Research Article
Ziraat Mühendisliği (379), 16-24
DOI: 10.33724/zm.1400491

Material and Airfoil-Based Wind Dynamics Analysis for Fixed-Wing Agricultural Unmanned Aerial Vehicles (UAV)

Sabit Kanatlı Tarımsal İnsansız Hava Araçları (İHA) için Malzeme ve Kanat Profili Tabanlı Rüzgâr Dinamiği Analizi

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Abstract

Materials science's high structural stiffness and weight reduction have led to the usage of numerous materials in agricultural unmanned aerial vehicles. So, in the research, the fluid dynamics model for agricultural UAV dynamic structure analysis is studied. The research compares high-performance evaluation outcomes for structurally strong and stiff materials. In analysis and design, both parameters bring unique obstacles. The study optimized design perception for selected material variations to design a wing. Many agricultural UAV airfoils are aerodynamically efficient. Thus, the focus is on optimal material formation based on stress and displacement for each wing airfoil. This study examined the airfoil design results of 500 mm long, 200, 250, and 300 mm wide polystyrene, PVC, and soft wood material airfoils. It is found that the NACA 4412 airfoil with a 200 mm width in PVC material has the maximum static pressure on the X axis (1.141e + 06 dynes) according to airflow direction. Also, it is determined that the NACA 2410 airfoil with a 250 mm width in PVC has the lowest static pressure (2.3104e + 05 dynes).

Keywords: Smart agriculture, UAV, Agricultural Aerodynamic, Material analysis, Durability.

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Gönderilme Tarihi : 05 Aralık 2023
Kabul Tarihi : 24 Nisan 2024

Özet

Malzeme biliminin yüksek yapısal sağlamlığı ve ağırlığın azaltılması, tarımsal insansız hava araçlarında çok sayıda malzemenin kullanılmasına yol açmıştır. Bu nedenle araştırmada tarımsal İHA dinamik yapı analizi için akışkanlar dinamiği modeli çalışılmıştır. Bu araştırma, yapısal olarak güçlü ve sert malzemeler için yüksek performanslı değerlendirme sonuçlarını karşılaştırmaktadır. Analiz ve tasarım, her iki parametre de benzersiz engeller getirmektedir. Çalışma, kanat tasarlamak için seçilen malzeme çeşitlerine göre tasarım algısını optimize etmektedir. Birçok tarımsal İHA kanat profili aerodinamik olarak verimlidir. Bu nedenle, her bir kanat kesiti için gerilme ve yer değiştirmeye dayalı olarak optimum malzeme formuna odaklanılmaktadır. Bu çalışmada 500 mm uzunluğunda, 200, 250 ve 300 mm genişliğinde polistiren, PVC ve yumuşak ahşap kanat profillerinin kesit tasarım sonuçları incelenmiştir. PVC malzemeden 200 mm genişliğe sahip NACA 4412 kanat profilinin, hava akış yönüne göre X ekseni üzerinde (1.141e + 06 dyne) maksimum statik basınca sahip olduğu bulunmuştur. Ayrıca PVC'den yapılmış 250 mm genişliğe sahip NACA 2410 kanat profili en düşük statik basınca (2.3104e + 05 dyne) sahip olduğu belirlenmiştir.

Anahtar Kelimeler: Akıllı tarım, Tarımsal İHA, Aerodinamik tasarım, Malzeme analizi, Dayanıklılık.

Introduction

Unmanned Aerial Vehicle (UAV) is the name given to aircraft that do not have a pilot on them in general (Devi & Avvari, 2022). The operator uses aerodynamic forces to lift the vehicle (Luo et al., 2022). The UAV can fly autonomously or be remotely controlled. The use of UAVs in agriculture is considered a wide application in the agricultural fields. With many failures and few successful designs in this field, people's knowledge of UAVs has been formed and continues to develop (El Adawy et al., 2023). Unmanned aerial vehicles for agricultural purposes in this context have proven their capabilities and have demonstrated their success in many fields by improving their skills with various applications for a long time and performing ever-changing tasks.

UAVs used in the agricultural field offer a special set of advantages such as smaller, safer, and lighter platforms. In addition, it is expected that UAVs in the future will perform much longer missions and exhibit higher aerodynamic performance, and higher degrees of automatic flight capabilities. Among the agricultural UAVs, which have very different design features, fixed-wing unmanned aerial vehicles exhibit flight characteristics such as high speed, long-range, and durability in various agricultural applications with a decrease in aerodynamic performance. A fixed-wing type will be preferred if durability is the priority in UAVs for agricultural purposes. The reason for this idea is flight efficiency, as can be clearly understood. An initial design step is essential for selecting a suitable airfoil for an agricultural UAV. The primary objective of this aerodynamic design is to choose an optimal propulsion system. This system should aim to minimize air resistance and generate ample lift, ensuring simple and efficient flight dynamics (Çetinsoy et al., 2012). The most critical factors in selecting an airfoil for UAVs are flight speed and take-off distance. To guarantee optimal performance, it is essential to conduct thorough testing of airfoils against these parameters.

In this computer-aided research application, Autodesk Inventor (used within the scope of Autodesk education license) models of fixed-wing UAV airfoils of agricultural unmanned aerial vehicles were examined and Autodesk CFD (used within the scope of Autodesk education license), performance analyses of wings with different airfoil characteristics and materials, as well as evaluations in terms of durability were carried out.

Materials and Methods

Material

The conceptual design step compares UAV designs to find the most efficient structure. El Adawy et al. (2023) studied the design and production of a fixed-wing unmanned aerial vehicle and noted that software may select airfoils.

Due to its focus on commercial agricultural UAVs, this study chose wing widths accordingly. Therefore, agricultural UAV airfoils were selected as NACA2410, NACA 4412, and NACA 23012. Because of their ubiquitous use in UAV building, polystyrene, PVC, and wood were evaluated.

Modern materials science has led to the widespread use of diverse materials in agricultural UAV design because of their high structural rigidity and weight reduction (Basri et al., 2019). Wood is ideal for agricultural drones due to its high axial compressive and tensile strength, strength-to-weight ratio, ease of usage, building, and repair. The wood's inhomogeneity, anisotropy, and moisture reactivity can offset biological drawbacks. Thus, synthetics have replaced wood (Lukowsky & Gohla, 2022). Polystyrene and PVC were also considered airfoil materials due to their extensive use. Airfoils are important structural components for agricultural UAVs (Figure 1). That is, the finite element approach of numerical solutions exposed to evaluations can forecast physical states under external effects in the structure of the wing design of unmanned aerial vehicles for agricultural use (Mehta & Joshi, 2016).

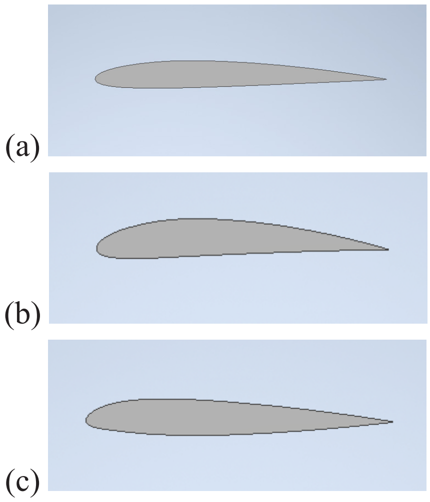

Figure 1. NACA 2410 (a), NACA 4412 (b), NACA 23012 (c) airfoils

Method

This research focuses on developing a viable UAV design approach. A thorough assessment of the design approach and process has three parts. The UAV design strategy involves conceptual, preliminary, and detailed phases. The conceptual design provides a distinct design from basic thoughts. It clarifies the path and whether to move to preliminary design, which involves a reliable assessment of performance, prognosis, and market capability, including cost. Preliminary design identifies weaknesses and proposes elegant solutions to build a flying prototype. The detailed design phase transforms the preliminary design into a tangible design. In this way, it is possible to create a design that can be manufactured and flown (Dündar et al., 2020). Kaya et al., (2018) reviewed geometric and aerodynamic elements that can be made calculations by considering the size and surface areas of the wings. While sizing, designing, and analyzing studies of agricultural unmanned aerial vehicles that are carried out, commercial agricultural unmanned aerial vehicle samples produced primarily in the world are examined. For this purpose, a UAV wing is to be dimensioned geometrically, first; the models of unmanned aerial vehicles that are currently sold have been examined and their wing length has been accepted as 500 mm and their wing widths as 200, 250, and 300 mm.

So, Figure 2 shows an Autodesk Inventor wing section design. This professional 3D CAD application has advanced mechanical design, documentation, and product simulation capabilities. Autodesk Inventor is used in engineering, design, manufacturing, and machine and mechanical part design for 3D modeling, prototyping, and product design. Modeling the wings used design knowledge from similar UAV systems. The Excel document from the Airfoil tools website for the provided dimension values was used to determine the geometric points of the models, which were assembled in Autodesk Inventor. Based on wing length, modeling was done for simulation.

After that, to calculate the surface pressure and shear values depending on the wing material in different axes, which are critical performance parameters, the wing sizing and properties based on the surface structure were analyzed with Autodesk CFD (Computational Fluid Dynamics), and the results were explained and interpreted in the results section. Computational fluid dynamics analysis software Autodesk CFD predicts liquid and gas performance under specified conditions. Using Autodesk CFD for analysis increases efficiency. In CFD, problems and fluid behavior are solved and analyzed on the computer with numerical methods and algorithms, so the results of this analysis method in the research on the airfoil of a UAV that can be used for agriculture are crucial for pre-manufacturing development processes.

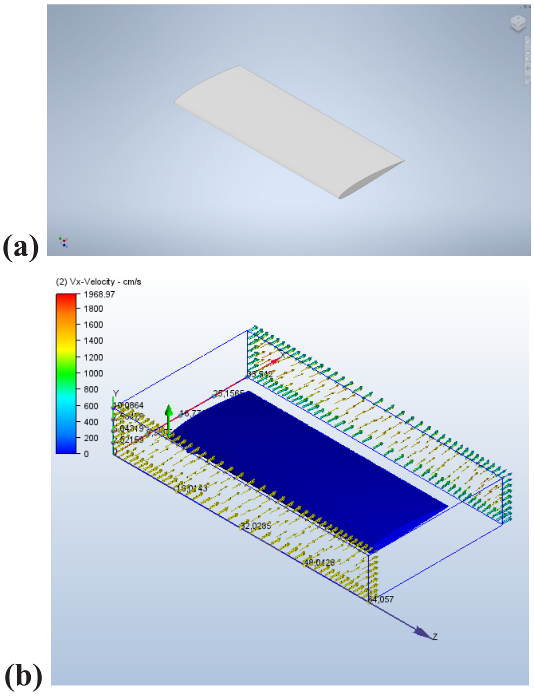

Figure 2. Design (a) and airflow direction (b) example of NACA2410 wing cross-section

Results and Discussion

In this study on the optimum material formation based on stress and displacement for each wing section, the cross-sectional design results on the edge of NACA2410, NACA 4412, and NACA 23012 airfoils with widths of 200, 250, and 300 mm, made of polystyrene, PVC, and soft wood, are shown in Figures 3–11 and Tables 1–9. The NACA 4412 airfoil with a 200 mm width in PVC material has the maximum static pressure on the X axis (1.141e + 06 dynes) according to airflow direction. The NACA 2410 airfoil with a 250 mm width in PVC has the lowest static pressure (2.3104e + 05 dynes).

Different airfoil sizes have been studied in the literature. In their work on the design and construction of a four-slope wing UAV, Çetinsoy et al. (2012) examined the relationship between UAV airfoil and speed. After extensive simulations, they found that the 25 cm wide NACA 2410 airfoil for 40 km/h airspeed is ideal for production. Again, El Adawy et al. (2023) evaluated the NACA 4412 airfoil for an empty weight of 15.43 Ibs, a wingspan of 70.1 inches, and a maximum speed of 78 ft/s in the design and manufacture of a fixed-wing unmanned aerial vehicle and chose it as the best final profile. In their design and performance investigation of the fixed-wing battery VTOL UAV. Dündar et al. (2020) found that the NACA 63-512 airfoil distributed surface pressure better than the other airfoil types which they analyzed.

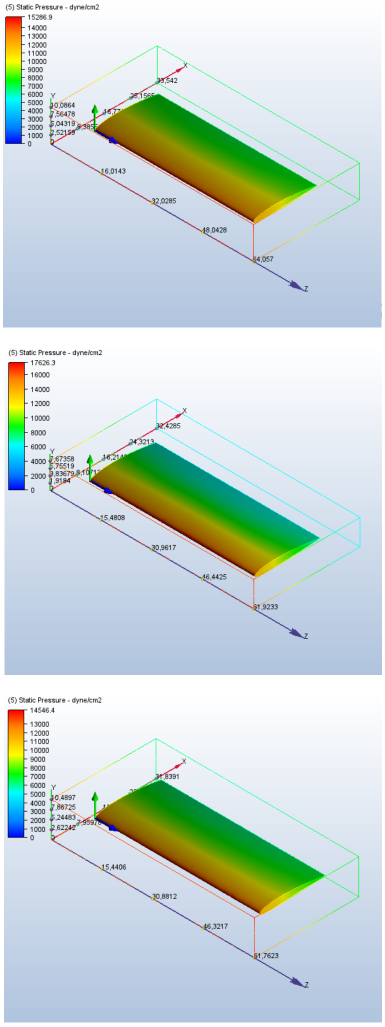

Figure 3. NACA 2410 – 200 mm polystyrene (top left), PVC (top right), wood (soft) (bottom) material static pressure results

Table 1. NACA 2410 – 200 mm wing static pressure results

Material	Direction	Shear (Dynes)	Press (Dynes)
Polystyrene	X	8.1845e+05	4.9912e+05
Polystyrene	Y	968.35	34823
Polystyrene	Z	-6392	57791
PVC	X	8.333e+05	7.3465e+05
PVC	Y	1041	15420
PVC	Z	-11053	70423
Wood (Soft)	X	8.2203e+05	4.9917e+05
Wood (Soft)	Y	420.46	-22466
Wood (Soft)	Z	-8910.1	95000

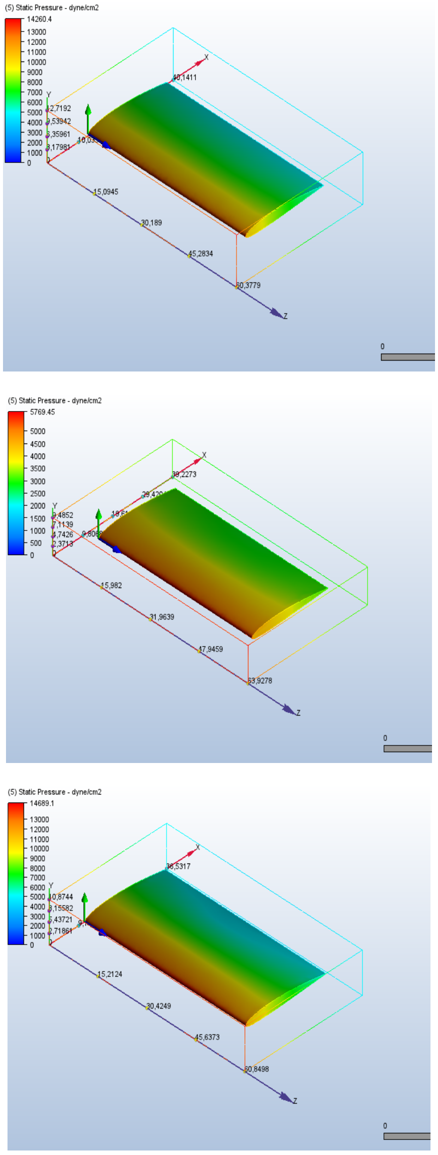

Figure 4. NACA 2410 – 250 mm polystyrene (top left), PVC (top right), wood (soft) (bottom) material static pressure results

Table 2. NACA 2410 – 250 mm wing static pressure results

Material	Direction	Shear (Dynes)	Press (Dynes)
Polystyrene	X	1.0463e+06	6.7413e+05
Polystyrene	Y	184.53	-34227
Polystyrene	Z	-897.57	-1694.7
PVC	X	2.9844e+05	2.3104e+05
PVC	Y	134.45	3090.8
PVC	Z	-1083.6	2588.4
Wood (Soft)	X	1.0141e+06	7.8849e+05
Wood (Soft)	Y	-569.91	737.57
Wood (Soft)	Z	3519.4	-38947

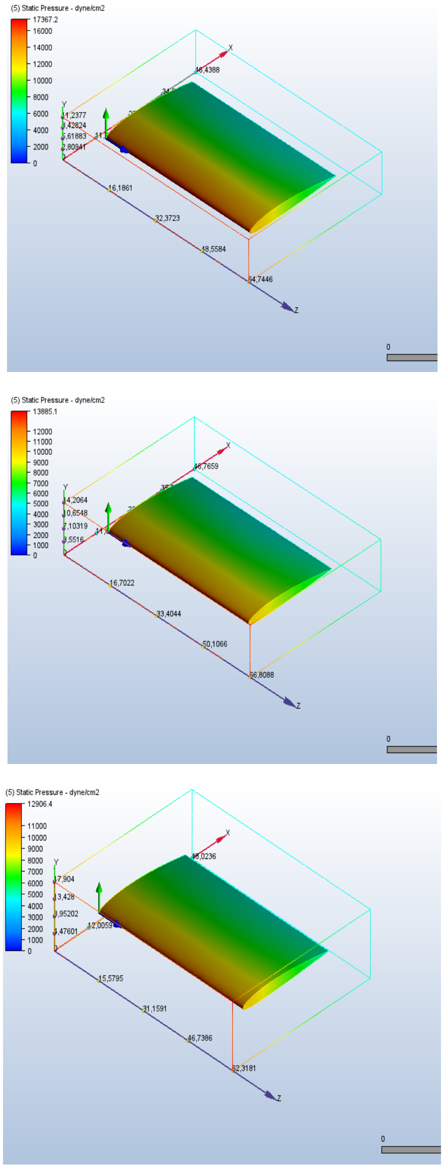

Figure 5. NACA 2410 – 300 mm polystyrene (top left), PVC (top right), wood (soft) (bottom) material static pressure results

Table 3. NACA 2410 – 300 mm wing static pressure results

Material	Direction	Shear (Dynes)	Press (Dynes)
Polystyrene	X	1.235e+06	1.0817e+06
Polystyrene	Y	516.82	-23423
Polystyrene	Z	8313.3	-56504
PVC	X	1.1992e+06	7.7691e+05
PVC	Y	2043.3	15378
PVC	Z	2432	43595
Wood (Soft)	X	1.2375e+06	6.6674e+05
Wood (Soft)	Y	355.47	-1053.3
Wood (Soft)	Z	-3680.1	12770

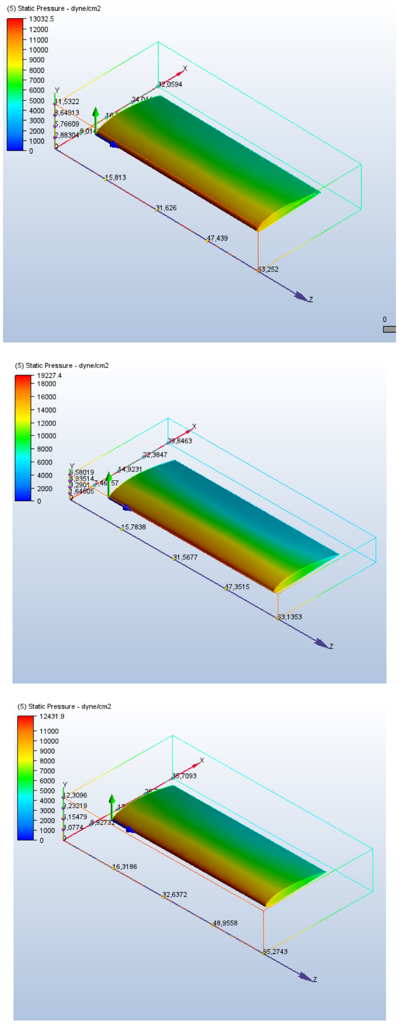

Figure 6. NACA 4412 – 200 mm polystyrene (top left), PVC (top right), wood (soft) (bottom) material static pressure results

Table 4. NACA 4412 – 200 mm wing static pressure results

Material	Direction	Shear (Dynes)	Press (Dynes)
Polystyrene	X	8.0748e+05	5.9777e+05
Polystyrene	Y	2023.1	-21170
Polystyrene	Z	-5060.9	37447
PVC	X	7.4796e+05	1.141e+06
PVC	Y	3400.6	57646
PVC	Z	-8494.7	51928
Wood (Soft)	X	8.4165e+05	6.0371e+05
Wood (Soft)	Y	715.3	-27739
Wood (Soft)	Z	-2864.3	8987.5

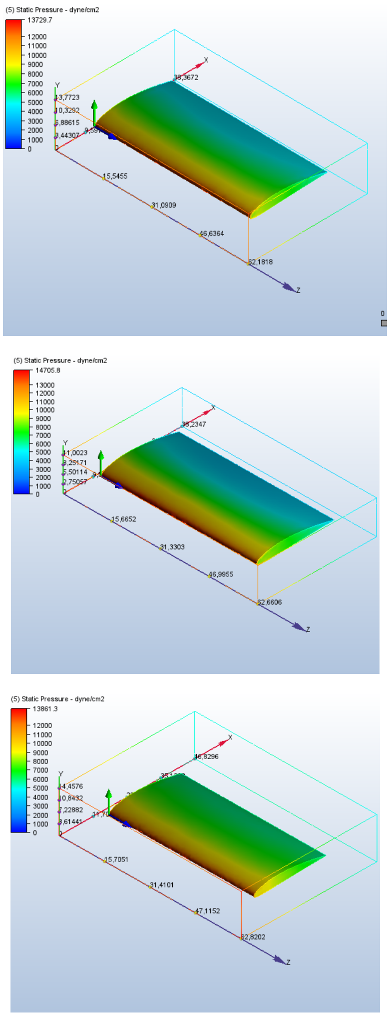

Figure 7. NACA 4412 – 250 mm polystyrene (top left), PVC (top right), wood (soft) (bottom) material static pressure results

Table 5. NACA 4412 – 250 mm wing static pressure results

Material	Direction	Shear (Dynes)	Press (Dynes)
Polystyrene	X	1.0441e+06	8.5364e+05
Polystyrene	Y	4551.2	-30796
Polystyrene	Z	3717	27917
PVC	X	1.0444e+06	1.0459e+06
PVC	Y	3655.2	8546.9
PVC	Z	14918	-54919
Wood (Soft)	X	1.0357e+06	7.1792e+05
Wood (Soft)	Y	3809.9	-14452
Wood (Soft)	Z	1722.9	-21919

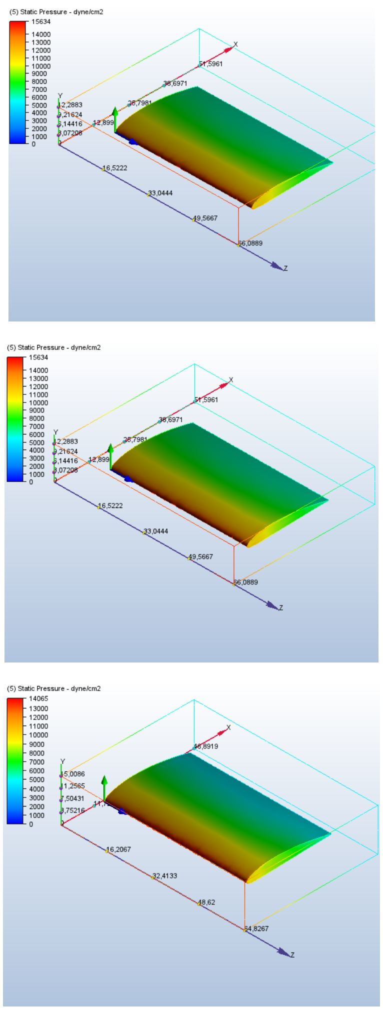

Figure 8. NACA 4412 – 300 mm polystyrene (top left), PVC (top right), wood (soft) (bottom) material static pressure results

Table 6. NACA 4412 – 300 mm wing static pressure results

Material	Direction	Shear (Dynes)	Press (Dynes)
Polystyrene	X	1.1479e+06	1.1221e+06
Polystyrene	Y	4764.3	13682
Polystyrene	Z	-2073.5	-33382
PVC	X	1.1479e+06	1.1221e+06
PVC	Y	4764.4	13682
PVC	Z	-2073.5	-33382
Wood (Soft)	X	1.2625e+06	1.1214e+06
Wood (Soft)	Y	2232.9	-40913
Wood (Soft)	Z	6638.4	-38681

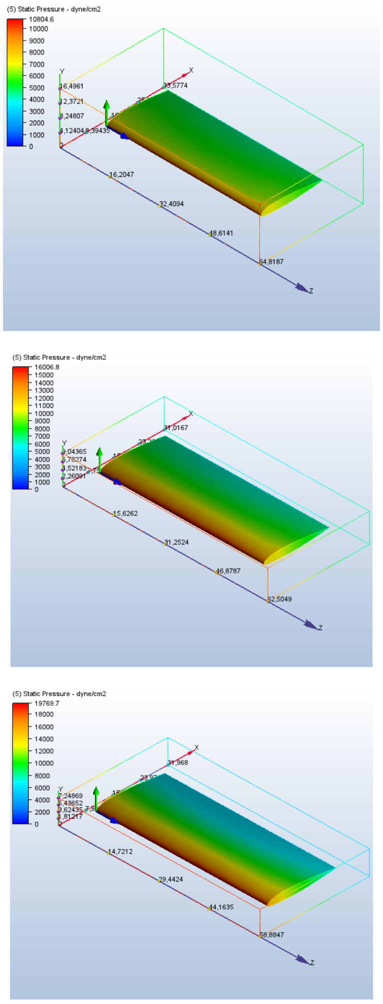

Figure 9. NACA 23012 – 200 mm polystyrene (top left), PVC (top right), wood (soft) (bottom) material static pressure results

Table 7. NACA 23012 – 200 mm wing static pressure results

Material	Direction	Shear (Dynes)	Press (Dynes)
Polystyrene	X	8.0772e+05	3.7842e+05
Polystyrene	Y	6451.7	49361
Polystyrene	Z	-3202.1	1829.9
PVC	X	8.4436e+05	7.7763e+05
PVC	Y	4529.8	14814
PVC	Z	-848.48	30194
Wood (Soft)	X	8.6565e+05	1.1401e+06
Wood (Soft)	Y	6251	73020
Wood (Soft)	Z	-77.053	11539

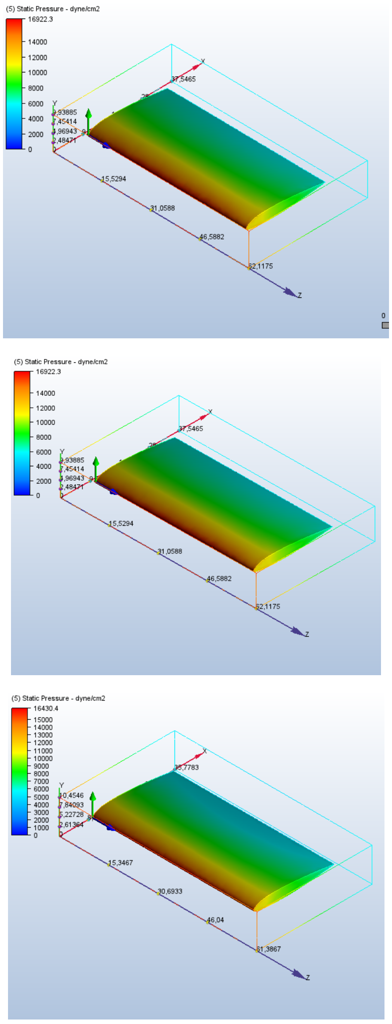

Figure 10. NACA 23012 – 250 mm polystyrene (top left), PVC (top right), wood (soft) (bottom) material static pressure results

Table 8. NACA 23012 – 250 mm wing static pressure results

Material	Direction	Shear (Dynes)	Press (Dynes)
Polystyrene	X	1.0597e+06	1.0802e+06
Polystyrene	Y	5321.9	14220
Polystyrene	Z	916.9	724.5
PVC	X	1.0597e+06	1.0802e+06
PVC	Y	5321.9	14220
PVC	Z	916.88	724.96
Wood (Soft)	X	1.0765e+06	1.1139e+06
Wood (Soft)	Y	7586.1	28065
Wood (Soft)	Z	12334	-34362

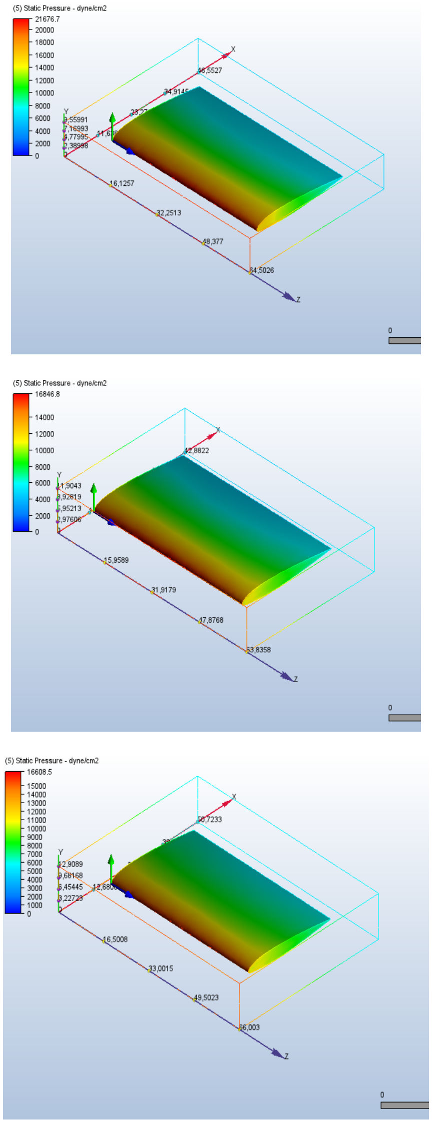

Figure 11. NACA 23012 – 300 mm polystyrene (top left), PVC (top right), wood (soft) (bottom) material static pressure results

Table 9. NACA 23012 – 300 mm wing static pressure results

Material	Direction	Shear (Dynes)	Press (Dynes)
Polystyrene	X	1.311e+06	1.9075e+06
Polystyrene	Y	8060.6	62809
Polystyrene	Z	-8049.5	49167
PVC	X	1.2903e+06	1.4514e+06
PVC	Y	7920.2	-15093
PVC	Z	9843.3	44364
Wood (Soft)	X	1.2789e+06	1.2098e+06
Wood (Soft)	Y	5751.1	-26483
Wood (Soft)	Z	12544	-1.1602e+05

Conclusions

The research optimizes the aerodynamic design of a horizontal-flying UAV using CAD models. Such innovations are usually tested through simulations and flying tests before mass production. Only simulations were done in this study, not flying test verifications, but future research may include flight test controls.

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