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Camber Morphing Wing Design and Aerodynamic Analysis for Fixed Wing UAV

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Abstract: This paper presents the design, development, and aerodynamic analysis of a camber morphing wing for fixed-wing UAV applications. A compliant trailing-edge mechanism was designed and improved through five structural design iterations to achieve smooth and continuous camber change without creating surface discontinuities. The final optimized model was manufactured using Thermoplastic Polyurethane (TPU) through Fused Deposition Modelling (FDM) and achieved trailing-edge deflections of up to 30°. Aerodynamic performance was studied using two-dimensional analysis in XFLR5 and three-dimensional steady-state CFD simulations at a Reynolds number of approximately 3×10^5. The morphing wing was compared with a conventional hinged flap configuration. Results showed that the morphing wing achieved an 8.7% increase in lift coefficient, a 5.6% reduction in drag coefficient, and a 15.1% improvement in lift-to-drag ratio. These findings indicate that camber morphing provides significant aerodynamic advantages over traditional flap mechanisms for low-speed UAV applications.

Keywords: Morphing wing, camber morphing, compliant mechanism, UAV, CFD, XFLR5, aerodynamic efficiency, TPU,PLA

I. INTRODUCTION

Conventional aircraft use control surfaces such as flaps and ailerons that are connected using hinges. These create sudden changes in the wing shape, which disturb the airflow. As a result, boundary layer separation increases, leading to higher drag and lower aerodynamic efficiency.

Morphing wings, inspired by bird flight, provide an alternative approach. In this concept, the wing shape changes smoothly according to flight conditions. This allows better aerodynamic performance without creating sudden surface discontinuities. Camber morphing is a type of morphing in which the curvature of the airfoil changes smoothly. This helps improve lift generation while maintaining smooth airflow over the wing surface. It also improves efficiency, increases the operating range of the UAV, and helps in reducing the effect of gust loads. This approach aligns with the broader objectives of morphing technology identified by Tavares et al. [1], who note that morphing primarily targets maximizing aerodynamic efficiency across all flight phases and enabling a single platform to perform multiple mission profiles that would otherwise require different specialized aircraft

However, designing a practical morphing mechanism is challenging. It requires a balance between flexibility (to allow deformation) and strength (to withstand aerodynamic loads)[2][3]. This has led to research in compliant mechanisms and the use of flexible materials. In this paper, a camber morphing mechanism is designed and analysed for a fixed-wing trainer UAV.

The study includes six design iterations, material selection, and aerodynamic evaluation using XFLR5 and three-dimensional CFD. The main objective is to compare the aerodynamic performance of a morphing wing with a conventional hinged flap under low Reynolds number conditions, which are typical for small UAVs [4].

II. LITERATURE REVIEW

The concept of changing aircraft shape during flight has been studied for many years. Barbarino et al [5]. classified morphing aircraft into different types, such as changes in wing shape, structure, and airfoil profile. Their study showed that camber morphing is one of the most effective and practical methods, especially for low-speed aircraft. Weisshaar also explained that adaptive and multifunctional structures are highly useful for UAVs operating under different flight conditions [6].

Kan et al. (2020) used CFD with dynamic mesh techniques to study the aerodynamic performance of a morphing wing with a flexible leading-edge based on a NACA 0012 airfoil. Their findings showed that downward leading edge deflection delayed stall onset, while unsteady aerodynamic behavior was highly dependent on deflection frequency and angle of attack [7]. Gandhi and Anusonti Inthra studied the design of wing skins for morphing airfoils. Their work showed that proper skin stiffness is important to ensure smooth deformation without wrinkles or unwanted shape changes [8].

Majid and Jo reviewed the challenges in implementing camber morphing systems. They identified structural fatigue, skin material selection, and actuator integration as the main issues [3]. Gong et al. showed that special structures with zero Poisson's ratio are suitable for morphing skins because they can deform without unwanted side effects [9].

Overall, previous research confirms that camber morphing improves aerodynamic performance compared to traditional flap systems, especially at low Reynolds numbers. However, most studies focus on either structural design or aerodynamic analysis separately.

The present work combines both aspects into a single study.

The main contributions of this paper are:

1) a structured six-iterated design process with clear identification of failure modes at each stage;
2) optimization of material and geometry using TPU to achieve 30° smooth deflection without structural failure;
3) aerodynamic validation using both XFLR5 (2D) and CFD (3D) methods; and
4) a direct comparison with a hinged flap configuration, showing improvements in lift, drag, and efficiency.

III. MORPHING MECHANISM DESIGN

The wing is divided into two main parts. The front section is rigid and maintains the aerodynamic shape of the airfoil. It also supports the actuation system, which includes a servo motor. The rear section is designed to deform when actuated, allowing controlled change in the trailing-edge camber.

The trailing-edge mechanism was designed to maintain surface continuity during deflection, consistent with findings by Kan et al. [7], who demonstrated that smooth leading-edge morphing reduces negative pressure gradients and delays flow separation. The selection of TPU as the skin material was guided by the dual requirement of deforming under low actuation forces while simultaneously resisting aerodynamic pressure loads [10], The six design iterations carried out in this study reflect the broader challenge identified by Majid and Jo [3], that achieving effective camber morphing requires balancing the competing demands of structural stiffness and morphing flexibility.

A. UAV Configuration

The UAV used in this study is a conventional fixed-wing trainer-type aircraft. It is designed mainly for stability and aerodynamic testing. A high-wing configuration is selected because it provides better stability and control.

The wing has a rectangular planform with a wingspan of 40 inches. This shape is chosen because it is easy to manufacture and provides predictable aerodynamic behavior. It also offers enough space to integrate the morphing mechanism.

B. Design Iterations

To achieve an effective morphing mechanism, five different design iterations were developed and tested.

1) Iteration 1: Razorback Configuration

The first design used a Razorback-type trailing-edge structure made from TPU using FDM 3D printing. In this design, only the trailing edge deforms while the rest of the airfoil remains rigid.

This behavior was similar to a normal hinged flap rather than a true morphing surface. The change in camber was very small, so aerodynamic improvement was limited. Therefore, this design was not suitable.

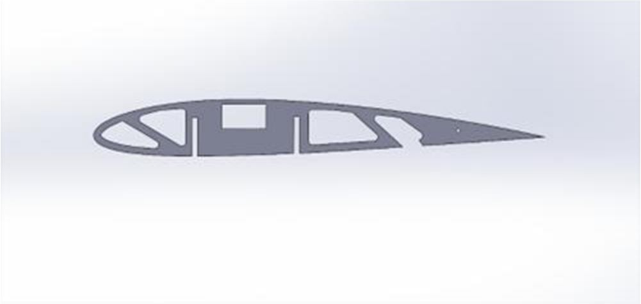

Fig. 1. Razorback configuration trailing-edge structure — Iteration 1.

2) Iteration 2: Serpentine (Sinusoidal) Structure

The second design introduced a sinusoidal internal structure to increase flexibility. This design allowed deformation to spread along the trailing edge instead of concentrating at one point.

Although flexibility improved, the structure showed unwanted deformation in other directions. Some of the servo input was lost in lateral deformation, reducing the effectiveness of camber change.

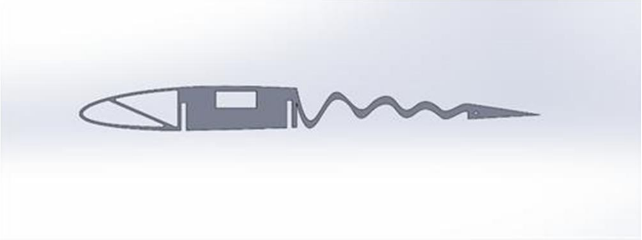

Fig. 2. Serpentine (sinusoidal) trailing-edge structure — Iteration 2

3) Iteration 3: Fishbone Structure

The third design used a fishbone structure with a central spine and ribs connected to the upper and lower surfaces. This design aimed to improve load distribution and control deformation.

While load distribution improved, the structure was weak at the rib joints. At higher deflections, stress concentration caused failure at these joints [11].

Aeroelastic studies of the FishBAC concept, which demonstrated that positioning the morphing region closer to the trailing edge maximizes lift coefficient for a given actuation force while minimizing the risk of aeroelastic instability [12].

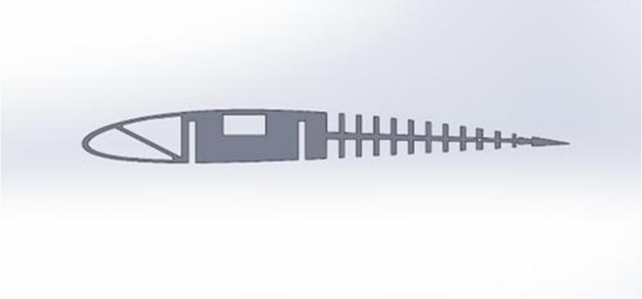

Fig. 3. Fishbone internal structure — Iteration 3.

4) Iteration 4: Slit-Stem Compliant Structure

The fourth design used a slit-and-stem pattern. This structure allowed smooth deformation by distributing strain across the material instead of concentrating it.

This design showed the best morphing performance among all iterations. However, the thin stems were weak and developed cracks under repeated loading. It also created difficulties during manufacturing.

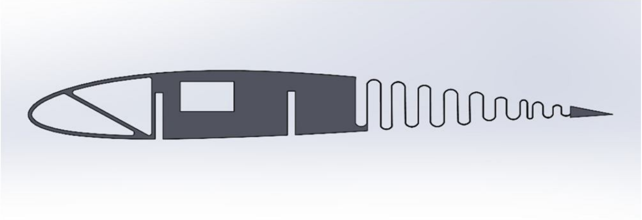

Fig. 4. Slit-stem compliant trailing-edge structure — Iteration 4.

5) Iteration 5: Rigid Rib-Reinforced Structure

The fifth design used a rigid rib structure made from PLA. This provided high strength and stability compared to previous designs.

However, due to high stiffness, the structure could not deform effectively. This showed that a balance between flexibility and strength is necessary for morphing.

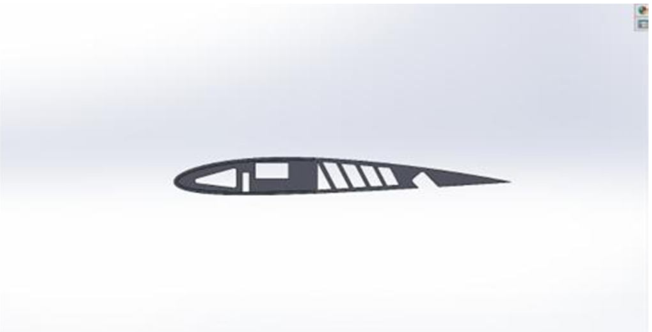

Fig. 5. Rigid rib-reinforced structure — Iteration 5.

C. Final Optimized Design

After evaluating all five design iterations, we designed a wing that combines the aerodynamic and structural lessons we learned in previous iterations. The design features a flexible trailing-edge structure that can bend up to 30 degrees which uses TPU and PLA [2]. The continuous and gradual camber is achieved across the chord. The airfoil has a total chord length of 227.53 mm and a maximum thickness of 13 mm. It also includes an internal flexible mechanism that spans 22 mm in the chordwise direction, with a 3 mm slot for the actuator interface. To further improve morphing performance, a slit is added along the lower surface of the trailing edge. This slit reduces internal resistance during actuation, allowing for smoother and more controlled camber deflection than the previous closed section design [2]. This change enables quicker morphing behaviour while keeping the shape of the upper aerodynamic surface intact. This ensures that pressure gradients and boundary layer development remain undisturbed during deflection. We confirmed that this design update maintains structural integrity under operational loads while enhancing actuation efficiency, making it the preferred choice for both experimental and computational testing.

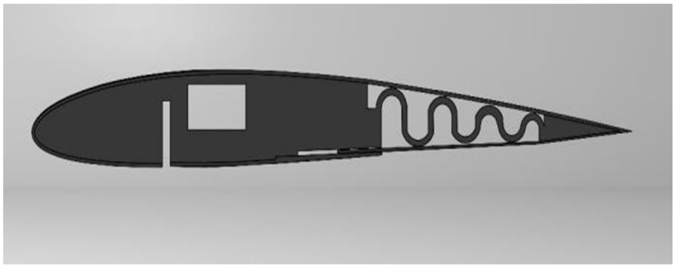

Fig. 6. Recambering compliant system structure — Iteration 6.

IV. AERODYNAMIC ANALYSIS

The wing is divided into two main parts. The front section is rigid and maintains the aerodynamic shape of the airfoil. It also supports the actuation system, which includes a servo motor. The rear section is designed to deform when actuated, allowing controlled change in the trailing-edge camber.

The aerodynamic performance of the camber morphing wing was studied using two levels of analysis:

1) two-dimensional airfoil analysis using XFLR5, and
2) three-dimensional CFD simulations.

The aim was to understand how camber change affects lift, drag, and overall efficiency under low Reynolds number conditions with use of XFLR5 and CFD for evaluating camber morphing performance follows the validated methodology adopted by Kumar et al. [4] for SUAV applications.

A. Two-Dimensional Analysis (XFLR5)

The airfoil used for analysis was NACA 2412 at a Reynolds number of 3×10^5.

Four configurations were studied:

1) baseline NACA 2412,
2) NACA 2412 with 15° hinged flap, (3) camber morphing at 15°, and (4) camber morphing at 20°.

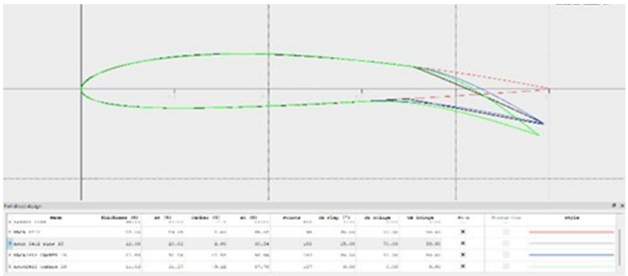

Fig. 8. Airfoil configurations analysed in XFLR5

The aerodynamic performance of the different airfoil configurations is further analysed using coefficient plots obtained from XFLR5. These graphs show the variation of lift coefficient (C_l), drag coefficient (Cd), and lift-to-drag ratio (C_l/Cd) with respect to angle of attack.

By comparing these plots for the baseline airfoil, hinged flap, and camber morphing configurations, the effect of camber modification on aerodynamic behaviour can be clearly understood.

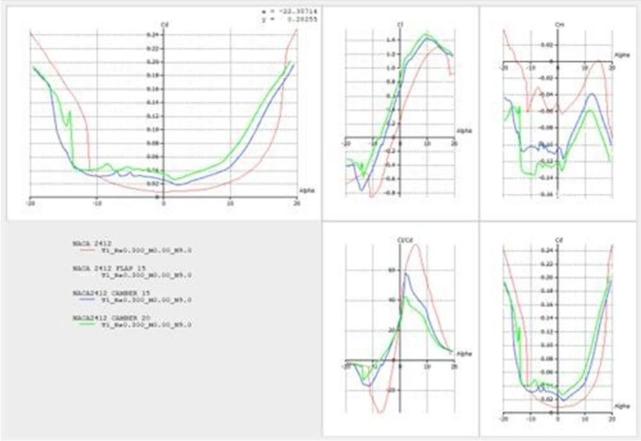

Fig. 9. Aerodynamic coefficient plots from XFLR5 analysis.

1) *Lift Characteristics*

The baseline airfoil shows smooth airflow and moderate lift. The hinged flap creates a sharp change in geometry, which causes early flow separation and earlier stall.

In contrast, the morphing configurations show smooth camber distribution. This results in better pressure distribution and more stable lift generation without sudden stall.

2) *Drag Characteristics*

The hinged flap increases drag due to flow separation near the hinge. This creates a wake region behind the flap.

The morphing wing maintains smooth airflow over the surface. This reduces separation and results in lower drag compared to the flap configuration.

3) *Aerodynamic Efficiency and Pitching Moment*

The morphing wing maintains a higher lift-to-drag ratio over a wider range of conditions.

It also produces a smoother and more predictable pitching moment. In contrast, the hinged flap causes sudden changes in pitching moment due to concentrated pressure at the trailing edge.

B. Three-Dimensional CFD Methodology

1) Geometry Definition

The airfoil data from XFLR5 was used to create a 3D wing model in SolidWorks.

Key dimensions:

Chord length = 0.2286 m
Wingspan = 1.016 m
Wing area ≈ 0.232 m²

Two configurations were analysed:
camber morphing wing
hinged flap (15° deflection)

2) Computational Domain and Mesh

A 3D flow domain was created around the wing. A tetrahedral mesh was used, with finer mesh near the wing and trailing edge to capture flow details.

Parameter	**Morphing**	**Hinged Flap**
Number of cells	~1.99 × 10^6	~6.39 × 10^5
Min. orthogonal quality	0.30	0.043
Max. aspect ratio	11.33	28.63

Table I. Mesh Statistics for CFD Configurations

3) Turbulence Model and Boundary Conditions

The Spalart–Allmaras turbulence model was used because it is suitable for external aerodynamic flows.
Boundary conditions used:
Velocity inlet
Pressure outlet
No-slip wall on wing surface

Flow conditions:
Velocity = 15 m/s
Reynolds number ≈ 3×10^5

4) Numerical Method and Convergence

A steady-state solver with second-order accuracy was used. The solution was considered converged when residuals dropped below 10^{-5} and lift and drag values became stable.
Around 600–700 iterations were required.

C. Three-Dimensional CFD Results

1) Aerodynamic Performance

The morphing wing produced higher lift and lower drag compared to the hinged flap under the same conditions.

Configuration	Lift (N)	Drag (N)	Cl	Cd	L/D
Camber Morphing	25.43	3.01	0.7947	0.0941	8.44
Hinged Flap (15°)	23.40	3.19	0.7310	0.0997	7.33

Table II. Aerodynamic Coefficients — Morphing Vs. Hinged Flap (Cfd Results)

2) *Lift Improvement*

The morphing configuration showed about 8.7% higher lift coefficient.
This is because camber is distributed smoothly along the wing, improving airflow and pressure distribution.

3) *Drag Reduction*

The morphing wing reduced drag by about 5.6%.
This is mainly because it avoids sharp discontinuities, which reduces flow separation.

4) *Aerodynamic Efficiency*

The lift-to-drag ratio improved by about 15.1%.
This means the morphing wing is more efficient and can improve UAV endurance and range.

5) *Flow Behaviour*

The morphing wing showed smooth and attached airflow with a smaller wake region.
The hinged flap showed disturbed flow near the hinge, with signs of separation and a larger wake, indicating higher energy loss.

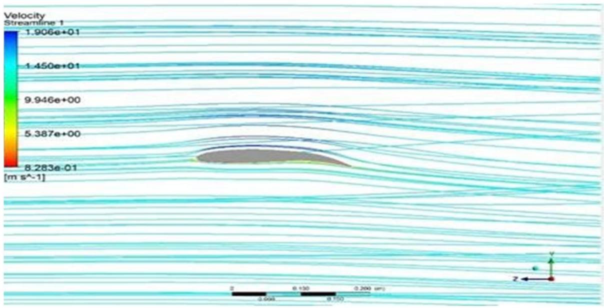

Fig. 10. Velocity streamlines — morphing configuration (15° deflection).

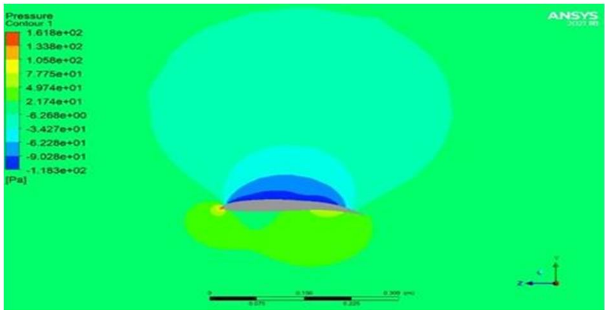

Fig. 11. Pressure contours — morphing configuration (15° deflection).

The hinged flap introduces a discontinuity at the flap junction, producing a low-momentum region and wake thickening downstream of the hinge, indicative of incipient separation and increased viscous dissipation.

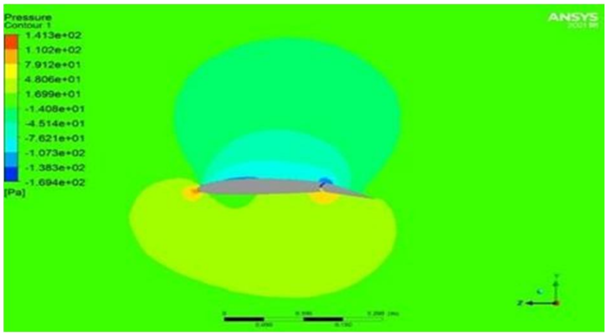

Fig. 12. Pressure contours— hinged flap configuration (15° deflection).

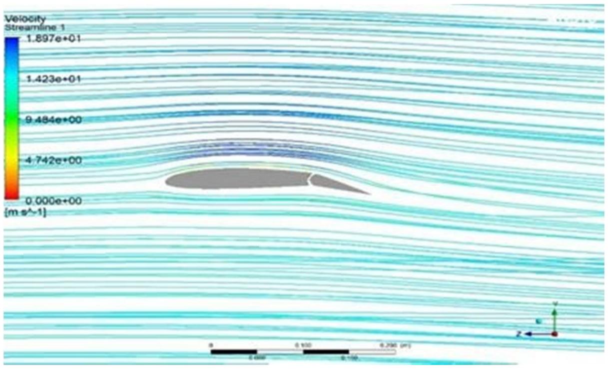

Fig. 13. Velocity streamlines — hinged flap configuration (15° deflection).

V. RESULTS AND DISCUSSIONS

The results obtained from XFLR5 and three-dimensional CFD analysis clearly show that camber morphing provides better aerodynamic performance than a conventional hinged flap under low Reynolds number conditions.

The 8.7% increase in lift coefficient and 5.6% drag reduction at Reynolds number ≈ 3×10^5 observed in this study are consistent with the aerodynamic improvements reported by [7], who found that flexible morphing surfaces outperform conventional rigid configurations in terms of lift-to-drag ratio and stall characteristics. Performance gains become more pronounced as Reynolds number increases within the low Reynolds number regime[4]. These improvements are mainly due to the smooth change in camber along the airfoil, which avoids sudden geometric discontinuities present in hinged flaps. Because of this smooth shape change, the airflow remains attached over the wing surface, reducing energy losses and improving pressure distribution. In contrast, the hinged flap creates a sharp change in geometry, leading to flow separation and higher drag.

The structural challenges encountered in this study, particularly the balance between flexibility and stiffness, are consistent with the broader challenges in morphing wing development reported in the literature [13]. Early designs either lacked sufficient deformation or failed due to structural weaknesses. The final optimized design successfully achieved large deflection while maintaining structural integrity [3]. The observed drag reduction and efficiency improvement are consistent with results reported in previous studies on morphing wings. This confirms that camber morphing is a promising solution for improving UAV performance.

However, the study has some limitations. The CFD analysis was steady-state and did not consider time-dependent effects during morphing. Also, experimental validation using wind tunnel testing was not performed. Another challenge observed was related to the wing skin, as conventional covering materials tended to wrinkle during deformation, affecting surface smoothness.

VI. CONCLUSION AND FUTURE WORK

This study successfully developed and analysed a camber morphing wing for a fixed-wing UAV.

The main conclusions are as follows:

1) A Recambered compliant trailing-edge mechanism made from TPU and PLA was developed through six design iterations, achieving smooth camber variation with deflections up to 30°[2].
2) XFLR5 analysis showed that morphing configurations provide smoother lift curves, reduced flow separation, and better pitching behavior compared to hinged flaps [4].
3) CFD results showed an 8.7% increase in lift coefficient, a 5.6% decrease in drag coefficient, and a 15.1% improvement in lift-to-drag ratio.
4) These improvements are mainly due to the smooth geometry of the morphing wing, which prevents flow separation and improves aerodynamic efficiency.

Future work can focus on the following areas:

a) Experimental validation using wind tunnel testing.
b) Unsteady CFD analysis to study dynamic morphing effects.
c) Integration of the morphing wing into a full UAV for flight testing.
d) Development of adaptive control systems for automatic camber adjustment.
e) Exploration of better materials for wing skin to avoid wrinkling and improve durability. [8]

VII. ACKNOWLEDGMENT

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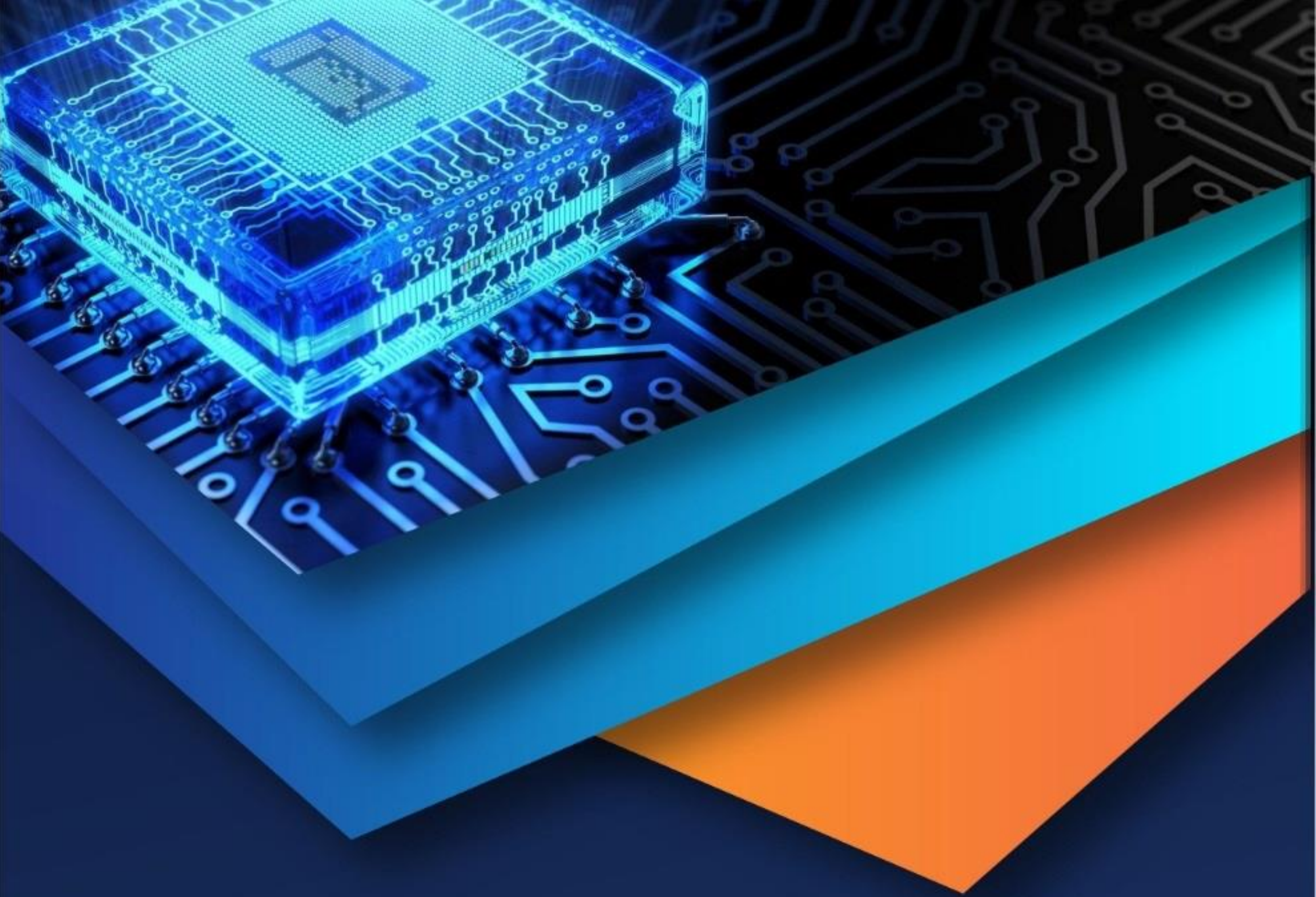

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