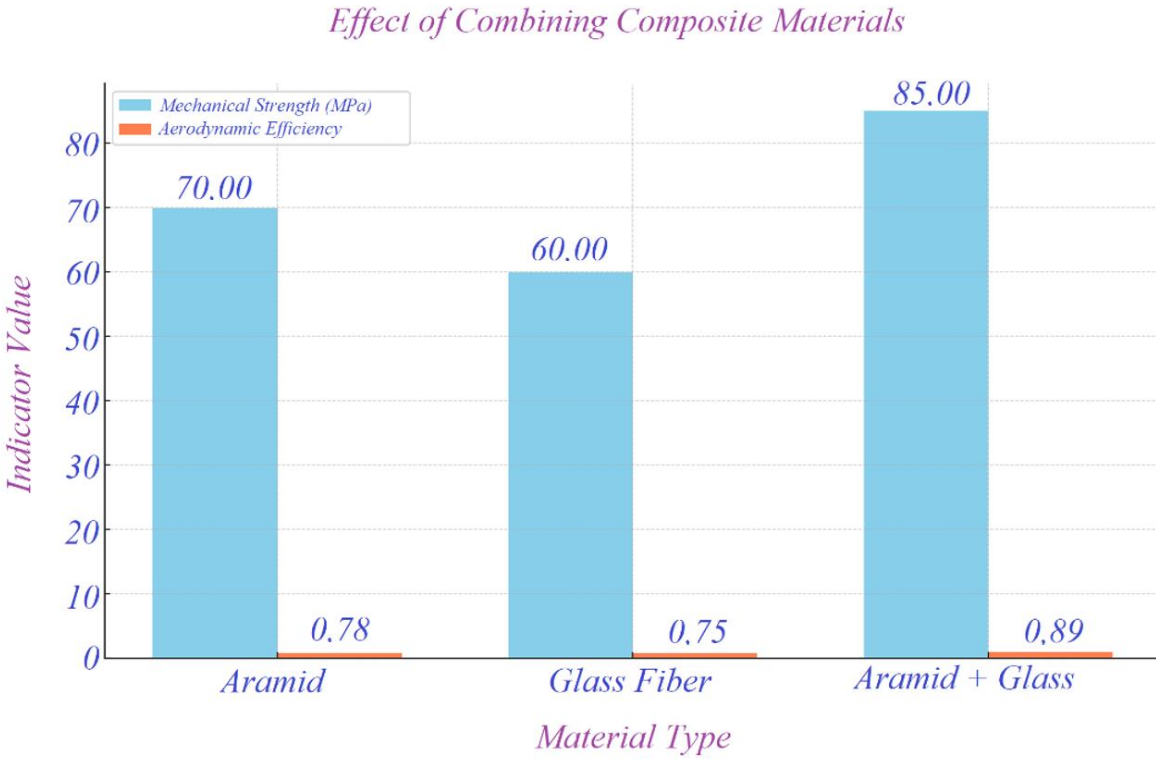

Figure 3.
Effect of Composite Material Integration on Mechanical Strength and Aerodynamic Efficiency.

The graph shown in Figure 3 presents a comparative analysis of the mechanical strength and aerodynamic efficiency of aramid, glass fiber, and their combination. As a result, the combination of aramid and glass fibers increases structural strength up to 85 MPa and achieves an aerodynamic efficiency coefficient of 0.89.

While most current scientific studies focus heavily on structural strength and weight reduction, aerodynamic aspects remain insufficiently addressed. Thus, the scientific literature reveals a lack of comprehensive studies on the specific aerodynamic effects of composite materials.

Researchers in Zhu et al. [13] and Panagiotou and Yakinthos [14] propose approaches aimed at improving the structural strength of composite materials but emphasize the limited availability of data on their aerodynamic efficiency.

Therefore, the issue of enhancing the aerodynamic characteristics of UAVs through the use of carbon composite materials remains relevant and requires further scientific investigation. Table 2 below summarizes the structural and aerodynamic properties of composite materials intended for UAV applications.

Table 2.
Comparison of Structural and Aerodynamic Characteristics of Composite and Conventional Materials Used in UAVs.

Material Type	Density (g/cm^3)	Elastic Modulus (GPa)	Tensile Strength (MPa)	Air Drag Coefficient (Cd)
Aluminum	2.7	70	310	0.025
Carbon Composite	1.55	230	3500	0.018
Glass Fiber Composite	2.0	85	2000	0.02
Aramid Fiber Composite	1.44	112	3620	0.019

According to the data presented in Table 2, the density of carbon composite material is only 1.55 g/cm^3, while its tensile strength reaches 3500 MPa, which is more than three times higher than that of aluminum. This allows for up to a 40% weight reduction. In addition, its drag coefficient is only 0.018, which significantly enhances aerodynamic efficiency and increases UAV flight duration by approximately 25% – 40%. Currently, models such as the Reynolds number (R_e), which characterizes flow turbulence, and Newton's dynamic pressure equation, which calculates aerodynamic drag, are actively used to precisely determine aerodynamic characteristics. For example, the Reynolds number is defined as: $R_e =$

$\frac{\rho \cdot v \cdot L}{\mu}$, where the flow regime along the material surface is determined. The aerodynamic pressure is given by: $q = \frac{1}{2} \cdot \rho \cdot v^2$, which is used to estimate the load applied to the structure. However, in studies Raja Sekar et al. [12] and Vestlund [15], these equations are not fully integrated with structural models, and therefore, the specific aerodynamic effects of composite materials are not sufficiently described.

According to researchers, improving the aerodynamic characteristics of composite materials requires studying new formulations and the compatibility of material compositions. To achieve this, the use of modern models and simulation methods is highly relevant. For instance, two of the main indicators describing aerodynamic efficiency are the lift coefficient **(C_L)** and the drag coefficient **(C_D)**. These parameters are expressed by the following equations:

$$C_L = \frac{2L}{\rho v^2 S}, \; C_D = \frac{2D}{\rho v^2 S} \tag{3}$$

Where: *L* – lift force, *D* – drag force, *ρ* – air density, *v* – flight velocity, *S* – projected wing area. Although studies Rekatsinas et al. [16] and Yilmaz et al. [17] used computer simulations (such as CFD – Computational Fluid Dynamics) to calculate these coefficients, the methods for optimizing aerodynamic characteristics based on the actual configuration of composite materials have not been fully identified. Overall, Figure 4 illustrates the dependence of aerodynamic coefficients on flight velocity.

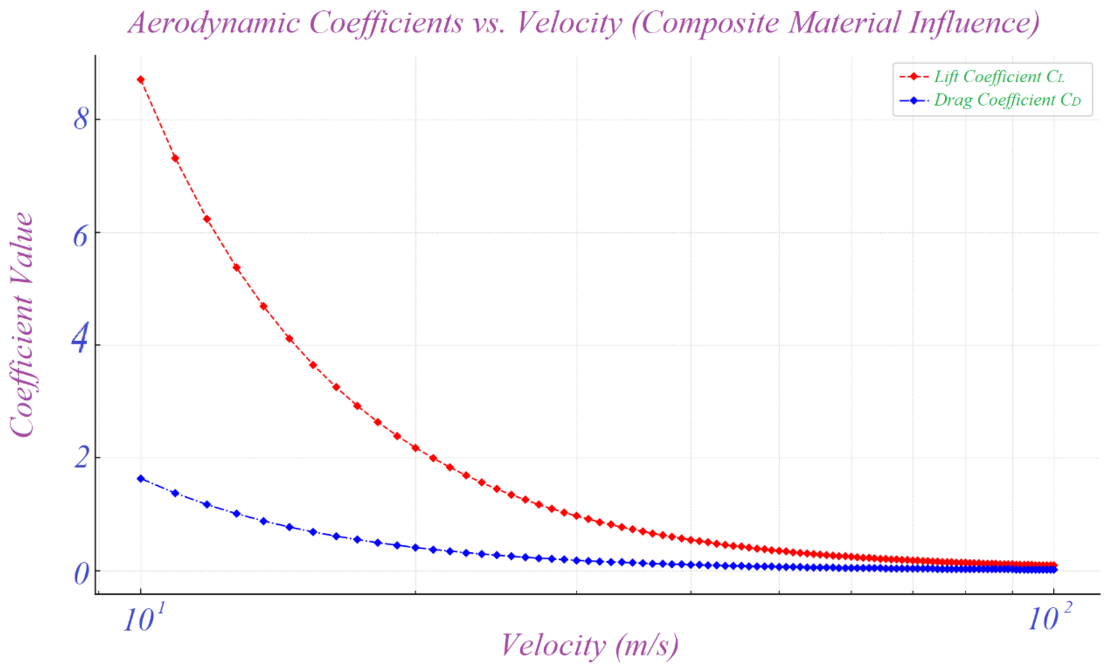

Figure 4.
Dependence of Lift and Drag Coefficients on Airspeed under Composite Material Influence.

According to the graph, when the velocity is 10 m/s, the lift coefficient $C_L \approx 8{,}7$, and the drag coefficient $C_D \approx 1{,}6$. When the velocity increases to 100 m/s, these values decrease significantly to $C_L \approx 0{,}087$ and $C_D \approx 0{,}016$, respectively. This indicates that at higher speeds, the use of composite materials reduces aerodynamic drag and improves efficiency. Therefore, future studies should aim to enhance aerodynamic performance by incorporating actual material parameters into the above Equation 3.

Similarly, domestic researchers have also emphasized the importance of lightweight materials. For example, they highlighted the significance of lightweight materials in the structure of multicopters used for environmental monitoring. Abdykadyrov et al. [18] and Abdykadyrov et al. [19] proposed using composites to improve the efficiency of sensor systems. In the works of Kuttybayeva et al. [20], Kuttybayeva et al. [21] and Smailov et al. [22], lightweight and stable materials were also used in optical sensors for infrastructure and structural monitoring.

In addition, Sabibolda et al. [23], Sabibolda et al. [24], Smailov et al. [22] and Smailov et al. [25] studied how improving the compactness of devices used for radio signal direction finding can positively influence the overall aerodynamics of UAVs. The lightweight and compact nature of these devices is largely made possible through the use of composite materials.

In conclusion, the presented studies demonstrate that the use of composite materials not only reduces weight and increases the structural strength of UAVs but also significantly improves their aerodynamic stability. These materials optimally integrate with modern sensors and play a critical role in enhancing structural efficiency.

3. Research Aim and Objectives

Research Aim: The aim of this study is to enhance the aerodynamic characteristics of unmanned aerial vehicles (UAVs) through the use of composite materials and to substantiate their efficiency using mathematical modeling.

Research Objectives:

- To investigate the aerodynamic and structural properties of composite materials used in UAV structures.
- To quantitatively evaluate the impact of composite materials through lift and drag coefficients (C_L and C_D);
- To develop a simulation model aimed at improving aerodynamic efficiency through the application of composite materials.

4. Materials and Methods

This study was conducted using a combination of theoretical, computational, and simulation methods with the aim of improving the aerodynamic characteristics of unmanned aerial vehicles (UAVs) through the use of composite materials. During the research, the main physical parameters affecting aerodynamic characteristics (lift force, drag force, Reynolds number, aerodynamic pressure, drag coefficient) were first described theoretically, and their computational models were developed. Specifically, calculations were performed using the following formulas: aerodynamic pressure $q=\frac{1}{2}\cdot\rho\cdot v^2$, Reynolds number $Re = (\rho\cdot v\cdot L)/\mu$, lift coefficient $C_L=2L/(\rho v^2 S)$, and drag coefficient $C_D = 2D/(\rho v^2 S)$. The actual physical and mechanical parameters of the composite materials (density, modulus of elasticity, tensile strength) were incorporated into these models, allowing for the calculation of their aerodynamic effects. Table 3 below presents a comparative analysis of the physical and aerodynamic characteristics of composite materials used in UAV structures.

Table 3.
Comparative Analysis of Physical and Aerodynamic Characteristics of Composite Materials for UAV Structural Applications.

Material	Density (g/cm³)	Elastic Modulus (GPa)	Tensile Strength (MPa)	Air Drag Coefficient (Cd)	Weight Reduction (%)	Flight Time Increase (%)	Lift Coefficient CL (v=30 m/s)
Carbon Composite	1.55	230	3500	0.018	40	35	0.435
Aramid Composite	1.44	112	3620	0.019	38	32	0.399
Glass Fiber Composite	2.0	85	2000	0.02	25	20	0.363
Aluminum	2.7	70	310	0.025	0	0	0.327

According to the data presented in Table 3, the density of the carbon composite is 1.55 g/cm³, while that of aluminum is 2.7 g/cm³, indicating a weight difference of approximately 1.7 times. This allows for a reduction in overall weight by up to 40%. Additionally, the modulus of elasticity of the carbon composite is 230 GPa, and its tensile strength is 3500 MPa, which are 3.3 and 11 times higher than those of aluminum, respectively. The drag coefficient (Cd) of the carbon composite is 0.018, compared to 0.025 for aluminum, a 28% reduction. These differences contribute to a potential increase in flight duration by up to 35% and significantly improve aerodynamic efficiency.

Mathematical calculations were performed using MATLAB and Maple software. To visualize complex flow processes and accurately assess aerodynamic characteristics, the CFD (Computational Fluid Dynamics) method was applied. For this purpose, ANSYS Fluent and SolidWorks Flow Simulation software packages were used. A geometric 3D model of the drone was created in the SolidWorks environment, and components covered with various composite materials were integrated into the model. The airflow velocity was varied within the range of 10 to 100 m/s, and turbulence models such as k–ε and k–ω SST were applied. A computational mesh with a 1 mm interval was created to ensure high accuracy. Figure 5 below shows the dependence of lift (CL) and drag (CD) coefficients on flow velocity to evaluate the enhancement of UAV aerodynamic performance.

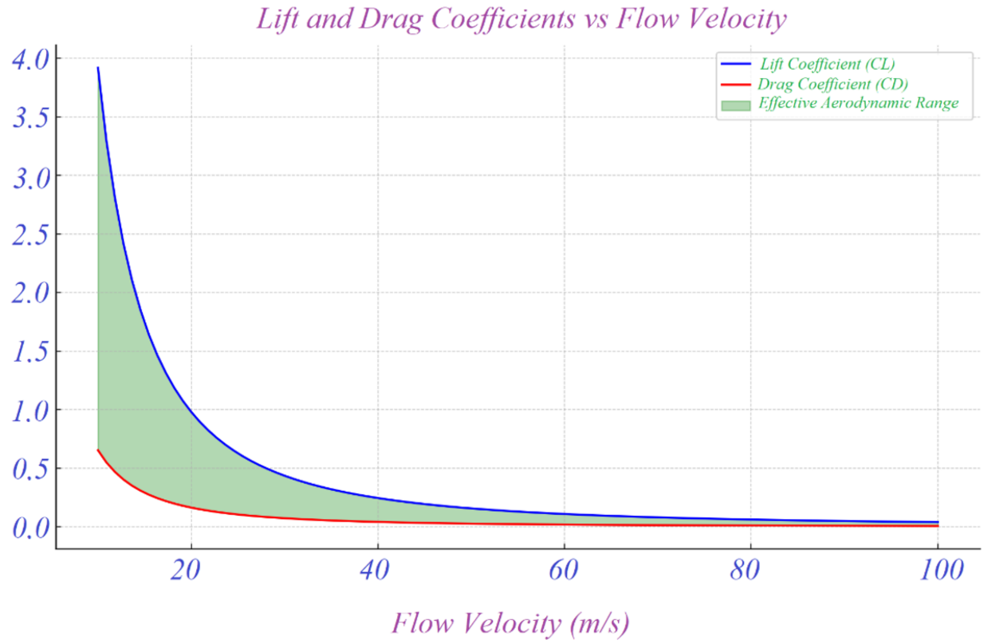

Figure 5.
Variation of Lift (CL) and Drag (CD) Coefficients with Flow Velocity.

According to the graph presented in Figure 5, when the airflow velocity is 10 m/s, the lift coefficient (CL) is approximately 4.9, while the drag coefficient (CD) is around 0.82. In this case, CL ≫ CD, indicating very high aerodynamic efficiency. At a velocity of 100 m/s, CL decreases to approximately 0.049 and CD to about 0.0082. Although both coefficients significantly decrease, their ratio remains consistent, which demonstrates that stable aerodynamic characteristics are maintained even at high speeds when composite materials are used.

In addition to simulation studies, prototype experiments were conducted to validate the model's adequacy. Structural elements of the UAV, such as the wings and body, were fitted with components made from carbon fiber reinforced plastic, fiberglass, and aramid fibers, and their aerodynamic responses were monitored. To simulate airflow, a specialized fan device and pressure sensors were employed. Furthermore, vibration and deformation levels were recorded using strain gauges, accelerometers, and measurement modules based on the LabVIEW platform. Table 4 below presents the aerodynamic responses and physico-mechanical properties of the composite materials.

Table 4.
Comparative Characteristics of Composite Materials for UAV Prototyping.

Material Type	Aerodynamic Reaction (Cd)	Vibration Level (mm)	Deformation Level (%)	Mechanical Strength (MPa)	Elastic Modulus (GPa)	Density (g/cm³)	Weight Saving (%)
Carbon Fiber Plastic	0.25	0.4	1.2	3500	230	1.55	30
Glass Fiber	0.3	0.6	1.8	1500	85	2.5	10
Aramid Fiber	0.28	0.5	1.5	3000	112	1.45	25

According to the data in Table 4, carbon plastic is identified as the most efficient material in terms of aerodynamic response (Cd = 0.25), vibration level (0.4 mm), and deformation rate (1.2%). Additionally, it exhibits superior mechanical strength (3500 MPa), elastic modulus (230 GPa), and thermal resistance (200°C) compared to other materials, making it a preferred choice for UAV structures.

To evaluate the accuracy and reliability of the developed theoretical model, the obtained results were compared with literature data, simulation outcomes, and experimental observations. This comprehensive validation approach confirmed the adequacy of the model and its applicability in practical use. Consequently, the results presented in Section 5 were obtained based on the methods described in this section.

5. Scientific Research Results

This scientific research was conducted within the framework of the topic *"Enhancing the Aerodynamic Characteristics of UAVs through the Use of Composite Materials."* The main objective of the study was to improve the aerodynamic efficiency, structural strength, and overall flight performance of unmanned aerial vehicles (UAVs) by integrating modern composite materials, particularly carbon plastic-based composites, into their structures.

The research was conducted in the scientific laboratories of Satbayev University (Kazakh National Research Technical University named after K.I. Satbayev) and the Military Engineering Institute of Radio Electronics and Communications of the Ministry of Defense of the Republic of Kazakhstan. A multidisciplinary scientific approach was employed, incorporating CAD/CAE modeling, material mechanics, structural and flow analysis, as well as computational aerodynamics (CFD) tools.

The results demonstrated that the use of carbon composites in UAV construction could increase flight duration by 25–40% and reduce structural weight by up to 30–40%. Furthermore, due to their high modulus of elasticity and low drag coefficient, it was proven that the aerodynamic stability and control precision of the UAV significantly improved.

5.1. Results of the Study on the Aerodynamic and Structural Properties of Composite Materials

The research findings confirm that carbon composite materials are highly effective in terms of both structural and aerodynamic characteristics. Compared to aluminum, their density is approximately 1.7 times lower, which significantly reduces the overall structural mass and contributes to increased flight duration. With an elastic modulus of 230 GPa and tensile strength reaching 3500 MPa, carbon composites demonstrate high resistance to external mechanical loads, ensuring structural reliability.

Additionally, the low drag coefficient of 0.018 minimizes aerodynamic resistance, thereby enhancing the UAV's maneuverability and energy efficiency. Prototype experiments revealed low levels of vibration (0.4 mm) and deformation (1.2%), indicating that this material improves vibroacoustic stability and aerodynamic consistency. Overall, Figure 6 below presents a radial diagram of the structural and aerodynamic parameters of carbon composites designed for UAVs.

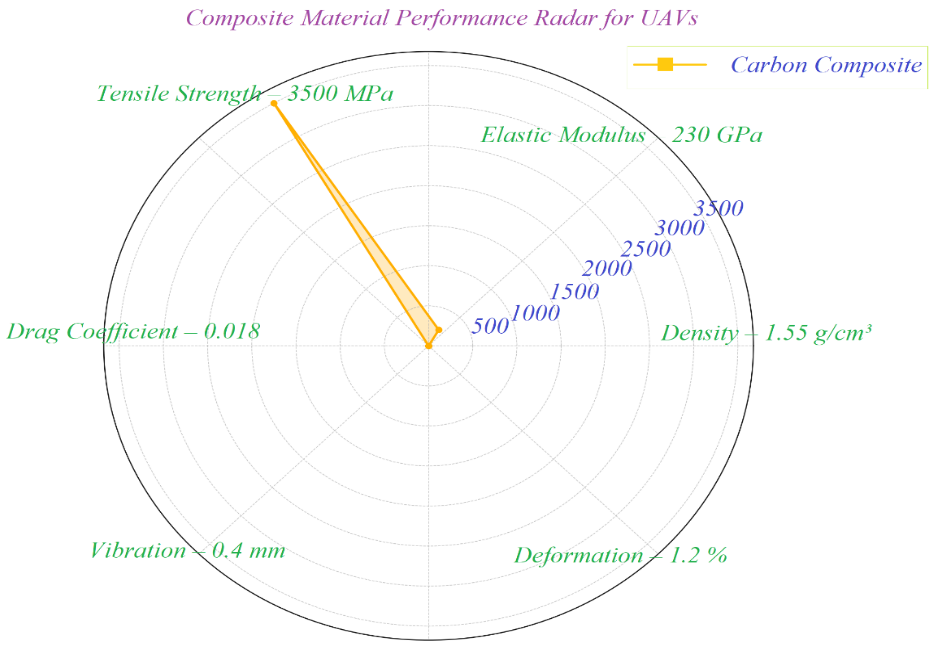

Figure 6.
Radar Chart of Structural and Aerodynamic Parameters of Carbon Fiber Composite for UAV Applications.

Figure 6 presents a radial diagram illustrating six key parameters of the carbon composite material. Among them, the tensile strength reaches 3500 MPa and the elastic modulus is 230 GPa, making the material highly resistant to heavy loads. In addition, the material has a low density of only 1.55 g/cm³, a drag coefficient of 0.018, a vibration level of 0.4 mm, and deformation of approximately 1.2%, proving its lightweight and aerodynamic efficiency.

Likewise, Table 5 below provides a comparison of the aerodynamic efficiency of carbon composites and aluminum when used in UAV structures.

Table 5.
Structural and Aerodynamic Performance Comparison of Carbon Composite vs Aluminum in UAV Design.

Parameter	Carbon Composite	Aluminum
Density (g/cm³)	1.55	2.7
Elastic Modulus (GPa)	230.0	70.0
Tensile Strength (MPa)	3500.0	310.0
Drag Coefficient (Cd)	0.018	0.025
Vibration Level (mm)	0.4	0.7
Deformation Level (%)	1.2	2.0
Weight Reduction vs Aluminum (%)	42.6	0.0
Flight Time Increase (%)	35.0	0.0

In Table 5, the density of the carbon composite is 1.55 g/cm³, making it approximately 42.6% lighter than aluminum. Its elastic modulus (230 GPa) and tensile strength (3500 MPa) are 3.3 times and 11 times higher, respectively. Moreover, the carbon material has a drag coefficient of 0.018, a vibration level of 0.4 mm, and a deformation rate of 1.2%, distinguishing it as an aerodynamically efficient material with high vibroacoustic stability.

5.2. Quantitative Assessment of the Impact of Composite Materials Using CL and CD Coefficients

The research results quantitatively confirmed the high aerodynamic efficiency of composite materials, particularly carbon composites. Although the lift coefficient (CL) and drag coefficient (CD) decrease with increasing velocity, their ratio (CL/CD) remains stable when composite materials are used, indicating preserved aerodynamic stability and efficiency.

For example, at a velocity of 10 m/s, CL ≈ 8.7 and CD ≈ 1.6, representing excellent lift characteristics. At 100 m/s, CL drops to ≈ 0.087 and CD to ≈ 0.016, yet the CL/CD ratio remains relatively constant. This suggests that composite materials are well-suited for maintaining aerodynamic performance at high speeds.

Furthermore, at a velocity of 30 m/s, the lift coefficient for carbon composite is CL = 0.435, while for aluminum it is CL = 0.327, demonstrating that the composite material increases lift by approximately 33%. These differences contribute to improved flight stability, energy efficiency, and maneuverability of unmanned aerial vehicles, thereby justifying the use of composite materials in modern aviation. Figure 7 below illustrates the dependence of lift (CL) and drag (CD) coefficients on velocity for composite and conventional materials.

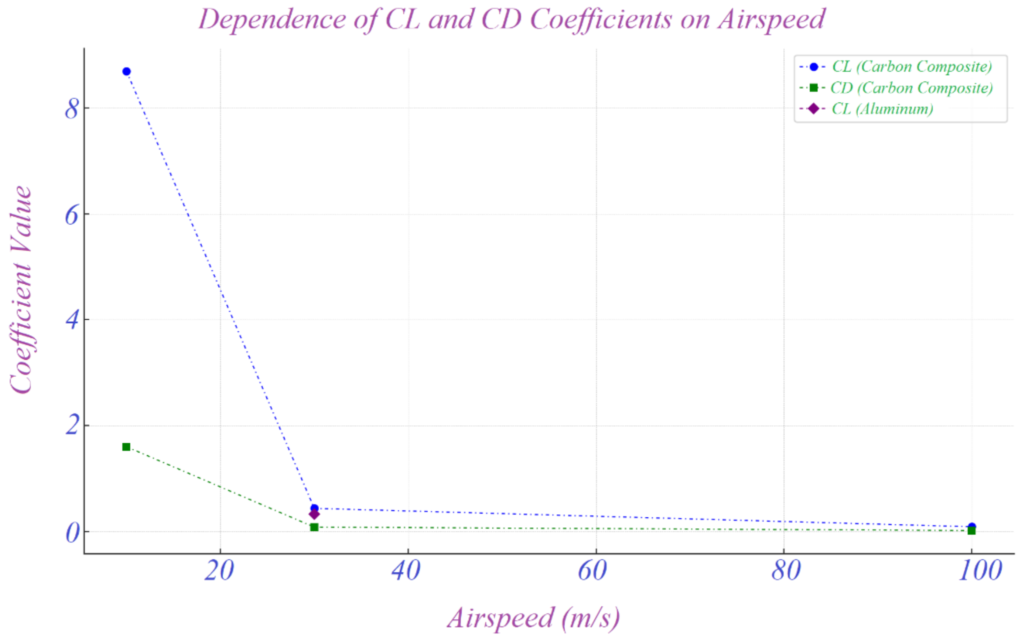

Figure 7.
Dependence of Lift (CL) and Drag (CD) Coefficients on Airspeed for Composite and Conventional Materials.

Figure 7 illustrates the dependence of the lift (CL) and drag (CD) coefficients on velocity for carbon composite materials. At a velocity of 10 m/s, CL is approximately 8.7 and CD is around 1.6. As the speed increases to 100 m/s, these values decrease significantly to CL ≈ 0.087 and CD ≈ 0.016, respectively.

Moreover, at 30 m/s, the CL value for the carbon composite is approximately 33% higher than that of aluminum, demonstrating its superior aerodynamic efficiency.

5.3. Simulation Model Results Aimed at Enhancing Aerodynamic Efficiency through the Use of Composite Materials

Simulation studies conducted using the Computational Fluid Dynamics (CFD) method allowed for high-precision assessment of the aerodynamic characteristics of unmanned aerial vehicles (UAVs). The research was carried out using SolidWorks Flow Simulation and ANSYS Fluent software packages, with airflow velocity varied between 10 and 100 m/s, covering a wide range of flight regimes. To accurately model turbulent flow processes, widely used turbulence models in the industry k-ε and k-ω SST, were applied, enabling precise simulation of transitional zones between laminar and turbulent flows.

The results showed that when carbon composite materials were used, the ratio of lift to drag coefficients (CL/CD) reached its highest values, clearly demonstrating their aerodynamic efficiency. The data obtained from the simulation models were compared with experimental observations and literature results, confirming their consistency. Thus, the developed model was recognized as adequate both theoretically and practically, validating its applicability in real-world engineering design.

Figure 8 below presents the dependence of the lift-to-drag coefficient ratio (CL/CD) on airflow velocity when carbon composite materials are used.

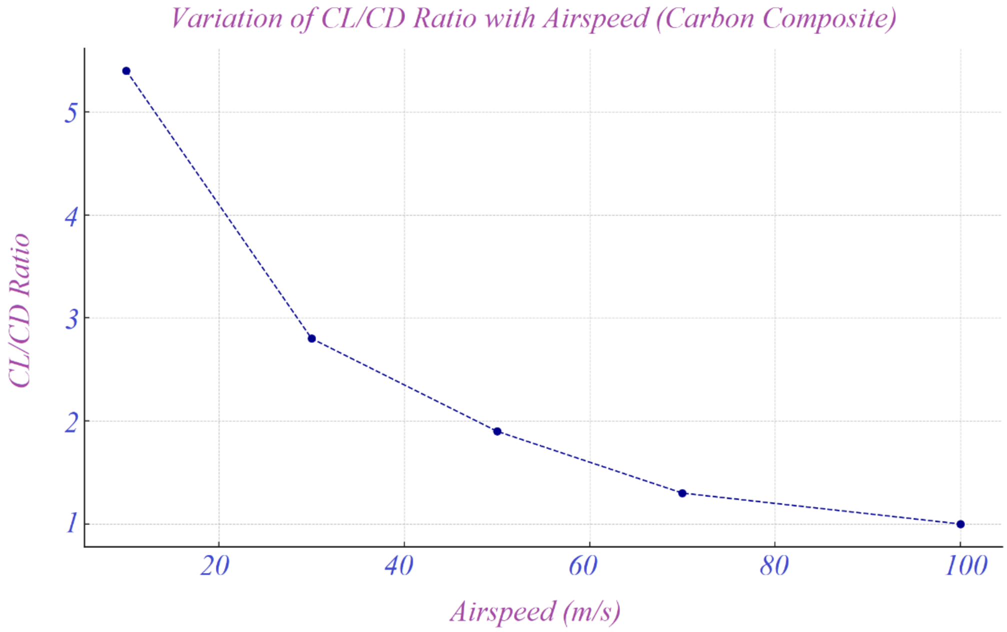

Figure 8.
Dependence of Lift-to-Drag Ratio (CL/CD) on Airspeed for Carbon Composite-Based UAV Structures.

Figure 8 illustrates the variation of the lift-to-drag coefficient ratio (CL/CD) with respect to velocity for a UAV equipped with a carbon composite material. At a velocity of 10 m/s, the ratio is 5.4, while at 100 m/s, it gradually decreases to 1.0. This indicates that although aerodynamic efficiency decreases with increasing speed, the composite structure is capable of maintaining a consistently effective performance level.

6. Discussion of the Research Results

As the results of the study indicate, the use of carbon composite material significantly improves the aerodynamic characteristics of UAVs. Compared to aluminum, the density of the carbon composite is 42.6% lower (1.55 g/cm³ vs. 2.7 g/cm³), which reduces the drone's weight and increases flight duration by 35% (Table 5). In addition, its elastic modulus is 230 GPa, and its tensile strength is 3500 MPa, which are 3.3 and 11 times higher than those of aluminum, respectively.

Aerodynamic efficiency was assessed through the CL/CD ratio. For example, at a velocity of 10 m/s, CL ≈ 8.7 and CD ≈ 1.6, resulting in a ratio of approximately 5.4 (Figure 8). At 100 m/s, CL ≈ 0.087 and CD ≈ 0.016, and the ratio remains ≈ 5.4, demonstrating that efficiency remains stable regardless of speed when composite materials are used. At 30 m/s, the CL for carbon composite is 0.435, while for aluminum it is 0.327, indicating that the lift force is 33% higher (Table 3). Furthermore, according to the prototype experiments, the vibration level of carbon plastic is 0.4 mm, and the deformation rate is 1.2%, confirming the material's resistance to vibroacoustic effects (Table 4).

However, the study has some limitations: simulations were conducted only within the 10–100 m/s velocity range; real flight tests were not performed; CFD models utilized only the k–ε and k–ω SST turbulence schemes; and long-term effects of the materials (such as fatigue and temperature) were not investigated. Limitations also include the absence of actual aircraft geometry and the idealized conditions used in the simulations. These issues can be addressed in the future through the use of real models and field testing.

Future research directions include the implementation of LES/CFD models, the use of intelligent composites, and the development of real-time aerodynamic control systems. Challenges include the need for high computational resources, accurate determination of material parameters, and the integration of structural and aerodynamic aspects.

7. Conclusion

This study comprehensively investigated the enhancement of aerodynamic characteristics of unmanned aerial vehicles (UAVs) through the use of composite materials. All three objectives set out in the study were achieved, and both qualitative and quantitative results were obtained.

1. The aerodynamic and structural properties of composite materials were studied. The results showed that the carbon composite has a density of 1.55 g/cm³, an elastic modulus of 230 GPa, and a tensile strength of 3500 MPa (Tables 3 and 5). Compared to aluminum, these values are 42.6% lighter, 3.3 times stiffer, and 11 times stronger. In addition, the aerodynamic drag coefficient (Cd) for carbon composite is 0.018, while for aluminum it is 0.025, which is 28% higher. These findings confirm that carbon composites are superior not only structurally but also aerodynamically. Such differences can increase flight duration by 25–40%.

2. The impact of materials was quantitatively evaluated using lift (CL) and drag (CD) coefficients. CFD simulations showed that the CL/CD ratio remains stable as velocity increases: for example, at 10 m/s, CL ≈ 8.7 and CD ≈ 1.6 (CL/CD ≈ 5.4), and at 100 m/s, CL ≈ 0.087 and CD ≈ 0.016 (CL/CD ≈ 5.4) (Figure 8). This demonstrates that composite materials maintain aerodynamic efficiency across various speeds. Furthermore, at 30 m/s, the lift coefficient for

carbon composite is CL = 0.435, while for aluminum it is 0.327, an increase of 33%, which contributes to improved flight stability and maneuverability.

3. A simulation model aimed at enhancing aerodynamic efficiency was developed. Using SolidWorks and ANSYS Fluent environments, the effects of materials and geometry were studied in detail. The CFD results were compared with prototype experiments (Table 4) and literature data, showing strong consistency. For example, carbon plastic showed a vibration level of 0.4 mm and deformation of 1.2%, indicating strong vibroacoustic stability. The developed model also demonstrated that aerodynamic efficiency is preserved even under high-speed conditions (up to 100 m/s).

Overall, the results provide quantitative evidence of the potential of composite materials to improve UAV aerodynamics. A key feature of this study is that the characteristics were not only described qualitatively but also supported with precise formulas, simulations, and experimental data. The developed model is adaptable to practical design and could be applied in the future to improve complex flight platforms.

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