Volume 5 Issue 1 (March 2025)
DOI 10.24191/jaeds.v5i1.99
eISSN 2805-5756

Journal of Applied Engineering Design & Simulation

Improvement of Aerodynamic Analysis on Helicopter Rotor Blade by Applying Passive Flow Control

Mohd Hafiz Mohd Noh[1], Ahmad Hussein Abdul Hamid[1], Muhammad Shahrul Azryn Hanif[1]
[1]School of Mechanical Engineering, College of Engineering, Universiti Teknologi MARA, Shah Alam 40450 Selangor, Malaysia.
*corresponding author: hafiz669@uitm.edu.my

ABSTRACT

Rotor blades are essential for helicopter flight as they provide lift similar to an airplane's wings, allowing the aircraft to take off, hover, and maneuver. However, they also generate aerodynamic drag, which can reduce maximum speed, stability, maneuverability, and fuel efficiency. The enhancement on the blade is usually done at the trailing edge area; however, this time it was done at the leading edge location. This study explored the use of passive flow control to enhance rotor blade performance by minimizing surface turbulence. Through Computational Fluid Dynamics (CFD) analysis, key parameters such as velocity and lift-to-drag ratios coefficient are examined at a Reynolds number (Re) of 3×10^6. The research utilized the SST k-ω turbulence model and an unstructured mesh to simulate airflow around a NACA 0012 airfoil at a 15° angle of attack. Passive flow control was applied using slots of 5%, 10%, and 15% of the chord length, placed in turbulent flow regions and extending downstream. The findings indicate that positioning passive flow control further downstream increases the lift-to-drag ratio with 5% slot sizes delaying turbulence, improving velocity reattachment to the blade surface and improving the lift-to-drag ratio by approximately 77% compared with non slot blade. This highlights the effectiveness of passive flow control in improving the aerodynamic efficiency of rotor blades.

Keywords: Helicopter aerodynamics; Passive flow control; Slot; Surface turbulence; NACA 0012 airfoil

Nomenclature (Greek symbols towards the end)

A_R	Surface area of rotor blade (m^2)
C_L	Lift coefficient
C_D	Drag coefficient
α	Angle of attack

Abbreviations

CFD	Computational fluid dynamics
PFC	Passive flow control
FEA	Finite element analysis
VG	Vortex generator
AI	Artificial intelligence

1.0 INTRODUCTION

Helicopters are extremely versatile aircrafts that can take off and land vertically, hover in one spot, and move in ways that airplanes cannot. Their hovering ability allows them to perform important tasks like search and rescue, aerial photography, and precise lifting [1] [2]. The progress in helicopter technology is due to continuous research and development, which have enhanced their design, efficiency, and safety. Over the years, engineers have improved rotor blade aerodynamics, reduced noise, and added advanced navigation and control systems. New materials, like strong yet lightweight composites, have also increased fuel efficiency and performance [3]. Additionally, modern helicopters now use artificial intelligence (AI) and automation, which improve safety by lowering the risk of pilot mistakes [4] [5]. AI and automation are likely to be important in the future of helicopters, with AI systems helping pilots or enabling self-flying capabilities. This can minimize human mistakes and enhance safety.

The two main factors that directly affect aerodynamic performance in flying vehicles are lift and drag. An item moving through the air is slowed down by drag force, which serves as resistance [6], but an aeroplane or helicopter can rise and remain in the air thanks to lift force. To achieve the best possible flying performance and guarantee safe and effective operations, these forces must be balanced. The aerodynamic design and optimisation of the rotor blade are the main topics of the study that is being presented. Slots in the rotor blade are included into the design as passive flow control techniques for delaying turbulence along the blade's surface. By more efficiently

Received on 10.03.2025
Accepted on 29.03.2025
Published on 30.03.2025

controlling airflow, this design aims to enhance aerodynamic performance. The use of fixed, non-moving elements to regulate and stabilise air flow and reduce turbulence without the use of mechanical or active devices is known as passive flow control [7]. In contrast to active flow control, which depends on moving components or outside energy, passive flow control employs structurally integrated design elements to autonomously control airflow [6]. Delaying the stall by encouraging the reattachment of split flows is another example that was frequently employed to improve performance at high angles of attack for low speed.

Vortex generators (VGs) were installed on the back entrance ramp of a heavy-class helicopter fuselage model based on the research by G. Gibertini [8]. The blunt fuselage form and the obvious upsweep at the back have made this area vulnerable to flow separation, which is why it was selected. The VGs were placed upstream of the considerable flow separation at the intersection of the tail boom and the backdoor, and directly downstream of the upsweep line, which is common in blunt helicopter fuselages. Apart from that, the combination of two PFC, such as slot and VG, was used in the earlier work of Bahador Bakhtiari [9]. VGs are usually positioned close to the airfoil's leading edge or mid-chord area, which is where boundary layer separation is most likely to happen. By placing them strategically, the flow is guaranteed to be energised early, postponing separation. In contrast, slots are strategically placed along the airfoil's chord length, frequently close to the mid-section or leading edge, to facilitate airflow and stabilise the boundary layer. According to the results, slots improve low-speed performance and eliminate stall, whereas VGs are especially good at preserving attached flow at greater angles of attack. The optimisation of wind turbine aerofoil design has demonstrated encouraging outcomes when both approaches are used. Dimple is another PFC approach that Yin Xie's research uses in addition to VGs [10]. The application of dimples as a passive flow control technique to reduce laminar separation on aerofoils running at low Reynolds numbers is examined in this paper. On the aerofoil surface, these dimples are positioned deliberately to target areas where laminar separation is most likely to take place. The dimples delay flow separation and improve overall aerodynamic efficiency by enhancing momentum transfer through the introduction of tiny vortices into the boundary layer. The results of the study show that adding dimples significantly raises the lift coefficient while lowering drag.

The objective of this research is to improve the aerodynamic efficiency of helicopter rotor blades by lowering drag and postponing surface turbulence. This is accomplished by using slots as a passive flow control method, which enhances airflow stability without using mechanical or active systems. The study has set three primary objectives. It first aims to validate the aerodynamic performance of a standard helicopter rotor blade in order to guarantee that the baseline efficiency is accurately ascertained. Second, the research concentrates on developing passive flow control components, such as slots, to enhance the blade's performance. Finally, the study assesses the aerodynamic properties of the enhanced rotor blade through the examination of variables such as velocity magnitude on blade surface, lift coefficient (C_L), and drag coefficient (C_D). These goals are combined to provide a rotor blade design that is more stable and effective.

2.0 METHODOLOGY

The methodology is divided into three phases which are pre-design, validation, and improvement design. In the pre-design phase, the problem is defined, the geometry is modeled and meshed, and the simulation setup is completed. during validation, simulation results are compared with previous studies to ensure accuracy, and refinements are made as needed. In the improvement design phase, the results are analysed, iterative adjustments are applied for optimization, and the final outcomes are documented. Figure 1 shows the methodology process in this study.

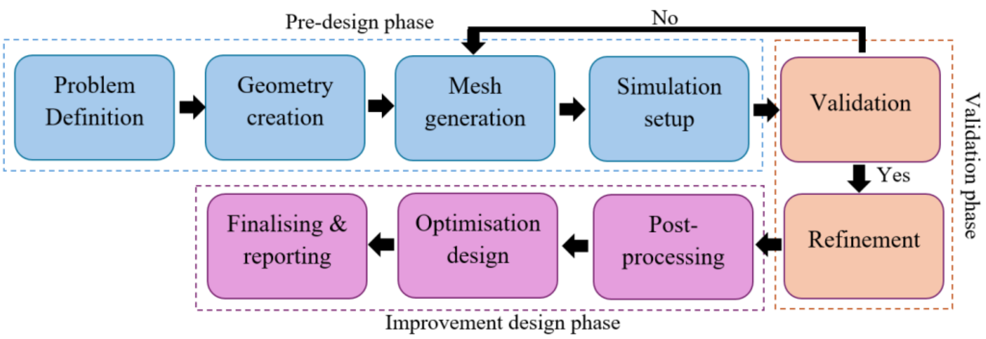


Figure 1 Flowchart for methodology process.

2.1 Pre-design phase

The baseline geometry for this study is the NACA0012 airfoil, a popular and extensively studied profile in aerodynamic research. The Airfoil Tool webpage (http://airfoiltools.com/airfoil/details?airfoil=n0012-il) provides the airfoil geometry, guaranteeing precision and compliance to accepted standards that have been used for preprocessing (Figure 2) and the geometry is loaded into ANSYS 2024 R2. To accurately mimic airflow, a C-shaped computational domain is created around the airfoil as shown in Figure 3. In order to reduce the influence of boundary effects and enable precise simulation of wake regions and flow behaviour, this domain design makes sure that there is sufficient upstream, downstream, and lateral clearance. In accordance with the normal working parameters for rotor blades, the airfoil is positioned at a 15° angle of attack. The domain is subjected to boundary conditions, with the outlet designated as a pressure outlet to permit the flow to easily escape and the intake is specified as a velocity inlet to specify airflow into the domain. In order to approximate real-world flow conditions as precisely as possible, this arrangement is chosen.

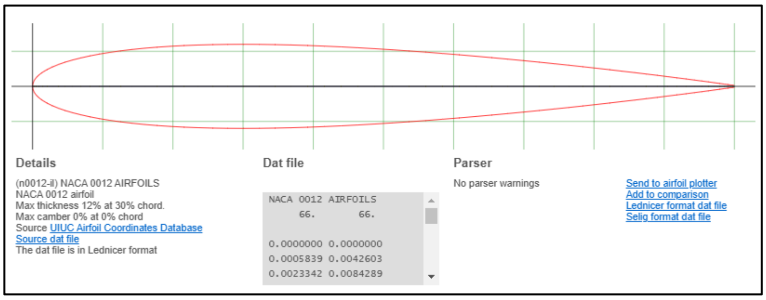


Figure 2 NACA0012 coordinate from Airfoil Tools web page. *[11]*

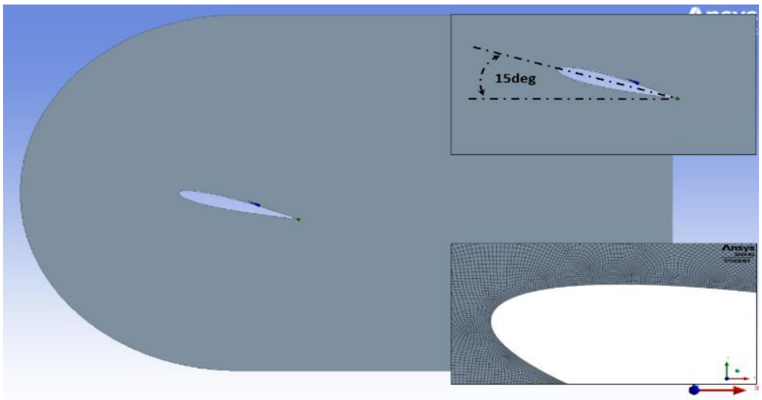


Figure 3 Geometry of airfoil with C domain and 15° angle of attack.

For the computational domain, an unstructured mesh is created in order to strike a compromise between computing efficiency and accuracy as shown in Figure 3. A consistent global element size of 2 mm is applied throughout the domain and the airfoil. Refinement mesh methods are used on the airfoil surface and domain to guarantee the precise resolution of important flow characteristics [12]. In high-gradient zones, these improvements increase the mesh density, guaranteeing well-resolved flow separation. The final mesh, which includes about 60,000 points, gives a thorough depiction of the area without requiring a lot of processing power.

Table 1 Parameters of the simulation.

Parameters	Value / Condition
Airfoil type	NACA0012
Turbulence model	k-ω SST
Mach number	0.15
Renolds number	6×10^6
Air velocity	87.65 m/s
Altitude	Sea level
Angle of attack	15 degree
Chord length	100mm

The air density is chosen at 1.225 kg/m³, and the simulation is run under typical sea-level atmospheric conditions. In order to ensure that the simulation matches actual operating circumstances, the velocity inlet boundary condition is calculated using a Reynolds number of 6 x 10^6. A pressure-based, steady-state solution is used to simulate the flow around the airfoil. The ability of the k-ω SST turbulence model to precisely forecast flow separation [12], reattachment, and other crucial aerodynamic properties leads to its selection. The purpose of this simulation is to analyse the aerodynamic forces operating on the airfoil in order to calculate its lift and drag coefficients. The performance gains brought about by the application of passive flow control are assessed using these coefficients. Table 1 shows the parameter being used in this study.

2.2 Passive flow control

Finding the best position and size of slots for passive flow control on a NACA0012 airfoil at a 15-degree angle of attack is the main goal of the study. The airfoil suffers from severe flow separation at this high angle, which results in decreased aerodynamic performance and increased drag. The study looks at three distinct slot placement positions in order to address this: prior to, during, and following the separation flow. The behaviour of the boundary layer, the delay or control of separation, and the lift-to-drag ratio are all significantly influenced by each site. The usefulness of the slot dimensions in controlling airflow is assessed by varying them within the range of 5%, 10%, and 15% of the chord length as shown in Figure 4 and Table 2. The modification is required to accommodate variations in flow behaviour and pressure gradients at various points of the airfoil surface, which requires customized slot size. Under these circumstances, the results provide important information on the best slot arrangements for enhancing the NACA0012 airfoil's aerodynamic performance.

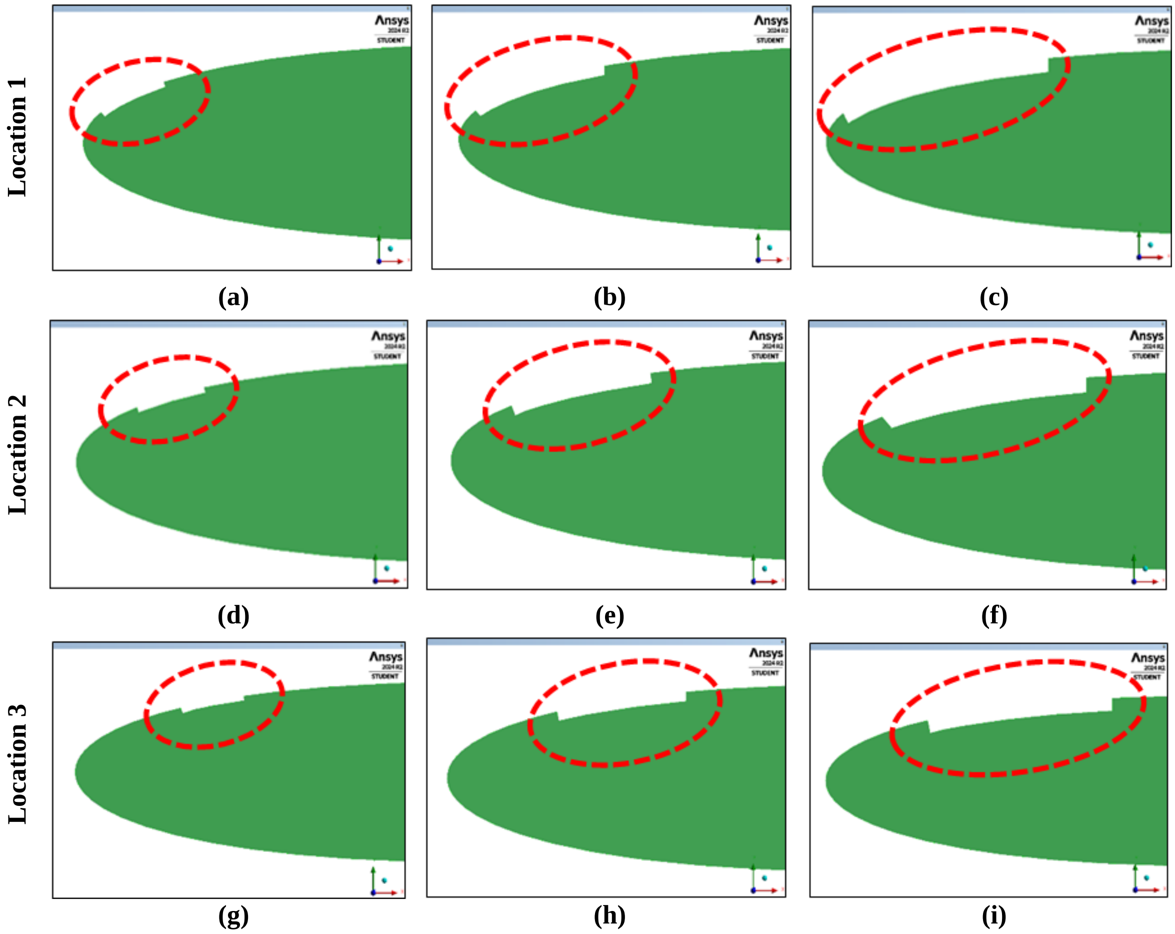


Figure 4 Location of the slot.

Table 2 Slot dimensions.

Slot size		Length	Thickness
5%	(a), (d), (g)	5mm	0.3mm
10%	(b), (e), (h)	10mm	0.6mm
15%	(c), (f), (i)	15mm	0.9mm

3.0 RESULTS AND DISCUSSION

The validation process has been done by comparing the computational result of pressure coefficient with a reference from NACA 0012 Airfoil – SimFlow Validation Case. Strong agreement between the two datasets was demonstrated by the comparison, which revealed that the changes in the pressure coefficient are closely matched with the reference findings. The accuracy and dependability of the existing analytical approach for forecasting the pressure distribution over the airfoil surface are demonstrated by this resemblance. The two angles of attack used for the validation procedure are 0º and 15º.

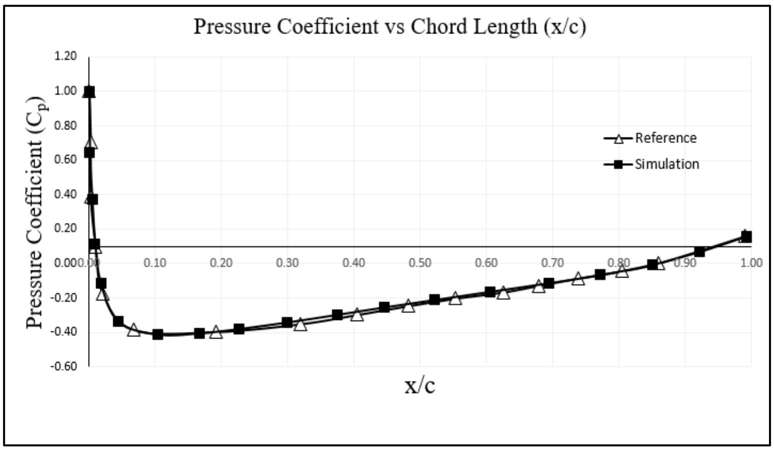


Figure 5 Validation for 0° angle of attack.

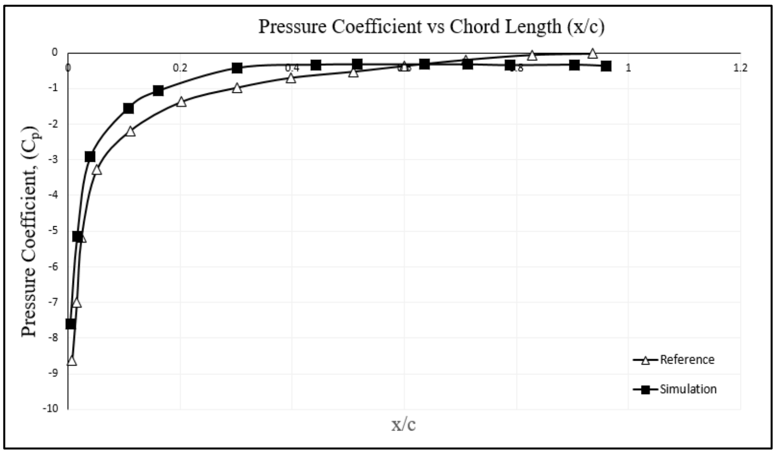


Figure 6 Validation for 15° degree angle of attack.

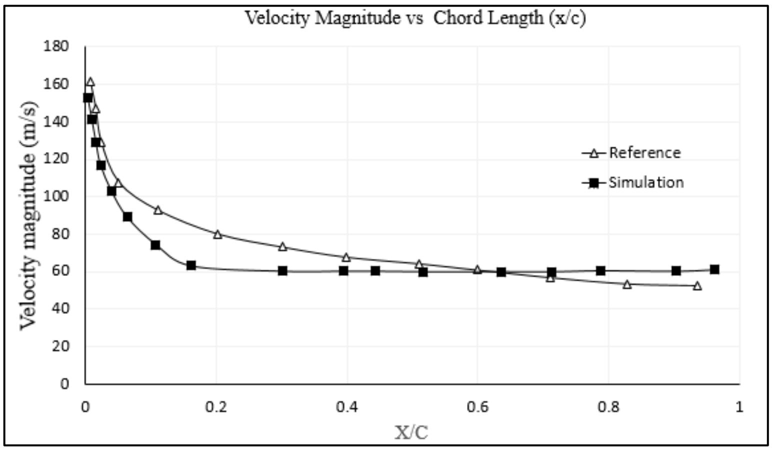


Figure 7 Validation on velocity for 15° degree angle of attack

The pressure coefficient profile matched the reference data and demonstrated the consistency of the results under low lift conditions at the 0º angle as depicted in Figure 5. The findings also closely matched the earlier research for the 15º angle of attack on Figure 6, where the airflow experiences more lift and stronger aerodynamic effects. The accuracy of the approach in recording flow behaviour throughout the airfoil surface is further supported by this agreement. Because the results of this study are also looking for velocity, validation on velocity magnitude is also being performed, resulting in a very good agreement between these two outcomes (Figure 7).

3.1 The result of lift to drag coefficient

The velocity magnitude contour, which depicts the flow separation on the airfoil's upstream surface prior to the slot's introduction, is shown in Figure 8. According to Table 3, the lift-to-drag coefficient ratio is found to be 1.659 in the absence of the slot. This figure indicates the airfoil's initial aerodynamic performance. The flow separation patterns are drastically altered by the slot's introduction; nevertheless, the slot's efficacy differs according to its size and placement. Figure 9 data for Location 1 revealed only a minor improvement in performance. The lift-to-drag coefficient ratio decreases somewhat from the baseline, indicating that the aerodynamic efficiency is not improved by this slot position. The slot at Location 1 may have prematurely interfered with the airflow, interrupting rather than aiding the natural flow pattern, as evidenced by the minor decrease in the coefficient values. This demonstrates that Location 1 is not the best place for the slot because it does not significantly improve the lift-to-drag ratio. Location 2, on the other hand, showed a more noticeable gain in aerodynamic performance, especially at the 10% slot dimension. The velocity profile for this design indicated a notable delay in flow separation, as seen in Figure 9, which raises the lift-to-drag coefficient ratio to 2.343. As it offers the best compromise between postponing flow separation and preserving aerodynamic stability, this indicates that the 10% slot dimension is the most efficient size for Location 2. However, very slight modifications are observed in the size of the 5% and 15% slots, suggesting that they are less effective here. The biggest gains are shown at Location 3, where the slot location causes a notable delay in flow separation in every dimension being examined. When it comes to improving aerodynamic performance, this position works well; at the 5% slot dimension, the maximum lift-to-drag coefficient ratio of 2.933 is attained. In order to reconnect the separated flow and decrease the size of the separation region, the results indicate that the slot at Location 3 introduces high-energy air into the boundary layer at the proper location. Because of the smoother airflow, lower drag, and higher lift that results, Location 3 is the best slot placement for optimizing aerodynamic efficiency.

Overall, the study emphasizes how important slot placement and dimension are in enhancing the airfoil's aerodynamic performance. Location 2 exhibited considerable increases, especially at the 10% slot dimension, while Location 1 showed no improvement and even slightly decreased the lift-to-drag ratio. The greatest improvement, however, was shown at location 3, where the 5% slot dimension produced the highest coefficient value. These results highlight how crucial it is to choose the slot size and location carefully in order to maximize aerodynamic performance.

Table 3 Comparison of lift and drag coefficient and lift to drag coefficient ratio

	Location 1			Location 2			Location 3		
	C_L	C_D	C_L/C_D	C_L	C_D	C_L/C_D	C_L	C_D	C_L/C_D
No slot	42.195	25.435	1.659	-	-	-	-	-	-
5%	36.763	24.757	1.485	37.97	22.037	1.723	58.739	20.029	2.933
10%	35.274	24.091	1.464	49.387	21.082	2.343	48.971	21.473	2.281
15%	36.189	24.702	1.465	37.463	21.655	1.729	49.704	22.064	2.253

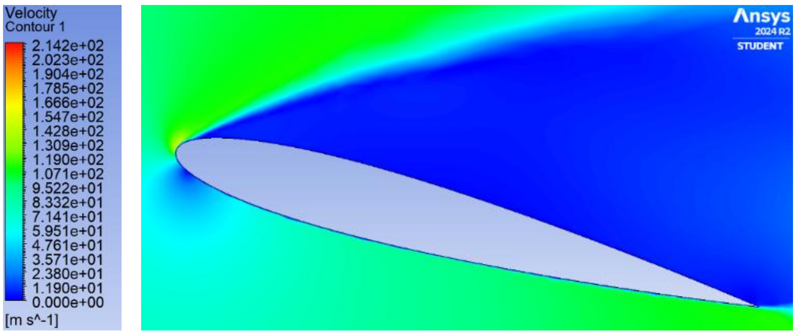
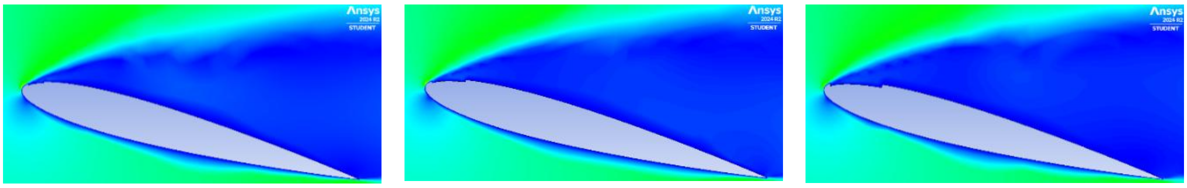
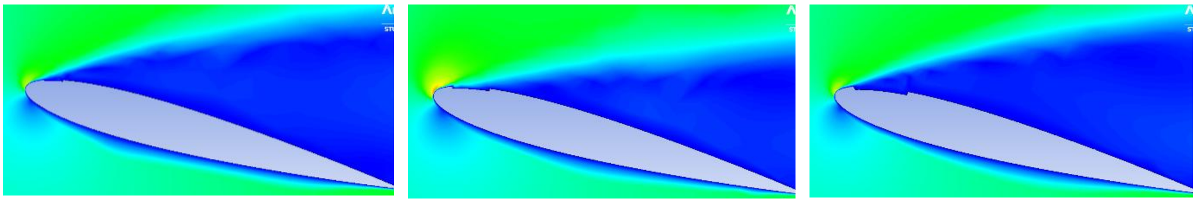


Figure 8 Initial flow separation of the airflow on airfoil surface.



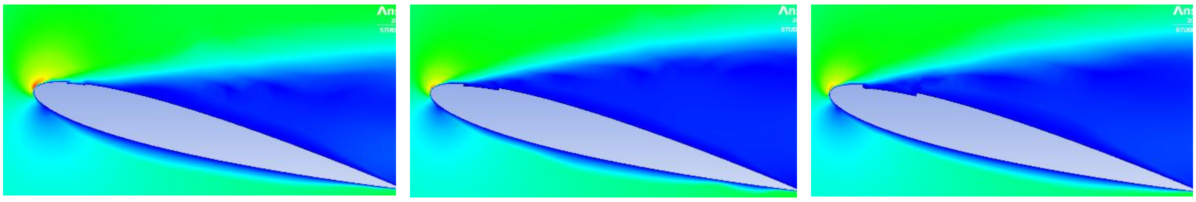
(a) (b) (c)

Figure 9 Comparison of the separation flow results for slot on Location 1 (a) 5%, (b) 10%, (c) 15%.



(d) (e) (f)

Figure 10 Comparison of the separation flow results for slot on Location 2 (d) 5%, (e) 10%, (f) 15%.



(g) (h) (i)

Figure 11 Comparison of the separation flow results for slot on Location 3 (g) 5%, (h) 10%, (i) 15%.

3.2 Velocity magnitude on airfoil surface.

A thorough illustration of the airflow behaviour close to the airfoil surface is given in Figures 12–14, which successfully depict areas of attached and separated flow. It is clear where flow separation starts by closely examining the velocity reduction along the airfoil surface. This investigation focuses on the chord length, where the velocity magnitude is measured from the leading edge to the 30-mm mark.

The velocity magnitude at Location 1 stays comparatively constant throughout the various slot designs, suggesting that the airflow behaviour varies very little as shown in Figure 12. This homogeneity indicates that the point of flow separation happens at the same location for every slot design evaluated and that the lift-to-drag coefficient ratio does not significantly change. The results from this site show that the slot size employed in this setup has little effect on the flow separation, which makes it less effective in changing the overall aerodynamic performance of the airfoil.

Figure 13 shows the result of velocity magnitude at Location 2. The velocity magnitude decreases a little more slowly than at Location 1. This suggests that the slots at this location offer some flow control, especially in postponing the start of flow separation. There are discernible variations depending on the slot dimensions, even though the separation still occurs at the same spot as in Location 1. The velocity magnitude decreases at a slightly later point for the 5% and 15% slot dimensions, indicating that these configurations provide some improvement in the airflow attachment. The 10% slot dimension, which is found to postpone the velocity drop more than the other slot sizes, is the most efficient arrangement at Location 2. Without sacrificing the airflow close to the airfoil surface, this dimension seems to achieve the ideal separation delay, which is consistent with the result of Tarek et al. by placing the active flow control at the leading edge area of the helicopter blade [13].

Last but not least, Position 3 is clearly the best place to postpone flow separation, which is presented in Figure 14. A lot greater control of the airflow is indicated by the velocity magnitude at this position dropping later at a higher point of the airfoil surface. Out of all the configurations examined, the 5% slot dimension at Location 3 exhibits the longest delay in flow separation. This finding indicates that the slots' size and location have a significant impact on the separation properties. The ideal configuration for avoiding early flow separation, which is essential for preserving equal airflow across the airfoil surface and improving overall aerodynamic efficiency, is suggested by the effectiveness of the 5% slot at Location 3. The improvement of the velocity also gives indication for drag reduction as explained in [14]. Furthermore, the velocity improvement also leads for better performance outcome as reported by [15] [16]. Overall, it has been demonstrated that the slot's size and location have a significant impact on the overall aerodynamics performance [17].

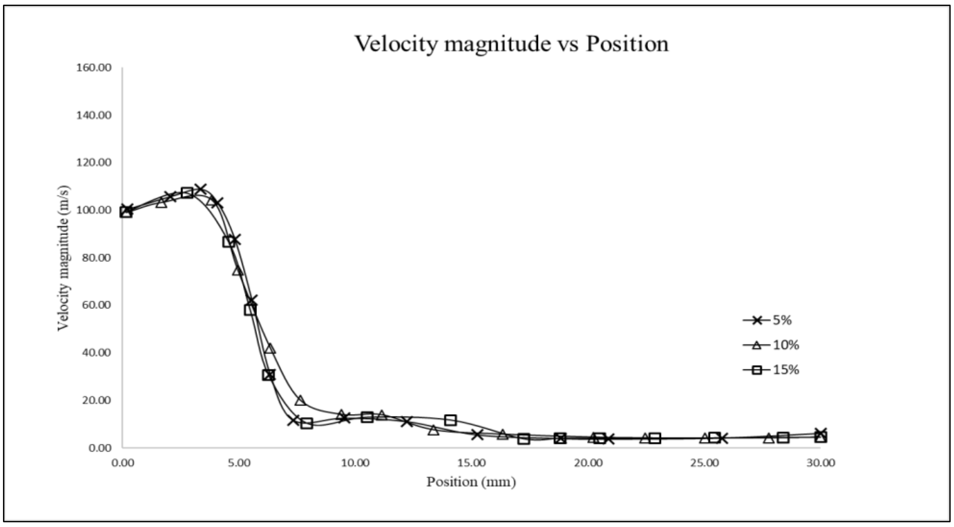


Figure 12 Velocity magnitude on airfoil surface at Location 1

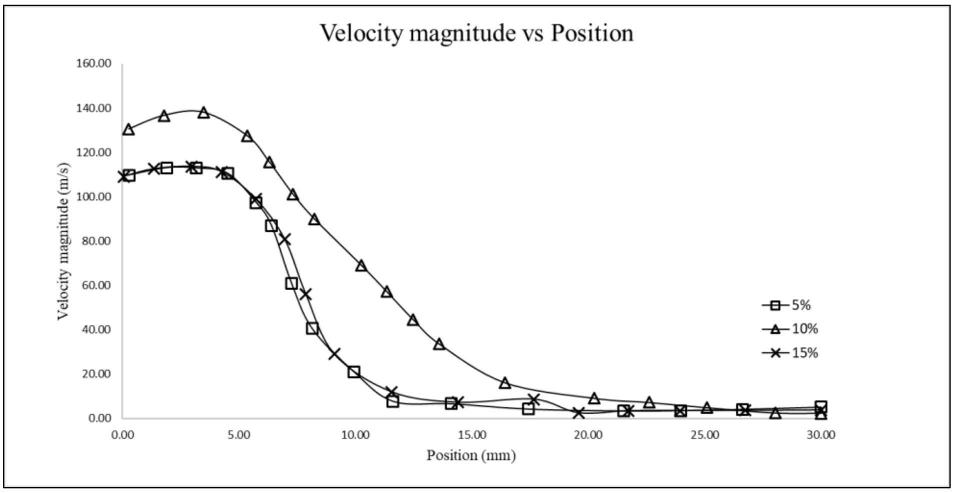


Figure 13 Velocity magnitude on airfoil surface at Location 2.

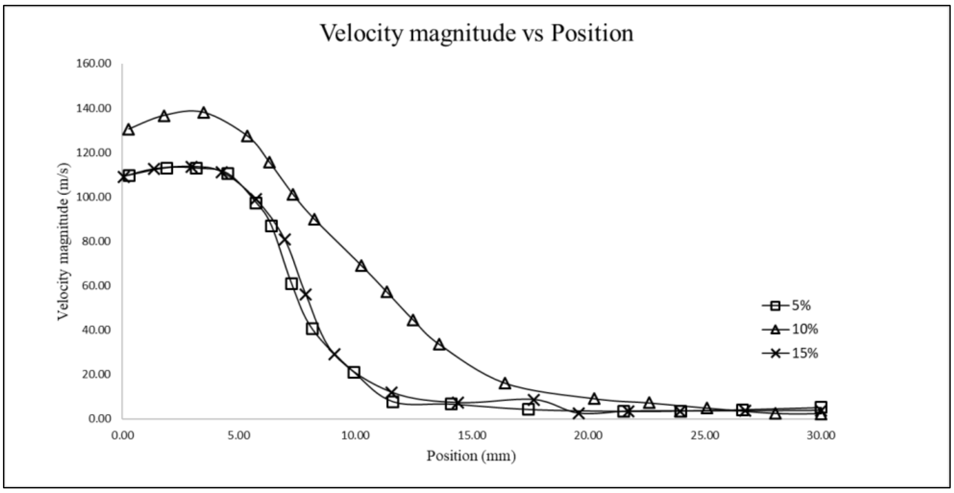


Figure 14 Velocity magnitude on airfoil surface at Location 3.

4.0 CONCLUSION

To sum up, this study has explored the use of a slot on the airfoil surface as a passive flow control device to increase the lift-to-drag coefficient ratio and, consequently, helicopter performance. The effects of slot placement and dimensions on the airfoil's aerodynamic properties are simulated and analysed using ANSYS Workbench R2. The results show that slot size and location have a major influence on flow behaviour and aerodynamic performance, confirming that the study has successfully met its goals. The findings show that various slot configurations have a direct impact on the lift-to-drag ratio by producing variable impacts on the flow separation and reattachment. Location 3 exhibits the best performance among the studied designs, with a slot size of 5% of the chord length. When compared to the baseline scenario without a slot, this arrangement produces an impressive 70% improvement in the lift-to-drag coefficient ratio. A considerable delay in flow separation results from the efficient reattachment of the separated flow to the airfoil surface, as indicated by the velocity magnitude for this configuration. The study emphasizes how crucial exact slot placement and sizing are in attaining aerodynamic efficiency. Because it can reenergize the boundary layer and sustain connected flow over a greater area of the airfoil surface, location 3 turns out to be the most efficient. This study offers important insights for future applications in helicopter design and other aerodynamic systems by demonstrating the potential of passive flow control approaches, such as slot implementation, to improve the aerodynamic performance of airfoils.

It is suggested that future research concentrates on using experimental testing to validate the numerical results of this study. Verifying the accuracy of the computational results and gaining important insights into the slots' actual performance would be possible through wind tunnel testing. Furthermore, more research into the effects of various slot shapes—such as angled, tapered, or curved designs—as well as different orientations may open up new avenues for improving aerodynamic performance and flow control. Furthermore, investigating the use of slots on various airfoil profiles would assist in figuring out whether the lift-to-drag ratio gains that have been seen are consistent across different airfoil designs or if slot implementation is more advantageous for particular profiles. The knowledge of passive flow control methods and their possible uses would be greatly expanded by following these directions.

ACKNOWLEDGEMENT

We extend our thanks to Universiti Teknologi MARA for providing the oppurtinity to use CFD software at the computer lab.

DECLARATION OF COMPETING OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

[1] J. D. Anderson, A History of Aerodynamics and Its Impact on Flying Machines, Cambridge, United Kingdom: Cambridge University Press, 1997.

[2] J. G. Leishman, Principles of Helicopter Aerodynamics, 2nd Edition, United Kingdom: Cambride University Press, 2006.

[3] J. J. Bertin and R. M. Cummings, Aerodynamics For Engineers, vol. 6th Edition, P. V. Reddy, Ed., England: Cambridge University Press, 2021.

[4] J. Hsueh, C. Fritz, C. E. Thomas , A. P. Reimer, A. T. Reisner, D. Schoenfeld, A. Haimovich and S. H. Thomas, "Applications of Artificial Intelligence in Helicopter Emergency Medical Services," Air Medical Journal, vol. 43, no. 2, pp. 90-95, 2024.

[5] S. Singh, S. Shrestha, P. Nakarmi, R. Yadav, S. Ulla, S. Singh, R. Pande, P. Kumar Jha, B. Joshi, A. Baniya, S. Thapa and S. Karki, "Evolution of Helicopter Services and Their Development From a Medical Standpoint," Air Medical Journal, vol. 44, no. 1, pp. 30-33, 2025.

[6] R. P. Patterson, Vibration Reduction in Rotorcraft Using Active Flow Control, 2021.

[7] D. Greenblatt, C. L. Rumsey and I. J. Wygnanski, "Aerodynamic Flow Control," Ensyclopedia of Aerospace Science, 2010.

[8] J. C. Boniface , G. Gibertini, A. Zanotti, G. Droandi, F. Auteri, R. Gavériaux and A. Le Pape, "Helicopter Drag Reduction by Vortex Generators," Aerospace Science and Technology, vol. 47, pp. 324-339, 2015.

[9] B. Bakhtiari Nia, M. Ja'fari, A. Reza Ranjbar and A. J. Jaworski, "Passive Flow Control of Boundary Layer Flow Separation on Wind Turbine Airfoil Using Vortex Generator and Slot," Ocean Engineering, vol. 283, 2023.

[10] Y. Xie, Y. Rao, Y. Cheng and W. Tian, "Investigation into the laminar separation flow control of airfoil at low Reynolds number by dimple vortex generator.," Aerospace Science and Technology, Shanghai, China, 2022.

[11] "NACA 4 digit airfoil generator (NACA 0012 airfoil)," Airfoil Tools, [Online]. Available: http://airfoiltools.com/airfoil/naca4digit?MNaca4DigitForm%5Bcamber%5D. [Accessed 29 August 2024].

[12] Ö. Faruk Buyukluoğlu and H. Bayram, "Aerodynamic Performance Analysis of Airfoils by Using CFD Method," in International Symposium on Sustainable Aviation, 2015.

[13] M. Tarek Tawfik Soltan and M. M. Abdelrahman, "Helicopter Performance Enhancement by Alleviating Retreating Blade Stall Using Active Flow Control," Scientific African, vol. 21, 2023.

[14] W. Shi, J. Li, H. Gao, H. Zhang, Z. Yang and Y. Jiang, "Numerical Investigations on Drag Reduction of A Civil Light Helicopter Fuselage," Aerospace Science and Technology, vol. 106, pp. 2-5, 2020.

[15] S. Kumar, S. K. Singh, S. Jha, K. Baskaran, K. Srinivasan and S. Narayanan, "On The Reduction of Airfoil Broadband Noise Through Circular Dimples," Applied Acoustic, vol. 217, 2024.

[16] W. Stalewski and W. Zalewski, "Performance Improvement of Helicopter Rotors Through Blade Redesigning," Aircraft Engineering and Aerospace Technology, vol. 91, no. 5, pp. 747-755, 2019.

[17] T. Oktay and Ö. Özdemir Kanat, "A Review of Aerodynamic Active Flow Control," in 8th International Advanced Technologies Symposium, Etciyes University, Kayseri, Turkey, 2017.