Effect of Surface Roughness on Aerodynamic Performance of the Wing with NACA 2412 Airfoil

YAGYA DUTTA DWIVEDI, SAMREEN TABASSUM, SONNAKULA MADHUMITHA, BANOTH KARTHIK
Department of Aeronautical Engineering
Institute of Aeronautical Engineering, Dundigal-500043,
Hyderabad
Telangana,
INDIA

Abstract: - The surface roughness over the wing is one of the primary factors affecting the aerodynamic performance of the airplane. The surface roughness is likely to alter the boundary layer thickness over the wing. This alteration of the boundary layer thickness will alter the lift and drag forces and also the ratio of the lift to drag, which is called aerodynamic performance. In this research paper, the effects of two different roughness values, i.e., 12-grit (0.0015 m), which is coarse, and 320-grit (5×10^{-7} m), which is very smooth and normally used for polishing surfaces, on aerodynamic performance are evaluated and compared with a smooth conventional NACA 2412 airfoil. The surface roughness is applied at 40- 50% of the chord length from the leading edge of the airfoil. The CAD models were prepared as per the roughness, and computational fluid dynamics (CFD) analysis was carried out using Ansys Fluent. The simulations are performed at the chord Reynolds number of 5×10^5 and angles of attack (AOA) of 00, 50, 100, and 150. The results showed that the lift coefficient (CL) increases up to 100 AOA for all three types of roughness, and at 150 AOA the CL falls sharply for both rough surfaces, but the smooth surface provides a better CL. The coefficient of drag (CD) for the 320-grit roughness airfoil was found to be much better than the other two conditions, i.e., the smooth and 12-grit roughness conditions. The fine roughness configuration (320-grit) and conventional smooth surface wing exhibited better aerodynamic performance comparable to the 12-grit roughness (most rough surface) conditions. These surfaces showed improved flow attachment at moderate AOA. On the other hand, the 12-grit coarse roughness configuration resulted in high CD and low CL and hence low aerodynamic performance (CL/CD ratio). The final finding is that the aerodynamic performance for the 320-grit rough surface is best up to 100 AOA, but at higher AOA the smooth conventional surface wing is only suitable.

Key-Words: - NACA 2412 airfoil, Aerodynamic performance, Surface roughness, Boundary layer, Flow separation, Lift-to-Drag ratio, Low-speed aerodynamics, Computational fluid dynamics (CFD)

Received: March 26, 2026. Revised: July 29, 2026. Accepted: August 23, 2026. Available online: November 20, 2026.

1 Introduction

The aerodynamic performance of an airfoil is related to the airfoil lift and drag. The ratio of the lift to drag is known as the aerodynamic performance. The lift is directly related to its airfoil shape, surface roughness, and flow behavior. In the same way, drag is also related to the boundary layer thickness, skin friction, density of the medium, and its wetted area. The boundary layer plays an important role in the generation of drag. The surface roughness generated over the airfoil is surely going to affect the aerodynamic performance [1].

In practical applications, airfoil surfaces are rarely perfectly smooth. Factors such as manufacturing imperfections, environmental exposure, erosion, dust accumulation, and material degradation can introduce surface irregularities that modify the flow field around the airfoil [2]. Surface roughness generally promotes an earlier transition from laminar to turbulent flow, resulting in increased skin-friction drag. However, under certain conditions, roughness can energize the boundary layer and improve its resistance to separation by increasing momentum exchange within the near-wall region [3].

Several studies have examined the influence of angle of attack, Reynolds number, and surface condition on airfoil performance. Previous investigations reported that the aerodynamic characteristics of NACA airfoils are significantly affected by flow transition and separation phenomena, especially at moderate and low

Reynolds numbers [4]. Numerical and experimental studies have also shown that localized roughness can alter pressure distribution and boundary-layer development, thereby influencing lift and drag characteristics [5]. In addition, passive flow-control approaches involving strategically placed roughness elements have demonstrated the potential to delay separation and improve aerodynamic efficiency under specific operating conditions [6]. Nevertheless, excessive roughness often results in increased drag and reduced overall performance [7].

The present study employs Computational Fluid Dynamics (CFD) simulations in ANSYS Fluent to investigate the aerodynamic behavior of a NACA 2412 airfoil subjected to different surface roughness conditions. Localized roughness corresponding to 12-grit and 320-grit configurations was introduced between 40% and 50% of the chord length. Simulations were carried out at angles of attack of 0°, 5°, 10°, and 15° to evaluate variations in lift coefficient, drag coefficient, pressure distribution, and flow-field characteristics. The objective is to assess the influence of roughness magnitude on boundary-layer development and aerodynamic performance under low-speed flow conditions.

2 Methodology

The airfoil NACA 2412 is the baseline airfoil because it has a simple geometry and maintains a favorable lift-to-drag ratio. This airfoil is highly useful in general aviation and is used for Cessna airplanes. It has excellent stall characteristics, a good lift-to-drag ratio, and stability characteristics for training flight. Its numerical profile is so simple to understand that it is used for both aeronautical and aerospace engineering very well.

2.1 Physical parameter

The physical parameters like angle of attack, Reynolds number, Density of the medium, characteristic length, viscosity, and velocity used for the CFD work are given in Table 1.

Table 1. Physical parameters used for investigation
Source: Created by the authors

Parameter	Value
Angle of attack (AOA)	0°, 5°, 10°, 15°
Reynold's Number (Re)	5 x 10^5
Density (ρ)	1.225 kg/m3
Length (L)	100mm
Viscosity (μ)	1.7894 x 10^{-5} kg/ms
Velocity (V)	73 m/s

2.2 Governing Equation

The flow field was simulated in ANSYS Fluent by solving the steady-state incompressible Navier–Stokes and continuity equations using the finite volume approach [8].

2.2.1 Continuity Equation (Steady, Incompressible flow):

The continuity equation used for the CFD simulation is given in Eq. 1, where u and v are the velocity components in the x and y directions

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

2.2.2 Momentum Equation (Navier–Stokes form):

The momentum equation used for this work is given in Eq. 2, where u and v are the velocity components in x and y direction respectively and $\frac{\partial \mathrm{p}}{\partial \mathrm{x}}$ is the pressure gradient in x direction.

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \quad (2)$$

Lift & drag coefficients were determined from the surface pressure and wall shear stress distributions using standard non-dimensional relationships [9].

2.2.3 Lift and Drag Coefficient Formulas:

The equations for the coefficient of lift CL and the coefficient of drag CD are given in Eq. 3 and 4, respectively. Where L is lift, D is drag, v is free-stream velocity, A is planform area, and ρ is the density of the fluid (Air).

$$C_L=\frac{L}{\frac{1}{2}\rho V^2 A} \quad (3)$$

$$C_D=\frac{D}{\frac{1}{2}\rho V^2 A} \quad (4)$$

2.3 Airfoil Geometry and Surface Modeling

The models of all three wings were generated using CATIA V5. In the first case, the model was made smooth without roughness. The second case was taken with 12-grit roughness (which is 0.0015 m); the roughness value Ra = 30- 50 micrometers. Another one is 320 grit roughness, which is very smooth (40-50 micrometers or $5x10^{-7}$ m) [10]. The Grit 12 is 50 to 60 times as coarse as the grit 320. The span of each wing was 150 mm, and the chord was 100 mm (Figure 1).

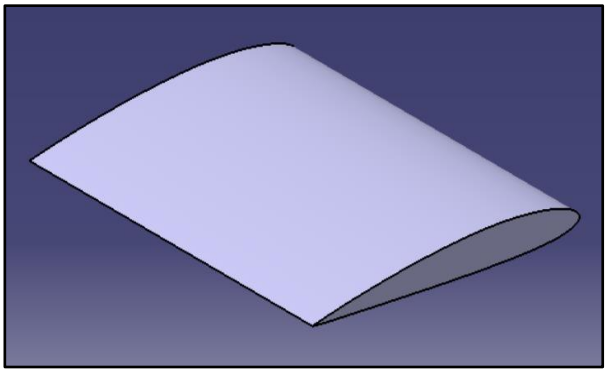


Fig. 1: CAD model of the wing
Source: Created by the authors

The roughness geometry was modeled as discrete surface protrusions distributed over the selected chordwise region. The selected roughness configurations were intended to represent different levels of surface irregularity and their influence on aerodynamic performance under low-speed operating conditions (Figure 2 & 3).

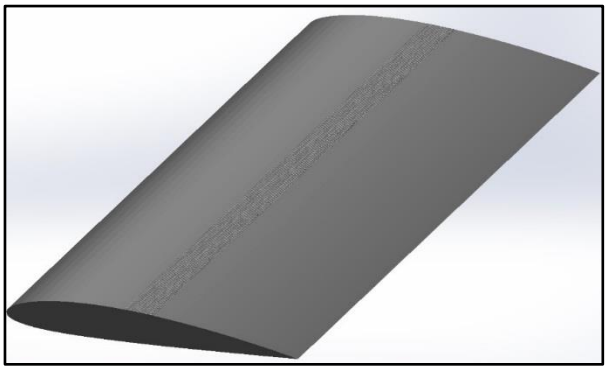


Fig. 2: Airfoil with surface roughness
Source: Created by the authors

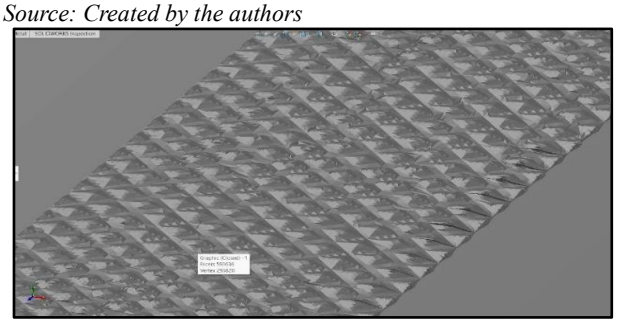


Fig. 3: Zoomed view of surface roughness element
Source: Created by the authors

2.4 Meshing

A structured mesh was used to design a numerical computational domain for the NACA 2412 airfoil, ensuring accurate prediction of aerodynamic properties. CFD simulations were enhanced using C-type computational domains to accurately simulate the flow field around the airfoil. The mesh was further refined near the leading and trailing edges to resolve regions with high pressure gradients and possible flow separation (Figure 4).

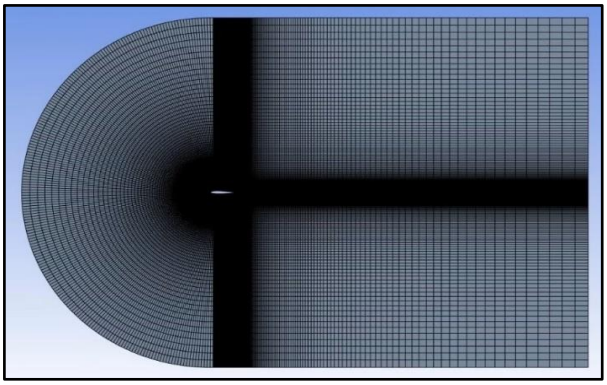


Fig. 4: Meshing domain of NACA 2412 airfoil
Source: Created by the authors

The quality of the mesh was examined using parameters including skewness, orthogonality, and growth rate to ensure accurate numerical solutions and stable flow representation. The final refined mesh satisfied the required quality standards, as presented in Table 2.

Table 2. Mesh quality parameters
Source: Created by the authors

Parameter	Value
Skewness	0.2
Orthogonality	0.99
Aspect Ratio	Close to 1
Wall Distance y^+	<1
Growth Rate	1.2
Inflation Layers	12

2.5 Grid Independence Study

A grid independence analysis was carried out to ensure that the numerical predictions were insensitive to mesh resolution and to assess the effect of mesh quality on solution accuracy. Three different mesh configurations were examined by evaluating the convergence of the lift coefficient at a Reynolds number of 5×10^5.

Grid 1 consisted of a coarse mesh with 80,000 cells. This configuration showed noticeable variations in aerodynamic coefficients due to insufficient near-wall resolution.

Grid 2 employed a fine mesh comprising 2,56,310 cells, incorporating local refinement near the leading and trailing edges. This grid yielded stable aerodynamic predictions with improved numerical convergence.

Grid 3 represented the finest mesh, containing 5,70,261 cells, and produced negligible improvement in accuracy compared to Grid 2. Therefore, Grid 2 was selected for all subsequent simulations, as it provided mesh-independent results while maintaining reasonable computational cost and efficiency (Figure 5).

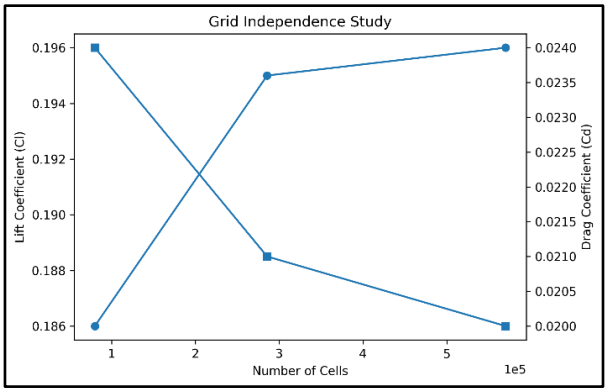


Fig. 5: Grid independence study showing variation of Cl and Cd with mesh quality
Source: Created by the authors

2.6 Boundary Conditions

The numerical domain for this study consists of an inlet boundary, outlet boundary, airfoil surface boundary, and far-field boundary. The initial conditions are set to standard atmospheric pressure (1 atm) and temperature (288 K). The SST k–ω turbulence model was selected because of its capability to predict adverse pressure-gradient flows and near-wall boundary-layer behavior.
The following are the input parameters:

1. Fluid: Air
2. Viscous Model: SST k-ω
3. Reference Area: 0.0015 m^2

3 Results and Discussion

CFD simulations were performed at angles of attack of 0°, 5°, 10°, and 15° to evaluate the aerodynamic performance of the NACA 2412 airfoil under various surface roughness conditions. The variation of aerodynamic coefficients, pressure distributions, velocity characteristics, and flow separation is analyzed for smooth and rough airfoil configurations. The results obtained from the simulations are presented and discussed in the following sections.

3.1 Flow Visualization

Pressure and velocity contour plots obtained from the CFD simulations were used to examine the flow characteristics around the NACA 2412 airfoil for different surface roughness configurations. At lower angles of attack, the flow remained largely attached to the airfoil surface, resulting in a relatively uniform pressure distribution and stable aerodynamic behavior (Figure 6 and Figure 7).

With increasing angle of attack, a pronounced low-pressure region developed over the upper surface of the airfoil, leading to an increase in lift generation. However, the stronger adverse pressure gradient associated with higher angles of attack promoted boundary-layer separation near the trailing edge. The velocity contours further revealed the development of a wake region downstream of the airfoil due to the separated flow (Figure 8 and Figure 9).

Among the roughness configurations considered, the fine roughness surface exhibited improved flow attachment at moderate angles of attack, indicating a beneficial influence on boundary-layer development. In contrast, the coarse roughness configuration generated greater flow disturbances, resulting in increased aerodynamic losses. At an angle of attack of 15°, extensive flow separation was observed for all cases, which contributed to a reduction in aerodynamic efficiency and a corresponding increase in drag (Figure 10 and Figure 11).

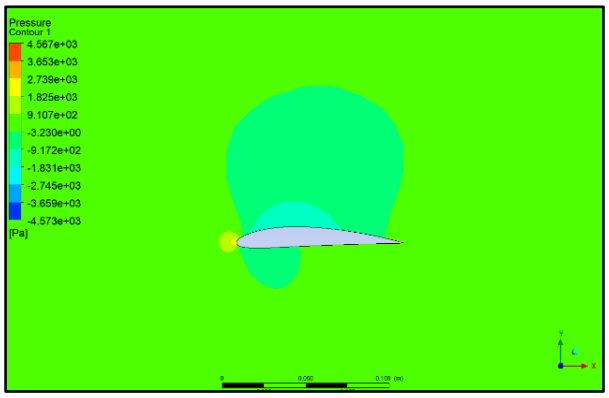


Fig. 6: Pressure contour of the smooth airfoil at 10° AOA
Source: created by the authors.

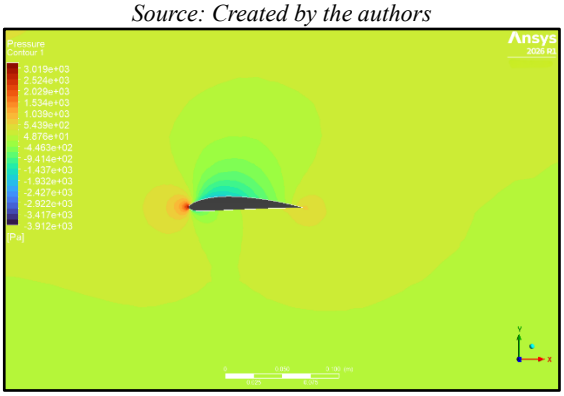


Fig. 7: Pressure contour of the rough airfoil at 10° AOA
Source: Created by the authors

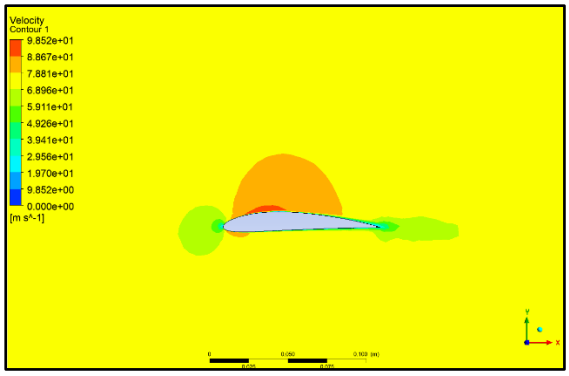


Fig. 8: Velocity contour of the smooth airfoil at 10° AOA

Source: Created by the authors

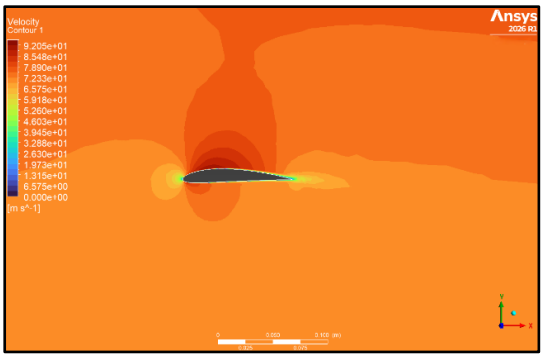


Fig. 9: Velocity contour of the rough airfoil at 10° AOA

Source: Created by the authors

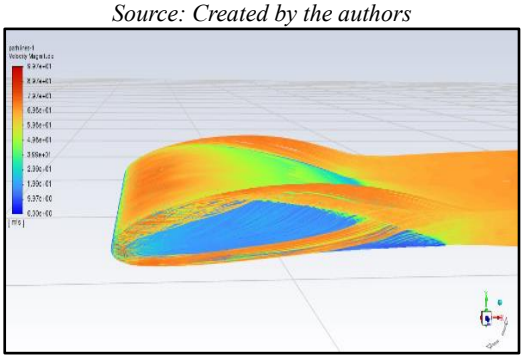


Fig. 10: Velocity pathlines of smooth airfoil at 15° AOA

Source: Created by the authors

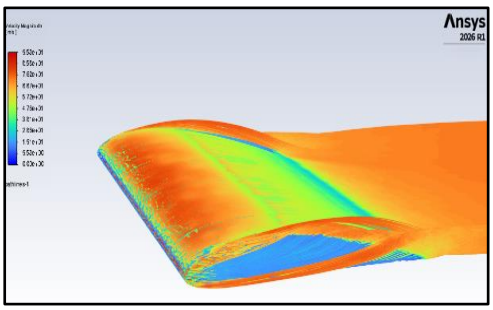


Fig. 11: Velocity pathlines of rough airfoil at 15° AOA

Source: Created by the authors

3.2 Variation of Lift Coefficient (C_l)

The lift coefficient exhibited an increasing trend with angle of attack up to 10°, primarily due to the enhanced pressure differential between the upper and lower surfaces of the airfoil. A decline in lift was observed beyond this point as a result of flow separation over the upper surface. The fine roughness configuration demonstrated marginally improved lift performance at moderate angles of attack, whereas the coarse roughness configuration led to a deterioration in aerodynamic characteristics at higher angles of attack (Figure 12).

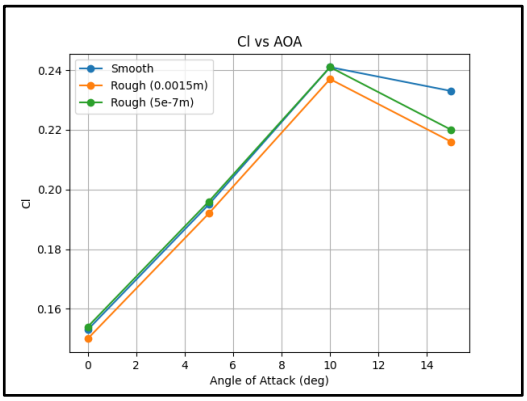


Fig. 12: C_l vs AOA

Source: Created by the authors

3.3 Variation of Drag Coefficient (C_d)

The drag coefficient increased gradually with increasing angle of attack for all surface configurations due to the growth of boundary-layer thickness and flow separation effects. At lower angles of attack, the drag values remained relatively small, whereas higher drag generation was observed at 15° angle of attack because of larger separated flow regions and wake formation. The roughness configurations produced variations in drag characteristics depending on the roughness intensity, with excessive roughness contributing to increased aerodynamic losses (Figure 13).

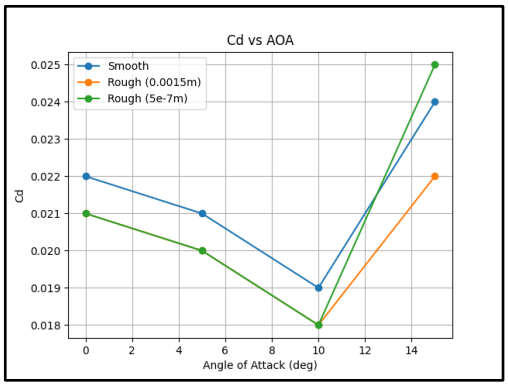


Fig. 13: C_d vs AOA

Source: Created by the authors

3.4 Variation of Coefficient of lift-to-drag ratio (C_l/C_d)

The Coefficient of lift-to-drag ratio (C_l/C_d) is a primary aerodynamic characteristic, which defines the aerodynamic performance or efficiency of any lifting surfaces like airfoils or wings. In this work, we took three different wing roughness conditions: smooth conventional, smooth roughness with 320-grit, and coarse roughness with 12-grit. The AOA chosen for this work are 0^0, 5^0, 10^0, and 15^0 (Figure 14, Table 3). The results as per AOA are enumerated below.

At 0^0 AOA, the C_L/C_D ratio of the 320-grit surface was found to be highest and the smooth conventional airfoil without roughness has the lowest value of this ratio. For AOA 5^0 and 10^0, the same pattern of C_L/C_D ratio exists. At 15^0 AOA, the smooth rough surface, i.e., 320-grit, CL/CD ratio fell sharply by approximately 10% compared to the smooth and 12-grit roughness airfoils.

These results predict that the 320-grit rough surface airfoil is much better suited for AOA below stall. The smooth surface airfoil and coarse roughness 12-grit could be used for the operation of high AOA flights at a given Reynold number of 5×10^5. Both have similar CL/CD ratios at high AOA operation.

Table 3. Results of the aerodynamic characteristics of the NACA 2412 airfoil for various surface roughness configurations

Configuration	AOA	C_l	C_d	C_l/C_d
Smooth	0°	0.153	0.022	6.95
	5°	0.195	0.021	9.28
	10°	0.241	0.019	12.6
	15°	0.233	0.024	9.7
Rough (0.0015m)	0°	0.150	0.021	7.14
	5°	0.192	0.020	9.6
	10°	0.237	0.018	13.1
	15°	0.216	0.022	9.81
Rough (5×10^{-7}m)	0°	0.154	0.021	7.33
	5°	0.196	0.020	9.8
	10°	0.241	0.018	13.3
	15°	0.220	0.025	8.8

Source: Created by the authors

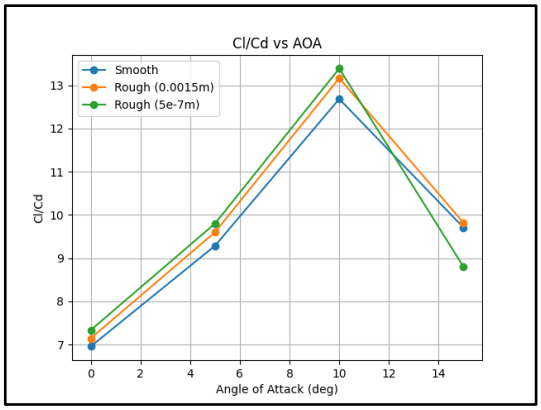


Fig. 14: C_l/C_d vs AOA

Source: Created by the authors

4 Conclusion

The effect of roughness over the wing having an airfoil NACA 2412 was investigated with two roughness conditions, i.e., 12-grit and 320-grit. 12-grit is the roughest one, having a roughness of 0.0015 m, and 320-grit is the smoothest grit, having a roughness of 5×10^{-7} m (50 micrometers). Simulations were performed for both roughness conditions and compared with a smooth airfoil of NACA 2412. The AOA for the tests were **0^0, 5^0, 10^0**, and **15^0** and the Reynolds number was 5×10^5. The roughness was set from 40 to 50% of the chord from the leading edge.

The main conclusions are given below:

1. The coefficient of lift (C_L) values of the 320-grit roughness and smooth airfoil without roughness were found to be almost the same up to 10^0 AOA. The 12-grit roughness airfoil produced 2% less CL than the other two. The smooth airfoil produced more C_L at higher AOA at 15^0. It's due to better boundary layer management at high AOA flows.
2. The coefficient of drag (C_D) values for the 320-grit rough surface was found to be 4-5% lower than the smooth conventional airfoil from 0^0 to 10^0 AOA. Beyond 10^0 AOA, say 15^0 AOA, the smooth conventional airfoil produced 12% less drag than both rough-surfaced airfoils.
3. The aerodynamic performance (C_L/C_D) of both rough-surface airfoils was better than that of the smooth, non-rough airfoil till 0^0 to 10^0 AOA. At high AOA (15^0), the rough surface airfoil (C_L/C_D) drops sharply to 10% compared to the smooth airfoil.

The results showed that the rough surface aerodynamic performance is better at low AOA zone and the rough airfoils may be used for the low angle of attack flight.

Future work may include the effects of surface roughness on the bio-inspired wings from the micro air vehicles. The effects of the roughness at different chord locations may also be studied to find the optimum location of the roughness.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) utilized artificial intelligence (AI) technologies solely for the purpose of linguistic refinement and grammatical correction. Following the application of these tools, the author(s) comprehensively reviewed, verified, and edited the resulting text. The author(s) maintain full accountability and responsibility for the accuracy, integrity, and final content of the publication.

References:

[1] Adiwibowo, P. H., Purwanto, A., Rasyid, A. H. A., & Saepuddin, A. (2025). Effect of Angle of Attack on Drag and Lift Coefficients on Naca Airfoil for Wind Turbine Application. Aceh International Journal of Science and Technology, 14(2), 153–162. https://doi.org/10.13170/aijst.14.2.47327

[2] Seetharam, H. C., Rodgers, E. J., & Jr. Wentz, W. H. (1977). Experimental studies of flow separation of the NACA 2412 Airfoil at low speeds. In Aeronautical Engineering Department, Wichita State University, & NASA Langley Research Center, Aeronautical Report 77-3 (Experimental Report NASA-CR-197497). https://ntrs.nasa.gov/citations/19950002355 (Accessed Date: September 21, 2026).

[3] Rafat, T., Shuchi, T. Z., Evan, F. R., & Rabby, I. I. (2024). Aerodynamic and Flow Characteristics of a Rough Airfoil: A Numerical Study. IOP Conference Series: Materials Science and Engineering, 1305(1), 012003. https://doi.org/10.1088/1757-899x/1305/1/012003

[4] Zhou, Y., & Wang, Z. J. (2012). Effects of surface roughness on separated and transitional flows over a wing. AIAA Journal, 50(3), 593–609. https://doi.org/10.2514/1.J051237

[5] V, Dhivyadharshini., R, S. Krishna., & V, Kamaleshwari. (2021, October 8). Investigation of aerodynamic efficiency on NACA 2412 airfoil. International Journal of Engineering Research & Technology. https://www.ijert.org/investigation-of-aerodynamic-efficiency-on-naca-2412-airfoil (Accessed Date: September 21, 2026).

[6] Noor, H. D., Al-fahham, M. A. H., & Mohammed, M. H. (2023). Effect of surface roughness size on the skin friction drag for NACA0012 airfoil. Proceedings of the 2nd International Seminar on Aeronautics and Energy, 73–81. https://doi.org/10.1007/978-981-99-6874-9_6

[7] Dhiliban, A., Meena, P., Narasimhan, P. S., Vivek, M., Pillai, S. N., & Parammasivam, K. M. (2013). Aerodynamic performance of rear roughness aerofoils. Proceedings of the Eighth Asia-Pacific Conference on Wind Engineering (APCWE-VIII), Chennai, India. https://doi.org/10.3850/978-981-07-8012-8_252

[8] Versteeg, H. K., and Malalasekera, W. (2007). An Introduction to Computational Fluid Dynamics: The Finite Volume Method, 2nd ed. Harlow, England: Pearson Education Limited. ISBN: 978-0-13-127498-3.

[9] Anderson, J. D., Jr. (2017). Fundamentals of Aerodynamics, 6th ed. New York: McGraw-Hill Education. ISBN: 978-1-259-12991-9.

[10] Reddy, P. (2026, February 18). Surface roughness chart: Guide to symbols, values, and measurement. Clarwe. https://www.clarwe.com/articles/surface-roughness-chart (Accessed Date: September 21, 2026).

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Dr. Yagya Dutta Dwivedi: Conceptualization, supervision, methodology, and review of the manuscript.
Samreen Tabassum: Literature review, CAD modeling, CFD analysis, Results analysis.
Sonnakula Madhumitha: Literature review, CAD modeling, and manuscript preparation.
Banoth Karthik: CFD support, data analysis.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflict of Interest

Conflict of Interest:
The authors declare that they have no conflict of interest.

Creative Commons Attribution License 4.0 (Attribution 4.0 International, CC BY 4.0)

This article is published under the terms of the Creative Commons Attribution License 4.0
https://creativecommons.org/licenses/by/4.0/deed.en_US