Improvement of Aerodynamic Performance of NACA 2412 Airfoil using Active and Passive Control Techniques

PARAMESH T.[1, 2], TSHERING TENZIN[1], MOHAMMAD SARWAR[1], AHMAD MUJEEB AZIZI[1],
HABTE GETANEH[1], AND TAMAL JANA[3,*]
[1]Department of Aerospace Engineering,
JAIN (Deemed-to-be University)
Bengaluru,
INDIA

[2]Department of Aeronautical Engineering,
Global Academy of Technology,
Bengaluru,
INDIA

[3]Department of Aerospace Engineering,
B.M.S. College of Engineering,
Bengaluru,
INDIA

*Corresponding Author

Abstract: - The study of aerodynamic characteristics plays a crucial role in the design and performance evaluation of various airfoil profiles. In this study, a comprehensive investigation of the modified NACA 2412 airfoil has been carried out, focusing on its aerodynamic characteristics and performance. To improve the aerodynamic characteristics and to delay the stall, active and passive control techniques are introduced. The computational investigation is carried out using commercial software Ansys Fluent. Especially, the Reynolds-Averaged Navier Stokes (RANS) equation is numerically computed employing the K-omega SST turbulence model. The active control is implemented using four microjets, each having diameters of 3 mm, 4 mm, and 5 mm, placed upstream of the flow separation location of the uncontrolled airfoil. The jet exit velocity is maintained the same as the freestream flow velocity. For each case, the tangential orientations of the jets are varied from 2 to 10 degrees with an increment of 2 degrees. Besides, the impact of jet separation distance is also evaluated. On the other hand, the passive control method is introduced by deploying vortex generators (VG) with varying heights of 2 mm, 3 mm, and 4 mm, placed upstream of the separation location. Aerodynamic characteristics, including Lift, Drag, and Stall angle, are measured to assess performance. The study reveals that microjets with a diameter of 5 mm at a 2-degree tangential orientation perform best with a maximum of 11.33% increase in lift coefficient (C_l). For all the three sizes of microjets, the drag coefficients (C_d) are minimum for 2-degree tangential orientation. Besides, the vortex generator of height 2 mm demonstrates superior performance with a maximum of 4% increase in lift coefficient. For both cases, the stall angle of the airfoil is delayed by 28.57%. In addition, except 2mm height of the vortex generator, all other vortex generators lead to an increase in drag coefficient. Importantly, the microjets are proved to be more efficient than the vortex generator in delaying the flow separation thereby reducing the drag and increasing the aerodynamic efficiency of the airfoil.

Key-Words: - Airfoil, Drag, Lift, Microjets, RANS, Vortex Generator.

Received: June 5, 2023. Revised: February 21, 2024. Accepted: April 2, 2024. Published: May 14, 2024.

1 Introduction

The NACA 2412 airfoil finds extensive applications in the aerospace industry, including aircraft, gliders, wind turbines, UAVs, and model planes, due to its versatile nature. Data for different baseline airfoils and typical wing characteristics are provided in numerous studies, [1]. Despite its recognized good performance, challenges exist in terms of maximum lift, minimum drag, stall angle of attack, performance at low Reynolds numbers, and transonic performance. To address these challenges, control techniques were implemented on the same airfoil, introducing the innovative concept of micro-jets for active control.

Micro-jets involve directing small jets of air into the airfoil's boundary layer to influence and manipulate its aerodynamic performance. The core idea is to inject additional momentum into the boundary layer. This effectively re-energizes the airflow and delays the flow separation.

Along with the study of active flow controls, passive flow control through the addition of vortex generators (VG) was introduced by several researchers in controlling both low and high-speed flows.

Vortex generators are the small protrusions over the surface of an airfoil that generate the vortices. These vortices increase the turbulence within the flow thus altering the aerodynamic characteristics of the airfoil. In 1997, the NACA 2412 airfoil was explicitly investigated to understand the various flow separation characteristics, [2]. Importantly, the synthetic jets, as an active flow control technique were used on a NACA 0015 airfoil to significantly increase lift coefficients, [3]. In subsequent investigations, the synthetic jet parameters were optimized to control the flow separation around a NACA 0015 airfoil. This optimized synthetic jet improves the lift-to-drag ratio by 66%, [4]. As an effective active control technique, the microjets were introduced over NACA 0015 airfoil to understand the efficacy of microjets over uncontrolled cases, [5]. It was found that microjets were effective in reducing the stall angle. Also, they are efficient in reducing the massive flow separation across various angles of attack. Further, the improvement in the lift is achieved with synthetic micro jet actuators through periodic blowing and suction, [6].

The optimum angle of attack for the NACA 2412 airfoil has been identified by researchers, emphasizing pressure distribution and the critical angle leading to stalling, [7]. An important investigation on NACA 2412 airfoil has been conducted at various angles, which show detailed pressure distribution data and the critical angle leading to stalling, [8]. Different passive control techniques have been investigated particularly with vortex generators and cavities, in increasing lift and reducing drag, [9], [10], [11], [12]. Importantly, the control boundary layer over the NACA 0015 Airfoil due to the use of vortex generators is responsible for reduced drag, [13]. Winglets and Vortex Generators were also described in literature to improve the aerodynamic performance of a wing, [14]. Recently, the influence of gothic vortex generators has been computationally investigated in improving the flow characteristics, [15].

It is evident from the existing literature that several attempts have been made to improve the airfoil aerodynamic characteristics. However, the comprehensive characterization of the active control and passive control techniques and their comparisons are rarely available. Keeping this in mind, the present study introduces micro jets of varied diameters with different angular orientations as an active control, and vortex generators of varied heights as a passive control. The main aim is to investigate their influence in improving aerodynamic efficiency.

Particularly, the study emphasizes the significance of micro jet inlets in actively controlling key aerodynamic characteristics such as lift generation, drag reduction, and stall behavior. Besides, the Vortex Generator is employed to manipulate flow characteristics, with a focus on improving lift generation and delaying flow separation.

2 Problem Formulation

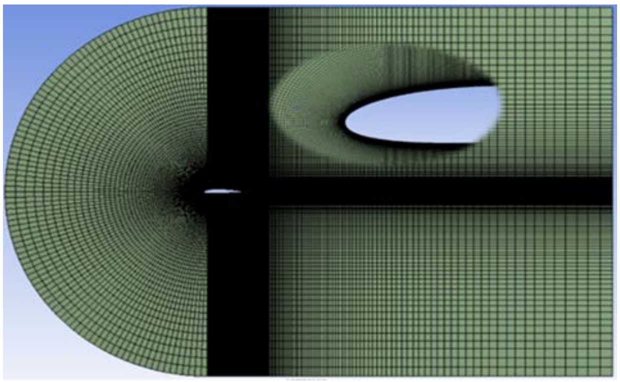


Fig. 1: Mesh structure of NACA 2412 Airfoil

In this study, airfoil and fluid domain models were constructed on the XY plane. The NACA 2412 aerofoil is plotted using the Airfoil Database Tool with a one-meter Chord length. A C-type fluid domain with ten times the chord length was created.

The domain was subdivided for enhanced control over mesh creation. The fine mesh is created in the regions of variation of flow properties, as shown in Figure 1. It critically captures the flow effects of the NACA 2412 with micro-jet integration tangential to the airfoil surface. Meshing is applied to discretize the geometry of the computational domain. To ensure precision and reliability in the simulation, a high-quality and well-structured mesh needs to be employed. The mesh utilized a quadrilateral structure with bias factor, enhancing accuracy and improving flow visualization.

The grid Independence study is carried out with 1.3, 2.1, 2.8, and 3.5 Lakh elements. The results deviate for 1.3 and 2.1 lakh elements whereas the 2.8 lakh elements were found to yield the most accurate results. With careful refinement of the computational model, the resulting fluid domain included 281,040 nodes and 280,000 elements.

The flow conditions were assumed to be steady, pressure-based, and 2D-space planar, with the selected material being fluid-air. The K-Omega SST model was employed for viscous modeling. The input velocity is taken as 45.27 m/s and since the associated Mach number is below 0.3, the flow is considered to be incompressible. The various boundary conditions were set up based on airfoil modifications. Table 1 outlines the boundary conditions and flow specifications applied to different configurations. The computational simulations being conducted in using Ansys Fluent 18.

Table 1. Setup specifications

Materials	Constant air (ρ= 1.2256 kg/m^3)
Operating Conditions	Velocity Inlet, V= 45.27m/s, No-slip Airfoil, Pressure Outlet
Momentum	2nd Order Upwind Scheme
Report	Force- Lift and Drag
Convergence	1e-6

The flow properties contour was visualized using Ansys Fluent's post-processing tools after the simulations converged. To gain insights into the flow patterns, pressure distribution, and other relevant parameters for each configuration are studied.

To verify the precision of numerical simulations, the obtained results were compared with experimental data. Simulations conducted were closely aligned with experimental data [1], as shown in Figure 2. Results illustrate the accuracy of the computational approach in capturing aerodynamic characteristics. This sets the benchmark for the simulation of various modified NACA 2412 airfoil configurations. For the uncontrolled airfoil, the experimental value of the lift coefficient is 1.509 [1], whereas, the lift coefficient calculated from the present computational study is 1.504. The percentage of error of the computational study from the experimentally available data is well below 1%.

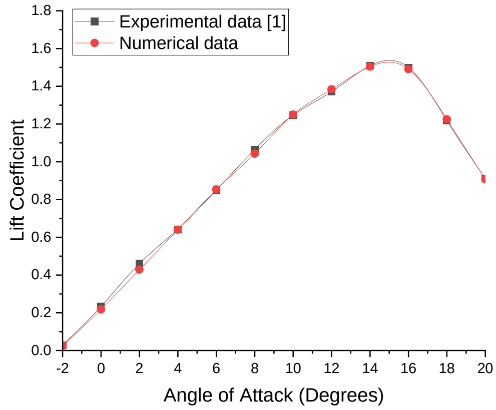
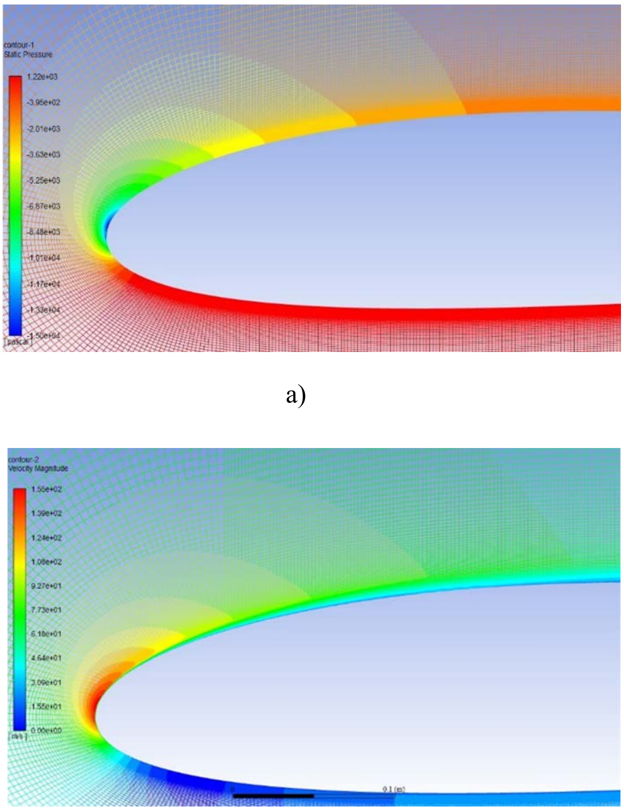


Fig. 2: Comparison of Cl for NACA 2412 of numerical work and Experimental data, [1]

3 Results and Discussion

3.1 Active Flow Control using Microjet

In order to improve the aerodynamic performance of the NACA 2412 airfoil, the microjet inlets are strategically incorporated over the airfoil.



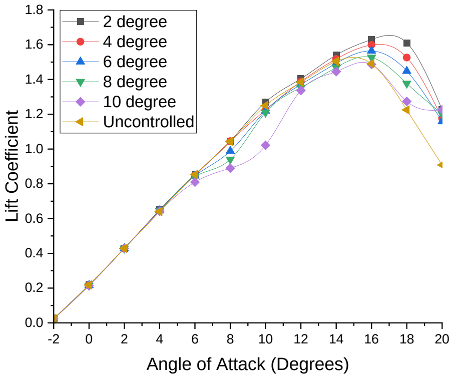
a)

b)

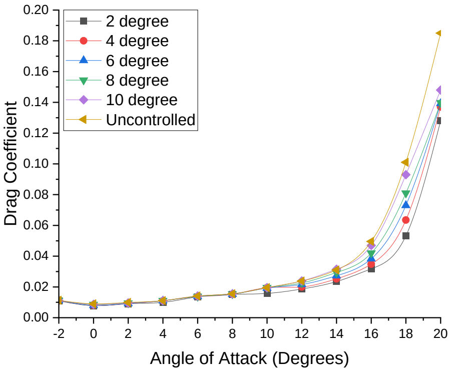
Fig. 3: a)Pressure and b)Velocity contours of microjets controlled airfoil

The size of the microjet inlet is varied (3mm, 4mm, and 5mm) and orientations (2° to 10°) at spaced intervals of 3mm. The study was conducted for a diverse range of airfoil angles of attack spanning from -2° to 20°. Figures 3(a) and 3(b) display the pressure and velocity contours, respectively. These visualizations illustrate the variation in flow patterns induced by the microjet.

a) Impact of varied diameters of Micro Jets:



(a)

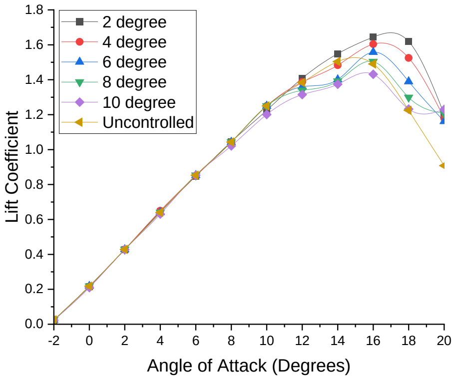


(b)

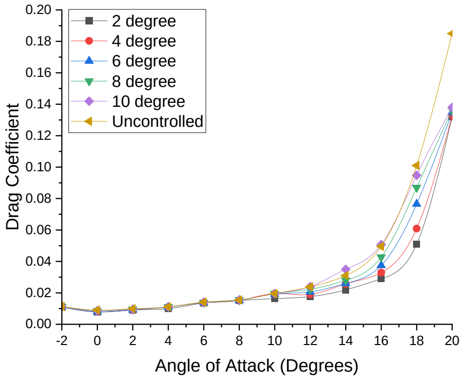
Fig. 4: (a)Lift, and (b)Drag coefficients for the airfoil with microjets of 3mm diameter deployed at different tangential orientations

In Configuration 1, where four 3mm micro jets are employed, the lift coefficient against different angles of attack for the controlled airfoil is shown in Figure 4(a). The peak coefficient of lift (C_l) is observed at an angle of attack of 16 degrees, which indicates delayed stall compared to the baseline NACA 2412 airfoil, where the stall angle is found to be 14 degrees. This shows a 14.29% increase in stall angle. Notably, the optimal tangential orientation for maximizing lift was found to be 2 degrees. The maximum coefficient of lift recorded is 1.63, indicating an 8.66% increase in lift coefficient. Essentially, the tangential orientation of the microjet inlets at 2 degrees facilitated more effective mixing with the surrounding flow. It imparts additional momentum to the boundary layer. This, in turn, delays boundary layer separation and stall angle. The drag coefficient (C_d) plot for the same configuration is shown in Figure 4(b), where microjets tangentially oriented at 2-degrees show minimum drag.

Configuration 2, which consists of a 4mm microjet, exhibits a peak coefficient of lift at 16 degrees angle of attack, indicating a 14.29% increment in stall angle, in comparison to the baseline case (Figure 5(a)). The optimal tangential orientation for maximum lift was consistently identified at 2 degrees. The maximum coefficient of lift achieved was 1.64, showing a 9.33% increment, which can be noticed in Figure 5(a). Essentially, the larger size of microjets of 4mm diameter continues to be superior in enhancing turbulent mixing. This supports the attachment of the boundary layer and contributes to delayed stall. Like 3mm microjets, the 4mm microjets at 2mm tangential orientation are the best in reducing the drag (Figure 5(b)).



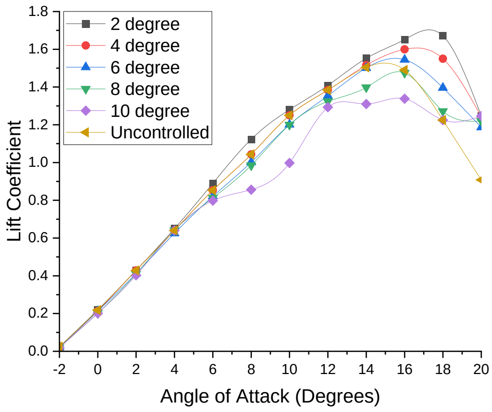
(a)



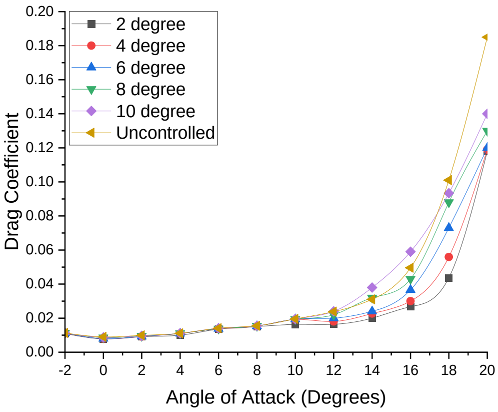
(b)

Fig. 5: (a)Lift and (b)Drag coefficients for the airfoil with microjets of 4mm diameter deployed at different tangential orientations

In Configuration 3, where four 5mm microjets were employed, the maximum coefficient of lift was attained at an angle of attack of 18 degrees (Figure 6(a)). This represented a further delay in a stall from 14 to 18 degrees when compared to the baseline NACA 2412 airfoil, showing a 28.57% increase in stall angle. Once again, the optimal tangential orientation for maximum lift was identified at 2 degrees which can be noticed in Figure 6(a). The maximum coefficient of lift recorded was 1.67, which demonstrates an 11.33% increment in lift coefficient. The larger microjets of 5mm diameter continued the trend of promoting efficient mixing, transmitting increased momentum to the boundary layer. This not only delayed stall but also resulted in an enhanced lift coefficient. Again, the microjets for configuration 3 at 2 mm tangential orientation are found to be the best in minimizing the drag (Figure 6(b)).



(a)



(b)

Fig. 6: (a) Lift, and (b) Drag coefficients for the airfoil with microjets of 5mm diameter, deployed at different tangential orientations

Independent of microjets diameters, the microjets of 2mm tangential orientations provide the maximum lift. The microjets enhance the mixing of high-energy air from the jet with the boundary layer. This mixing promotes smoother airflow over the airfoil surface, reducing the drag coefficient. Essentially, the microjets at 2mm tangential orientation disturb the incoming flow very little while effectively energizing the same flow to delay flow separation.

Moreover, it was observed that the optimum drag coefficient was consistently achieved when the microjet was tangentially aligned at 2 degrees. This trend held for various microjet heights, including 3mm, 4mm, and 5mm. The tangential placement of the microjet at 2 degrees plays a crucial role in controlling the boundary layer on the airfoil surface. Directing the microjet tangentially, effectively influences the boundary layer separation and reattachment points. This control mitigates adverse effects like flow separation, leading to a reduction in drag. This underscores the robustness and effectiveness of this microjet active control strategy on the NACA 2412 airfoil.

b) Impact of Separation Distance of Microjets:

To understand the impact of separation distance, the best configuration, which is configuration 3 (four 5mm micro jet inlets tangential at 2 degrees), was analyzed with varying spacing distances, as shown in Figure 7. Interestingly, altering the separation distance from 3mm to 4mm and subsequently to 5mm had a negligible effect on lift generation.

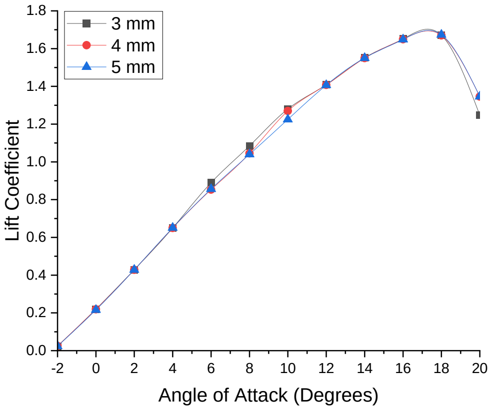
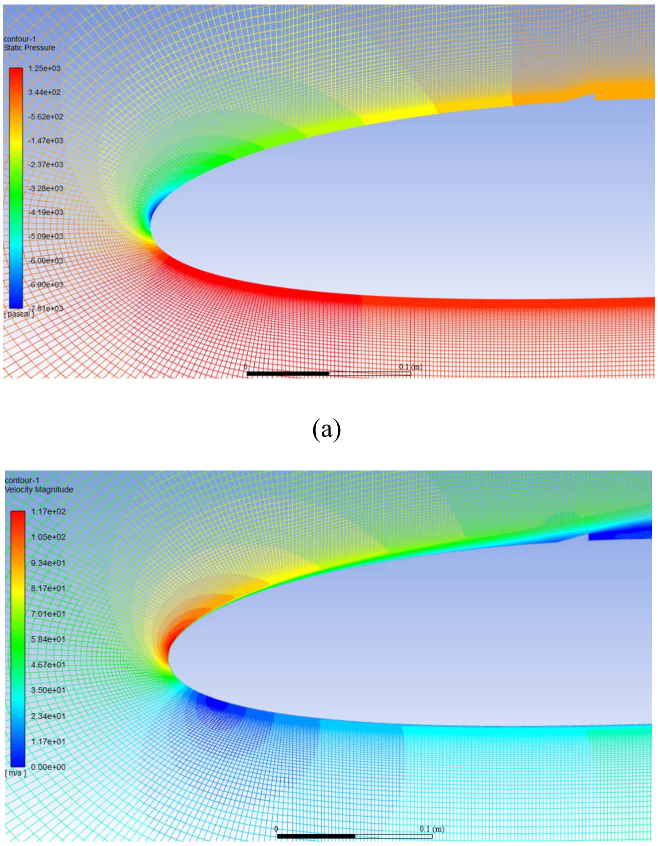


Fig. 7: Lift coefficient for the airfoil with for microjets with varied separation distances

The stall angle remained unchanged at 18 degrees for all the separation distances. The consistent stall angle at 18 degrees implies the similar impacts for all separation distances in successfully mitigating of boundary layer separation.

3.2 Passive Flow Control using Vortex Generator

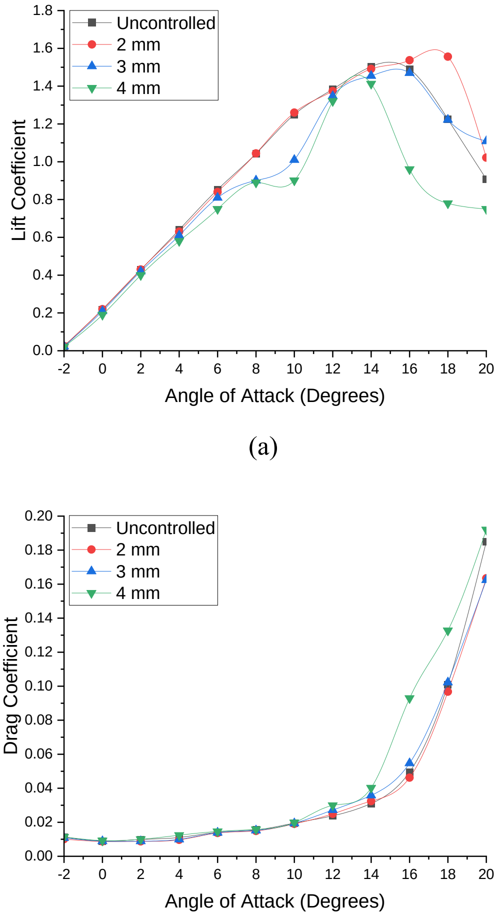
In addition to active flow controls, the aerodynamic performance of passive flow control is investigated with the varied heights of vortex generators (VGs). A vortex generator is a small protrusion, strategically placed on the airfoil surface to manipulate flow characteristics by generating vortices. Since the vortices are responsible for bringing high energy fluid towards the lower energy boundary layer flow, flow separation is delayed which thereby improves lift generation. In this present study, the vortex generators of varied heights of 2mm, 3mm, and 4mm are introduced over the NACA 2412 airfoil. The simulations have been conducted at different angles of attack ranging from -2 degrees to 20 degrees to assess their impact on aerodynamic performance. Figures 8(a) and 8(b) display the pressure and velocity contours with VG, respectively. These visualizations illustrate the alterations in flow patterns induced by the vortex generators.



(a)

(b)

Fig. 8: (a)Pressure and (b)Velocity contours for vortex generator controlled airfoil



(a)

(b)

Fig. 9: (a)Lift and (b) Drag Coefficients for the airfoil with vortex generators of varied heights

Figure 9(a) provides the values of the coefficient of lift (C_l) at different angles of attacks for the varied height of vortex generators. Notably, the optimal result was achieved with a vortex generator height of 2mm, showcasing a maximum C_l of 1.56, which therefore shows a 4% increment in lift coefficient. The stall angle was also extended from 14° to 18°, demonstrating a 28.57% increment in stall angle.

Further, increase in the height of the vortex generators, surprisingly, decreases the maximum coefficient of lift of the controlled airfoil. This trend underscores the importance of selecting an optimal vortex generator of a height of 2mm for the enhanced aerodynamic performance of the NACA 2412 airfoil. In addition, except 2mm height of the vortex generator, all other vortex generators lead to an increase in drag coefficient (C_d), as observed in Figure 9(b). This is essentially due the substantial flow disturbances induced by the vortex generator of larger heights.

Essentially, the vortices generated by the vortex generators facilitate in delaying of separated flow, thereby generating additional lift. The observed decrease in C_l with increasing vortex generator height indicates a critical balance in design. While vortex generators can enhance lift, an excessive height may lead to undesirable effects due to higher drag, emphasizing the need for careful consideration in their placement. The stall angle's postponement from 14° to 18°, which is a 28.57% increment in stall angle, suggests that the modified airfoil with vortex generators exhibits improved stall characteristics, crucial for maintaining lift under varying flight conditions.

4 Conclusion

In the present study, the influences of microjets as an active control and vortex generator as a passive control are examined. Out of 3mm, 4mm, and 5mm, the 5mm microjet most effectively improves the lift coefficient. It can be noted that the microjets exhibited improved aerodynamic performance when positioned tangentially at a 2-degree angle to the airfoil surface. Importantly, 5mm microjets, oriented tangentially at 2 degrees, demonstrated an increased maximum lift coefficient by 11.33%, delayed stall angle by 28.57% in comparison with the uncontrolled airfoil. For all the three sizes of microjets, the drag coefficients are minimum for 2-degree tangential orientation. Surprisingly, the alteration of separation distances between microjets had a negligible impact on lift improvement.

Additionally, the 2mm, 3mm, and 4mm height of vortex generators of a 2mm height significantly improved the lift coefficient, demonstrating an increase of 4%, showcasing their effectiveness in improving aerodynamic lift and reducing drag coefficients. The observed increase in stall angle of 28.57% underscores the ability of vortex generators to delay flow separation and enhance stability in the NACA 2412 airfoil. In addition, except 2mm height of the vortex generator, all other vortex generators lead to an increase in drag coefficient. Note that, out of microjets and vortex generators, the microjets are proven to be more efficient in improving aerodynamic performance. These improvements are attributed to the efficient mixing and momentum transfer facilitated by the microjets.

The current flow control technique over the NACA 2412 airfoil provides valuable insights for optimizing airfoil design across diverse engineering applications. The study can be extended for different control methods such as synthetic jet, pulsed jet, or cavity in effectively improving the aerodynamic efficiency of an airfoil. Moreover, the study can be extended to a three-dimensional wing structure where an array of vortex generators, microjets, or other control techniques can be deployed.

References:

[1] Abbott, I.H., and Von Doenhoff, A.E., *Theory of Wing Sections*, Dover Publications, New York, 1959.

[2] Seetharam H. C., E. J. Rodgers, and W. H. Wentz Jr., *Experimental studies of flow separation of the NACA 2412 airfoil at low speeds*, No. AR 77-3, NASA-CR-197497, 1977.

[3] Parthasarathy, T., and S. P. Das, *Some aspects of flow control over a NACA0015 airfoil using synthetic jets*. Journal of Physics: Conference Series, IOP Publishing, Fifteenth Asian Congress of Fluid Mechanics (15ACFM), Kuching, Sarawak, Malaysia Vol.822, No.1, 2017.

[4] Montazer, Elham Mirzaei, Masoud & Salami, Erfan Ward, Thomas Romli, Fairuz Kazi, S.N., *Optimization of a synthetic jet actuator for flow control around an airfoil.*, IOP Conference Series: Materials Science and Engineering. AEROTECH VI - Innovation in Aerospace Engineering and Technology, Kuala Lumpur, Malaysia, Vol. 152, 2016.

[5] Shih, C, Beahn, J, Krothapalli, A, & Chandrasekhara, MS., *Control of Compressible Dynamics Stall Using Microjets*, Proceedings of the ASME/JSME 2003 4th Joint Fluids Summer Engineering Conference. Honolulu, Hawaii, USA. Vol.2, 2003, pp. 1141-1146.

[6] Donovan, John, Linda Kral, and Andrew Cary, *Active flow control applied to an airfoil,* 36th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, U.S.A., 1998.

[7] Sarkar Shivananda and Shaheen Beg Mughal. *CFD analysis of effect of flow over naca 2412 airfoil through the shear stress transport turbulence model,* International Journal of Mechanical and Production Engineering, Vol.5, No.7, 2017, pp. 2320-2092.

[8] Varatharajan R Madhanraj and Dilip A Shah, *CFD Analysis of NACA 2421 Aerofoil at Several Angles of Attack*, Journal of Aeronautics & Aerospace Engineering, Vol.8, No.217, 2019, pp. 1-4.

[9] Bragg M. B, and G M Gregorek, *Experimental study of airfoil performance*

with vortex generators, Journal of aircraft, Vol.24, No.5, 1987, pp. 305-309.

[10] Olsman, W. F. J., and T. Colonius, *Numerical simulation of flow over an airfoil with a cavity*. AIAA journal, Vol.49, No.1, 2011, pp.143-149.

[11] López Calle, Oriol. *Preliminary study of the effects of vortex generators in ultralight aircraft*, BS thesis, Universitat Politècnica de Catalunya, 2015.

[12] Arunvinthan, Raatan V.S, Pillai, Nadaraja, Pasha Amjad, Rahman M, & J Khalid, *Aerodynamic characteristics of shark scale-based vortex generators upon symmetrical airfoil,* Energies, Vol.14, No.7, 1808, 2021, pp.1-22.

[13] Silva Douglas da, and Vinicius Malatesta, *Numerical simulation of the boundary layer control on the NACA 0015 airfoil through vortex generator,* Journal of Aerospace Technology and Management, Vol.12, 2020, pp. 1-30.

[14] Abdul Qader Hasan, Nasr M. Al-Khudhiri, Muhammad A. Iqbal, Sharul Sham Dol, Abid Abdul Azeez, and Mohamed S. Gadala, *Aerodynamics analysis on wings with winglets and vortex generators*, WSEAS Transactions on Fluid Mechanics, Vol.15, 2020, pp. 193-201.

[15] Zidhane Aliffaputra, Setyo Hariyadi Suranto Putro, Nyaris Pambudiyatno, Analysis of the *Effect of Gothic Vortex Generator Using Computational Fluid Dynamic on NACA 2412,* Proceedings of the International Conference on Advance Transportation, Engineering, and Applied Science (ICATEAS 2022), Jawa Timur, Indonesia, 2023, pp.26-39.

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

T Paramesh, Tshering Tenzin, Mohammad Sarwar, Ahmad Mujeeb Azizi, and Habte Getaneh conducted the computational study. T Paramesh wrote the first draft. Tamal Jana supervised and reviewed the final draft. The authors read and approved the final manuscript.

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

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare.

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