



International Journal of Sustainable Aviation

ISSN online: 2050-0475 - ISSN print: 2050-0467

<https://www.inderscience.com/ijsa>

Experimental and computational study on a morphed trailing edge airfoil for enhanced lift and stall characteristics

Krish V. Raibole, Kundlik V. Mali

DOI: [10.1504/IJSA.2025.10070605](https://doi.org/10.1504/IJSA.2025.10070605)

Article History:

Received:	15 July 2024
Last revised:	30 October 2024
Accepted:	11 December 2024
Published online:	17 April 2025

Experimental and computational study on a morphed trailing edge airfoil for enhanced lift and stall characteristics

Krish V. Raibole*

Department of Mechanical Engineering,
Dr. Vishwanath Karad MIT World Peace University,
Survey No. 124, Paud Rd., Kothrud,
Pune, Maharashtra 411038, India
and
Indian Institute of Technology Bombay,
Main Gate Rd., IIT Area, Powai, Mumbai,
Maharashtra 400076, India
Email: krishraibole@gmail.com
*Corresponding author

Kundlik V. Mali

Department of Mechanical Engineering,
Dr. Vishwanath Karad MIT World Peace University,
Survey No. 124, Paud Rd., Kothrud,
Pune, Maharashtra 411038, India
Email: kundlik.mali@mitwpu.edu.in

Abstract: The current study presents a morphed trailing edge methodology applied to a Clark-Y airfoil in order to improve the effective stall angle of the specific airfoil under definite conditions. A morph of 2° was provided to the trailing edge of the Clark-Y airfoil in consideration. The performance of the morphed wing was analysed by varying two parameters, the angle of attack (AOA) and the freestream flow velocity. The AOA was varied from 0° to 50° , while the flow stream velocity was 10 m/s and 12 m/s. The morphed airfoil showed a maximum increase in the lift-to-drag ratio at 15° and 10 m/s flow velocity. Although at the cost of lift force and a minor increase in drag, the stall angle of the airfoil is improved from 22° to 25° . Numerical simulations showed a maximum deviation of 12.7% with the experimental data, affirming the reliability of the simulations and the methodology.

Keywords: morphed; trailing edge; airfoil; stall; angle of attack; AOA; drag; lift.

Reference to this paper should be made as follows: Raibole, K.V. and Mali, K.V. (2025) 'Experimental and computational study on a morphed trailing edge airfoil for enhanced lift and stall characteristics', *Int. J. Sustainable Aviation*, Vol. 11, No. 1, pp.99–114.

Biographical notes: Krish V. Raibole is a mechanical engineering graduate from the Dr. Vishwanath Karad MIT World Peace University in Pune, India. He has achieved notable milestones, including a published patent in South Africa and research paper presentations at the international conferences.

Currently, he is a research scholar at the IIT Bombay in the Aerospace department. His passion for engineering drives his dedication to making a difference through research and innovation.

Kundlik V. Mali is a distinguished academic professional, serving as a Professor since 2015 at the Dr. Vishwanath Karad MIT World Peace University in Pune, India. With a specialisation in the mechanical department, his expertise lies in the field of heating, ventilation, and air conditioning (HVAC). He has made significant contributions to the academic and research community, with publications in esteemed journals. His academic journey includes an MTech in Mechanical Engineering from the COEP Technological University (2014–2016) and a PhD in Thermal HVACR from the Savitribai Phule Pune University.

1 Introduction

The aviation sector has come under intense pressure in the last few decades to reduce worldwide fuel consumption and emissions arising from its consumption (Bashir et al., 2021). This has led the industry to implement modern technologies like advanced propulsion techniques, air traffic management, and laminar flow techniques. Out of these technologies, morphing and morphed wing technology is two of the most promising technologies that display high potential for decreasing fuel consumption in the near future (Pecora, 2021). A morphed airfoil serves different advantages over a symmetrical low lift-drag ratio airfoil used in low velocity conditions as it provides passive control over the flight performance. In 2018, a single deployable scissor-structural mechanism (SSM) (Şahin and Yaman, 2018) was developed, synthesised, and analysed with six SLE's, which were analysed aerodynamically with XFLR5. A study conducted in 2019 (Geva et al., 2019) developed and experimentally investigated an innovative mechanism for a morphing aircraft that has the ability to vary between two discrete working points such that its resulting endurance was enhanced by 50% when compared to conventional aircraft wings. Recently in 2020 (Rajendran et al., 2020), a morphing airfoil was additively manufactured with a variable camber by using a compliant rib mechanism. More recently in 2021 (Bashir et al., 2021), an aerodynamic optimisation method was established for a morphing trailing and leading edge for the UAS-S45 unmanned aerial vehicle with the help of Bezier-PARSEC parameterisation. Their studies revealed that the morphed trailing edge amplified the efficiency of $C_L^{3/2}/C_D$ by 10.25% while also demonstrating enhanced endurance of the structure. In 2022 (Mekonnen et al., 2022), dielectric elastomer actuators (DEA) were implemented and, with the use of 3D printing, a prototype was manufactured that made use of entrenched distributed actuators, enabling wing morphing while also sustaining heavy loads.

Another study (Srinath et al., 2022) involved the use of Bezier curve parametrisation along with synthetic jet modules to enhance flight properties of a morphing wing.

In 2016, a study (Yeong and Dol, 2016) experimentally validated the CFD results of a modified propeller for a micro-aerial vehicle to enhance lift characteristics, along with the formation of a design matrix for the selection optimisation of the most suitable airfoil. This paper focuses on implementing morphed trailing edge methodology on airfoils suitable for low-velocity flight conditions so as to increase stall angle and enhance the

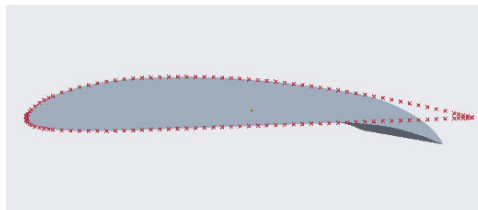
lift-to-drag ratio. With the enhancement of the wing's stall angle, the safety of the unmanned aerial vehicles (UAV) is improved as it provides an increased domain of operation. With higher stall angles, the aerial vehicle can sustain harsh weather conditions successfully while also reducing the chances of sudden drops in altitude due to sudden pressure differences, thereby avoiding stall. Morphing technology mainly includes two subdivisions: active morphing and passive morphing. Active morphing technologies allow for a variety of dynamic wing shape modifications, involving adjustments to the span and sweep, variations in twist or dihedral angle, airfoil camber, or thickness distribution (Dhileep et al., 2020; Bashir et al., 2023). Whereas in a passively morphed structure, only specific passive changes such as drooping the trailing edge or leading edges are implemented in the design phase and stay constant throughout the application of the airfoil. Both military and civilian aircraft typically fly at just one or a few ideal flight conditions during the design phase; however, morphing is intended to enhance the number of ideal operational regions for a particular aircraft (Communier et al., 2019). Due to the limitations of the practical application of the dynamic morphing technology, this study implements a passive morphed trailing edge airfoil that encompasses a few advantages of the dynamic morphing while also preserving the structural integrity of the orthodox airfoil, which is presently extensively used globally.

2 Materials and methods

2.1 Modelling and geometry morphing

The base airfoil was selected after shortlisting five airfoils from the global airfoil database that are more commonly used for low velocities, low altitudes, and lightweight flights, mainly in order to suit drone applications. The airfoils considered in this study were NACA 0012-34, Eppler 423, NACA0012H, SG6043, and Clark-Y. Out of these, Clark-Y was chosen for its cambered geometry while also providing a high lift-to-drag ratio for varied angles of attack. Recently in 2022 (Kapoulas et al., 2022), an airfoil selection methodology was developed, especially for low Reynolds number airfoils, using XFLR5 software. Although the implementation of an airfoil selection methodology is beyond the scope of this study. The selected airfoil's coordinates were imported and plotted using Creo Parametric, while to produce the appropriate morphed geometry, morphing was accomplished using the shape morphing tool in CATIA V5. Figure 1 displays the comparison between the morphed airfoil and the unmorphed airfoil geometry, represented by the red plotted line.

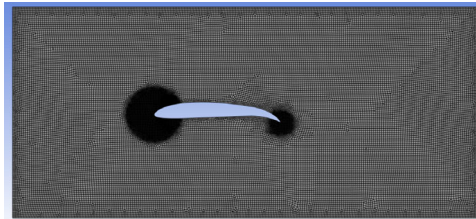
Figure 1 Morphed Clark-Y Airfoil geometry (colour) (see online version for colours)



2.2 Computational analysis

A simple two-dimensional case, with a velocity inlet and a pressure outlet, was setup in Ansys Fluent to analyse the lift and drag forces on the morphed and unmorphed airfoils. A fine mesh was generated, and two spheres of influence were provided, one at the trailing edge and one at the leading edge, respectively, to record the gradients. Additionally, the mesh near the airfoil's wall was kept finer to effectively capture the boundary layer gradients. The domain was discretised using 150 grids along the width and 300 grids along the length, with a total cell count of 48,000. A cell count of 48,000 was deemed appropriate for the present study considering its two-dimensional nature and the simplicity of the fluid flow involved (Şahin and Acir, 2015). To ensure reliability on the results obtained from a mesh of 48,000 cells, a single case with a cell count of 58,000 was run and its results were compared with those obtained from the domain with a cell count of 48,000. The results showed a nominal difference. Thus, a cell count of 48,000 was used in the present study. Meshing of the domain is illustrated in Figure 2. Apart from the inlet and outlet, all the other boundaries were set as a wall with no-slip boundary condition. A pressure-based solver was used with steady flow conditions due to its suitability for low velocities (Aftab et al., 2016). Turbulence intensity was fixed at 5% with a turbulence viscosity ratio of 10. The SST $k-\omega$ (two equations) model, developed in the 1990s by Menter (1992, 1994), was used as the turbulence model for the current study. This turbulence model is one of the most widely accepted models as it combines the advantages of both, the $k-\omega$ model (Wilcox, 1993) and the $k-\varepsilon$ model (Lauder and Spalding, 1983). The pressure based coupled scheme was chosen for the pressure-velocity coupling owing to its suitability for low Mach number flows (Karimian and Schneider, 1994; Chen and Przekwas, 2010; Denner, 2018). The solution was run until successful convergence of the residuals was achieved. Similar methodology was followed for both the unmorphed and morphed airfoils for all angles of attack and flow velocities. This computational analysis was done as a preliminary step only to assess feasibility and also served to verify if the morphed airfoil would provide positive results, before proceeding to experimentation (Prasad et al., 2013).

Figure 2 Meshing of the domain (see online version for colours)



2.3 Additive manufacturing (AM)

The Ultimaker S5 3D printer was used to manufacture both the airfoils (Raibole and Deshmukh, 2024). Tough PLA material was used with an infill density of 10%, as stress or load bearing capacity was beyond the scope of this study. A total of 82 g of material was used to make both the airfoils, resulting in a very lightweight and durable structure. Figure 3 shows the printing process used to manufacture the airfoils. Figures 4 and 5

show the cross-sectional view of the final product and the isometric view of the airfoils, respectively.

Figure 3 3D printing in Ultimaker S5 (colour) (see online version for colours)



Figure 4 Cross-sectional views of morphed vs. unmorphed airfoil (colour) (see online version for colours)

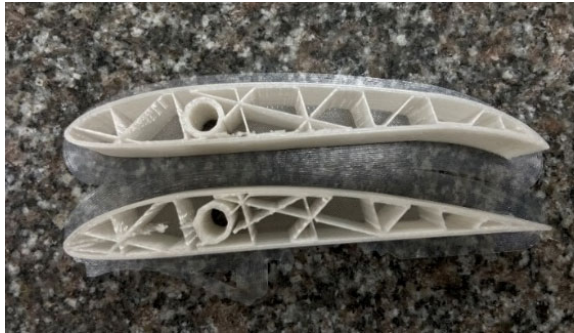
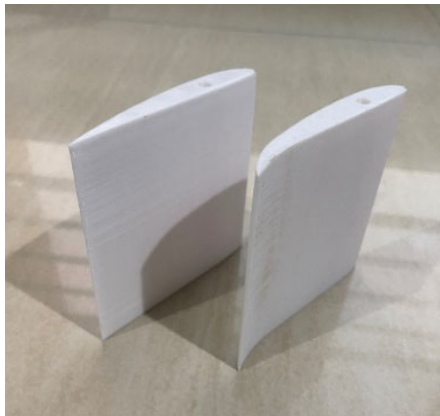


Figure 5 Final prototypes of the airfoils (colour) (see online version for colours)



3 Experimentation

Essom's MP315D subsonic wind tunnel was used as the setup to experimentally validate the performance of the airfoils. Figure 6 shows the setup that was used, which has a maximum limit of 30 m/s of flow velocity that was achieved with a fan of diameter 300 mm. The flow velocity was controlled by varying the power delivered to the fan and is indicated with the help of an inclined manometer. The wind tunnel's high contraction ratio (9:1) ensures a uniform flow velocity across the transparent test section measuring 150 mm $\times$ 150 mm $\times$ 450 mm in length. Once the airfoil model was mounted in the centre of the test section, so that it is equally spaced from every neighbouring wall, the flow velocity was gradually increased till it reached the desired velocity of 10 m/s or 12 m/s. This was done in order to minimise any disturbances within the flow, thus maintaining a uniform flow in the test section. Lift and drag forces acting on the morphed airfoil were calculated using the setup, first for 10 m/s and then for 12 m/s. The setup makes use of a two-component balance for measuring the lift and drag forces acting on the model and the data is digitally displayed, which varies in almost real-time with varying AOA. For every AOA, the values of lift and drag forces displayed were recorded only after the flow velocity was observed to have stabilised. The mount on which the airfoil is set up, includes a graduated dial on the outside of the test section through which the AOA of the airfoil model can be varied. Low flow velocities of 10 m/s and 12 m/s were chosen in the present study considering the application of the proposed methodology which targets small scale drones or UAV which mostly fly below speeds of 15 m/s (Mohsan et al., 2023). Furthermore, at such velocities, the flow is mostly laminar and would provide reliable and accurate results.

Figure 6 Experimental setup (colour) (see online version for colours)



A similar procedure was followed for the unmorphed airfoil. Figures 7 and 8 are graphical representations of the obtained experimental data to show the relation between AOA and the lift and drag forces acting on the morphed airfoil under flow velocities of 10 m/s and 12 m/s, respectively.

All the measurements for the lift and drag forces mentioned in this study are measured in kg. While Figure 9 displays the experimental setup with the morphed airfoil prototype inside the wind tunnel. Figures 10 and 11 are graphical representations of the

obtained experimental data to show the relation of AOA with the lift and drag forces acting on the unmorphed airfoil under flow velocities of 10 m/s and 12 m/s, respectively. Figure 12 displays the experimental setup with the unmorphed airfoil prototype inside the wind tunnel.

Figure 7 Lift and drag forces for morphed airfoil at 10 m/s (colour) (see online version for colours)

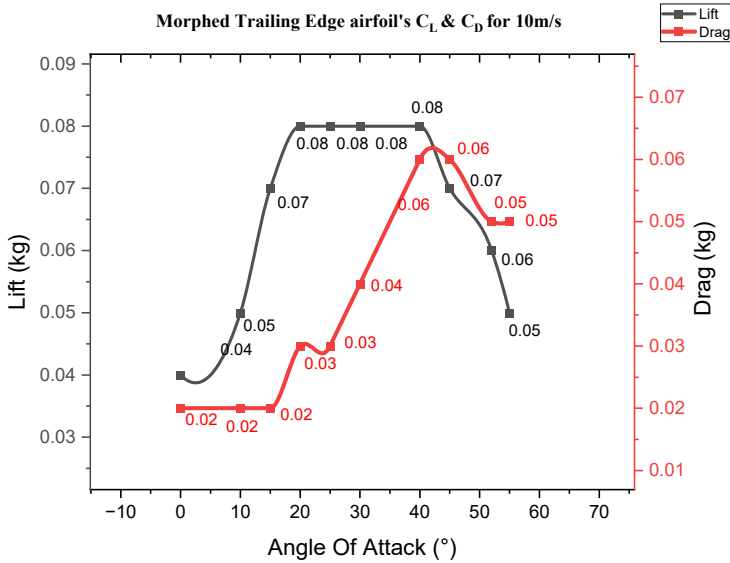


Figure 8 Lift and drag forces for morphed airfoil at 12 m/s (colour) (see online version for colours)

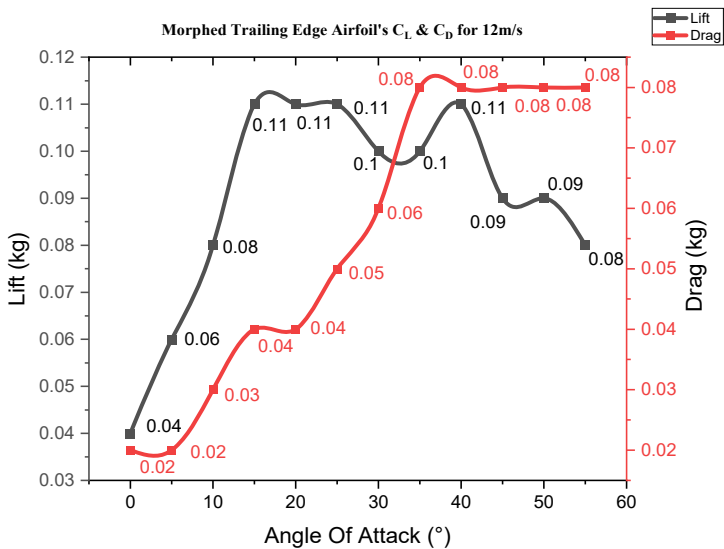


Figure 9 Morphed airfoil in subsonic-wind tunnel (colour) (see online version for colours)

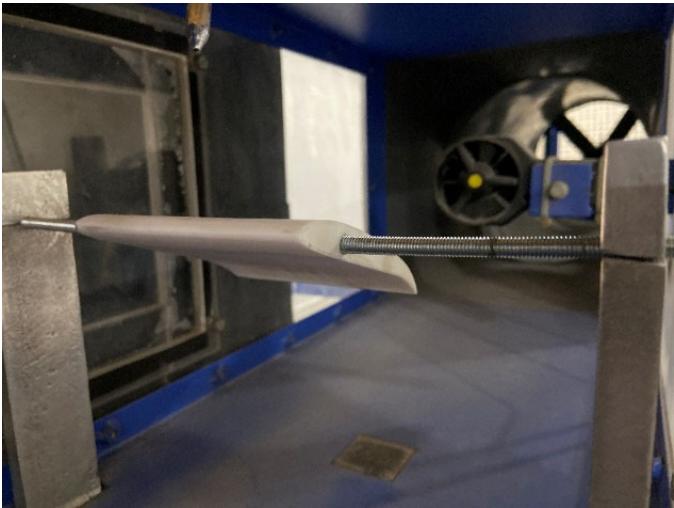


Figure 10 Lift and drag forces for unmorphed airfoil at 10 m/s (colour) (see online version for colours)

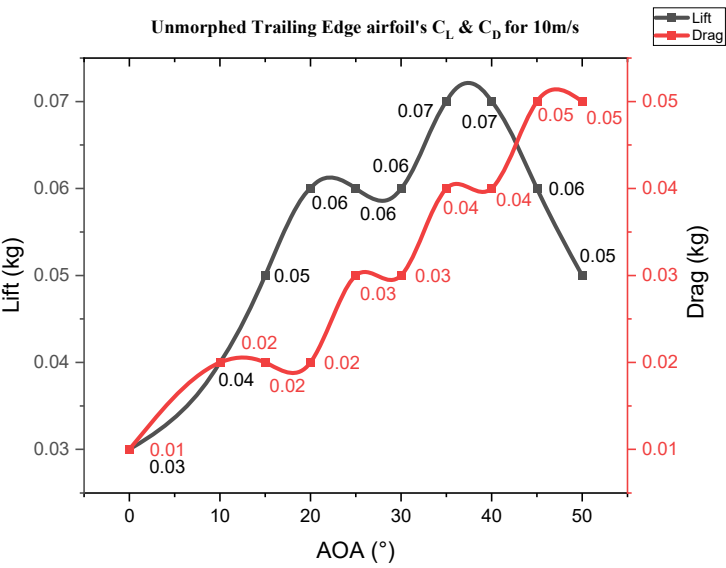


Figure 11 Lift and drag forces for unmorphed airfoil at 12 m/s (colour) (see online version for colours)

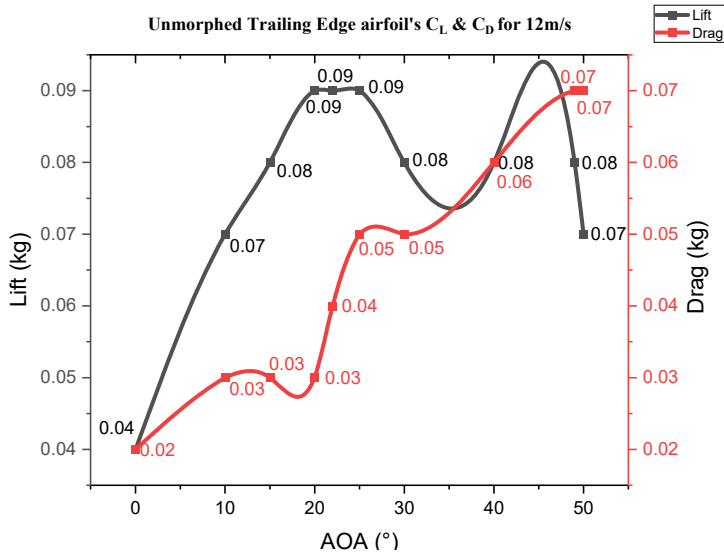
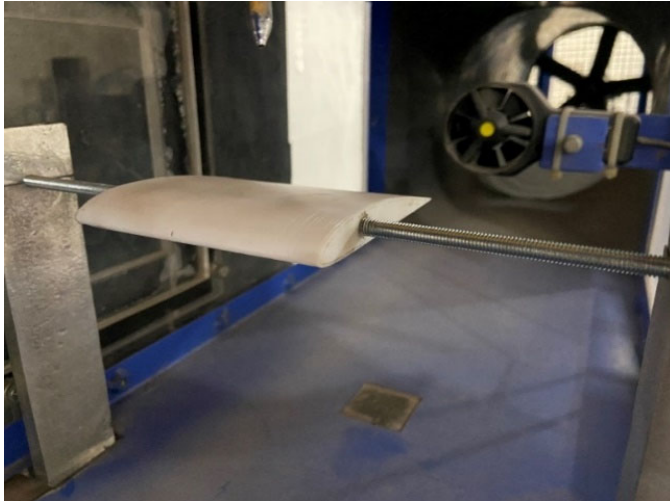


Figure 12 Unmorphed airfoil in the subsonic wind tunnel (colour) (see online version for colours)



4 Results and discussion

The morphed airfoil showed considerable and promising outcomes, with the aim of enhancing the flight performance of the Clark-Y airfoil. Under both flow stream velocities of 10 m/s and 12 m/s, the morphed airfoil showed an increase in lift forces, stall angle, and a substantial increase in the (C_L/C_D) under some AOA's. The non-

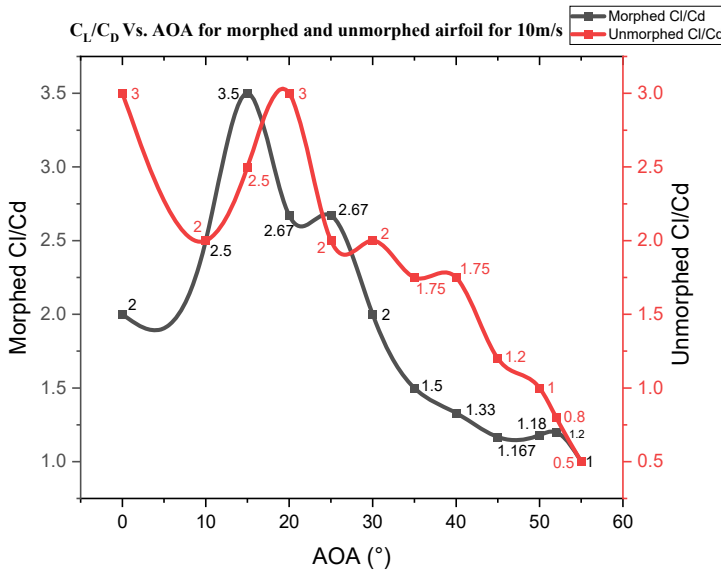
dimensional lift (C_L) and drag coefficients (C_D) are given by equations (1) and (2) respectively:

$$C_L = \frac{F_L}{\left(\frac{1}{2}\right)\rho V^2 A} \quad (1)$$

$$C_D = \frac{F_D}{\left(\frac{1}{2}\right)\rho V^2 A} \quad (2)$$

F_L and F_D are the lift force and drag forces (N) acting on the airfoil, V is the flow velocity (m/s), ρ is the fluid's density (kg/m^3) and A is the swept area of the airfoil (Contreras Montoya et al., 2021; Liu, 2021). Figure 13 displays the comparison of the lift-to-drag ratio between the morphed and the unmorphed airfoil at 10 m/s. At an AOA of 10° , C_L/C_D increased from 2 to 2.5 for the morphed airfoil. Similarly, for 15° AOA, (C_L/C_D) increased from 2.5 to 3.5, and for 25° AOA, (C_L/C_D) increased from 2 to 2.67 for the morphed airfoil, with the maximum increase of 1° at 15° . Past studies which have implemented dynamic wing morphing techniques also showcased a similar result, wherein with insignificant changes in the (C_L/C_D) ratio, morphed airfoils exhibited higher lift values (Vale et al., 2011; Majid and Jo, 2021). Additionally, the reduced drag forces on the morphed airfoil in the present study are in line with the trends observed by previous researchers (Suzuki et al., 2010; Namgoong et al., 2012).

Figure 13 C_L/C_D comparison at 10 m/s (colour) (see online version for colours)



A significant increase of 3° in the stall angle, from 22° to 25° , was achieved in the morphed airfoil for a 10 m/s flow stream velocity, as can be seen in Figure 13. Similar results were obtained for 12m/s as well, as seen in Figure 15, with the maximum increase in (C_L/C_D) ratio at 25° AOA. For 10° AOA, (C_L/C_D) increased by 0.34. Figures 14 and 16 graphically demonstrate the % change in (C_L/C_D) ratio achieved for the morphed

airfoil at 10 m/s and 12 m/s, respectively. Similar to 10m/s, at 12m/s too, an increase of stall angle from 22° to 25° was observed. Experimental studies from the past have reported a similar effect of wing morphing, wherein the stall angle of the airfoil is observed to be delayed as a result of higher lift coefficients at the critical stall angles of the airfoil (Gamble et al., 2017; Kan et al., 2020).

Figure 14 Percentage change in lift to drag ratio for 10 m/s (colour) (see online version for colours)

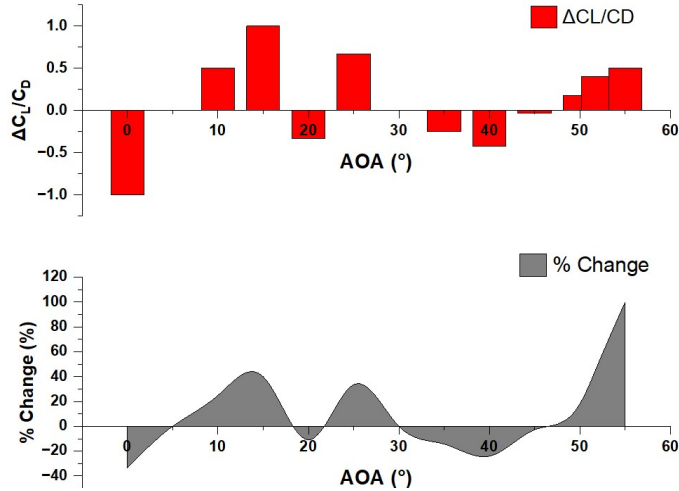
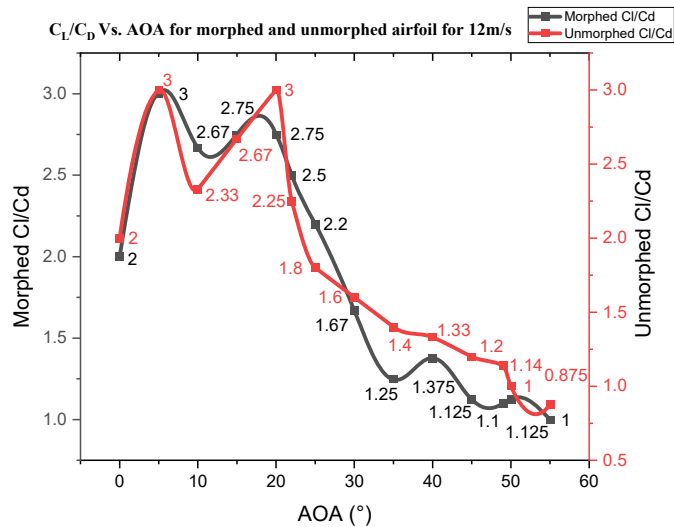


Figure 15 C_L/C_D comparison at 12 m/s (colour) (see online version for colours)



Computational simulations provided similar results for all angles of attack and both flow stream velocities of 10 m/s and 12 m/s. Pressure and velocity contours were studied to analyse the flight performance of the airfoils. A significant rise in pressure on the lower surface of the morphed airfoil was observed as compared to the unmorphed airfoil. The

reason for this sudden increase in pressure magnitude can be attributed to the morphed structure which exerts a passive control on the flow separation, in line with the results reported in earlier studies (Jones et al., 2018; Olivett et al., 2021).

Figures 17 and 18 show pressure contours for 8° and 25° AOA, with the lower edge of the airfoil at 111.2 Pa while the upper edge being under negative pressure of up to −62.4 Pa. This drastic change in pressure of more than 170 Pa, along with a controlled flow separation, corresponds to the increased lift forces on the morphed airfoil.

Figure 16 Percentage change in lift to drag ratio for 12 m/s (colour) (see online version for colours)

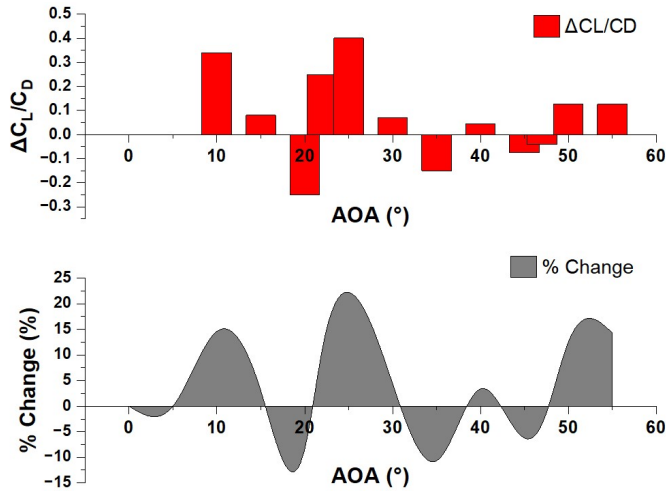


Figure 17 Pressure contour for 25° AOA and 10 m/s (colour) (see online version for colours)

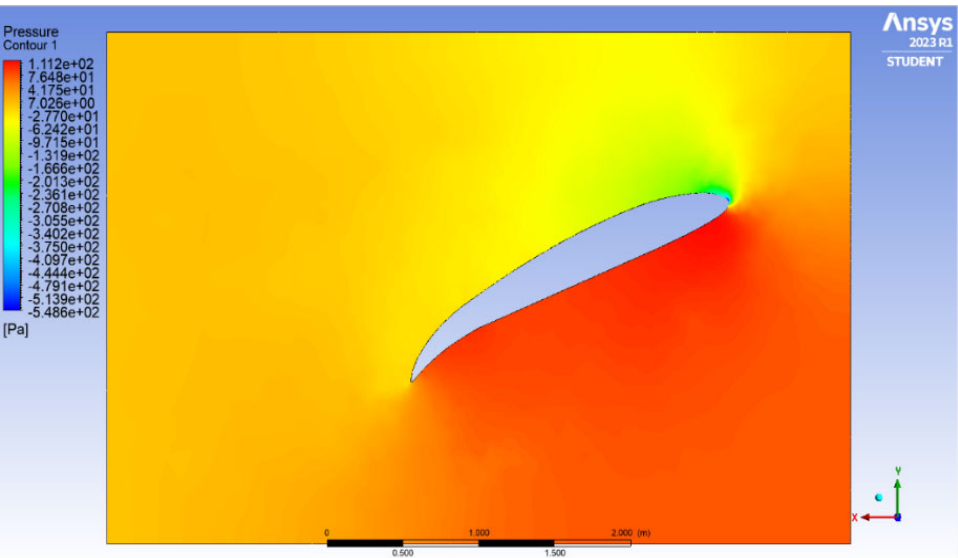
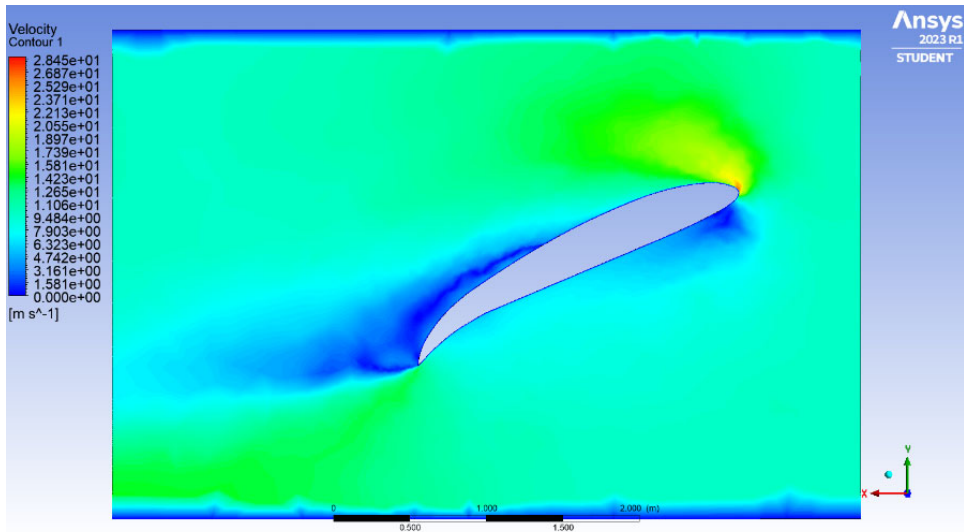


Figure 18 Velocity contour for 25° AOA and 10 m/s (colour) (see online version for colours)

5 Conclusions

The present study demonstrates an effortless methodology that has been implemented to improve the flight performance of certain airfoils, particularly at low flow velocities. This study presents as a viable technique in improving the lift and stall angles of airfoils, particularly for small scale drones and UAV's which fly at low altitudes and velocities. Two primary results were successfully obtained and demonstrated for the morphed airfoil, which are an increase in the lift-to-drag ratio and a significant increase in the stall angle. These advantages of passive morphing over active morphing were verified using experimental methods which demonstrated how, without compromising the structural integrity of airfoils by adding moving parts, flight performance can be enhanced. For 10 m/s velocity, a maximum increase of 1 in (C_L/C_D) was observed at 15° AOA, wherein (C_L/C_D) increased from 2.5 to 3.5. Whereas for a 12 m/s velocity, the maximum increase in the (C_L/C_D) ratio of 0.4 was observed at 25° AOA. Thus, the morphed airfoil showcased better enhancement in flight performance at the lower flow velocity of 10 m/s. The capability of the passive geometry morphing proposed in this study with increasing flow velocities above 12 m/s should be investigated in future studies. The percentage difference between the simulation and experimental results was 12.7%. For all AOA and flow velocities, a difference of 8%–12% was found between the simulated and experimental data. For 25° AOA and 10 m/s inlet velocity, the experimentally calculated (C_L/C_D) was 2.67, whereas the lift-to-drag ratio obtained from the computational simulation was observed to be 2.33. With the maximum difference between the simulated and experimental (C_L/C_D) ratios being 0.34.

Furthermore, in the future, this methodology can be implemented to different airfoil geometries in order to improve their performance, which could thereby provide a comparative analysis showcasing the effect of passive morphing on a range of airfoils. Future studies along the same lines, should also consider the effect of strong turbulent

flows occurring at high Reynolds numbers which would further enhance the practicality and viability of this methodology.

Data availability

The dataset supporting the conclusions of this article is included within the article and its additional files.

References

- Aftab, S.M.A. et al. (2016) ‘Turbulence model selection for low Reynolds number flows’, *PLoS ONE*, Vol. 11, No. 4, <https://doi.org/10.1371/journal.pone.0153755>.
- Bashir, M. et al. (2021) ‘Aerodynamic design optimization of a morphing leading edge and trailing edge airfoil-application on the uas-s45’, *Applied Sciences (Switzerland)*, Vol. 11, No. 4, pp.1–34, <https://doi.org/10.3390/app11041664>.
- Bashir, M. et al. (2023) ‘Flow control around the UAS-S45 pitching airfoil using a dynamically morphing leading edge (DMLE): a numerical study’, *Biomimetics*, Vol. 8, No. 1, <https://doi.org/10.3390/biomimetics8010051>.
- Chen, Z.J. and Przekwas, A.J. (2010) ‘A coupled pressure-based computational method for incompressible/compressible flows’, *Journal of Computational Physics*, Vol. 229, No. 24, pp.9150–9165, <https://doi.org/10.1016/j.jcp.2010.08.029>.
- Communier, D., Botez, R.M. and Wong, T. (2019) ‘Experimental validation of a new morphing trailing edge system using Price – Païdoussis wind tunnel tests’, *Chinese Journal of Aeronautics*, Vol. 32, No. 6, pp.1353–1366, <https://doi.org/10.1016/j.cja.2019.03.016>.
- Contreras Montoya, L.T. et al. (2021) ‘8 – wind power plant planning and modeling’, in *Hybrid Renewable Energy Systems and Microgrids*, pp.259–312, Elsevier, Academic Press, USA, <https://doi.org/10.1016/B978-0-12-821724-5.00012-X>.
- Denner, F. (2018) ‘Fully-coupled pressure-based algorithm for compressible flows: linearisation and iterative solution strategies’, *Computers & Fluids*, <https://doi.org/10.1016/j.compfluid.2018.07.005>.
- Dhileep, K. et al. (2020) ‘Numerical study of camber morphing in naca0012 airfoil’, in *AIAA AVIATION 2020 Forum*, American Institute of Aeronautics and Astronautics Inc, AIAA, <https://doi.org/10.2514/6.2020-2781>.
- Gamble, L.L., Pankonien, A.M. and Inman, D.J. (2017) ‘Stall recovery of a morphing wing via extended nonlinear lifting-line theory’, *AIAA Journal*, Vol. 55, No. 9, pp.2956–2963, <https://doi.org/10.2514/1.J055042>.
- Geva, A., Abramovich, H. and Arieli, R. (2019) ‘Investigation of a morphing wing capable of airfoil and span adjustment using a retractable folding mechanism’, *Aerospace*, Vol. 6, No. 8, <https://doi.org/10.3390/AEROSPACE6080085>.
- Jones, G. et al. (2018) ‘Control of flow separation around an airfoil at low Reynolds numbers using periodic surface morphing’, *Journal of Fluids and Structures*, Vol. 76, pp.536–557, <https://doi.org/10.1016/j.jfluidstructs.2017.11.008>.
- Kan, Z. et al. (2020) ‘Delaying stall of morphing wing by periodic trailing-edge deflection’, *Chinese Journal of Aeronautics*, Vol. 33, No. 2, pp.493–500, <https://doi.org/10.1016/j.cja.2019.09.028>.
- Kapoulas, I.K. et al. (2022) ‘Fast airfoil selection methodology for small unmanned aerial vehicles’, *Applied Sciences (Switzerland)*, Vol. 12, No. 18, <https://doi.org/10.3390/app12189328>.

- Karimian, S.M.H. and Schneider, G.E. (1994) 'Pressure-based computational method for compressible and incompressible flows', in *Journal of Thermophysics and Heat Transfer*, pp.267–274, American Institute of Aeronautics and Astronautics Inc., <https://doi.org/10.2514/3.533>.
- Lauder, B.E. and Spalding, D.B. (1983) 'Paper 8 – the numerical computation of turbulent flows', in *Numerical Prediction of Flow, Heat Transfer, Turbulence and Combustion*, pp.96–116, Elsevier, Pergamon, USA, <https://doi.org/10.1016/B978-0-08-030937-8.50016-7>.
- Liu, T. (2021) 'Evolutionary understanding of airfoil lift', *Advances in Aerodynamics*, Vol. 3, No. 37, <https://doi.org/10.1186/s42774-021-00089-4>.
- Majid, T. and Jo, B.W. (2021) 'Comparative aerodynamic performance analysis of camber morphing and conventional airfoils', *Applied Sciences (Switzerland)*, Vol. 11, No. 22, <https://doi.org/10.3390/app112210663>.
- Mekonnen, D.T. et al. (2022) 'Morphing control surfaces by additively manufactured dielectric elastomer actuators', in *AIAA Science and Technology Forum and Exposition, AIAA SciTech Forum 2022*, American Institute of Aeronautics and Astronautics Inc, AIAA, <https://doi.org/10.2514/6.2022-1552>.
- Menter, F.R. (1992) 'Improved two-equation k-turbulence models for aerodynamic flows', *NASA Tech Memo 103975*, pp.1–31.
- Menter, F.R. (1994) 'Two-equation eddy-viscosity turbulence models for engineering applications', *AIAA Journal*, Vol. 32, No. 8, pp.1598–1605, <https://doi.org/10.2514/3.12149>.
- Mohsan, S.A.H. et al. (2023) 'Unmanned aerial vehicles (UAVs): practical aspects, applications, open challenges, security issues, and future trends', *Intelligent Service Robotics*, Vol. 16, No. 1, pp.109–137, <https://doi.org/10.1007/s11370-022-00452-4>.
- Namgoong, H., Crossley, W.A. and Lyrantzis, A.S. (2012) 'Morphing airfoil design for minimum drag and actuation energy including aerodynamic work', *Journal of Aircraft*, Vol. 49, No. 4, pp.981–990, <https://doi.org/10.2514/1.C031395>.
- Olivett, A., Corrao, P. and Amin Karami, M. (2021) 'Flow control and separation delay in morphing wing aircraft using traveling wave actuation', *Smart Materials and Structures*, Vol. 30, No. 2, <https://doi.org/10.1088/1361-665X/abd347>.
- Pecora, R. (2021) 'Morphing wing flaps for large civil aircraft: evolution of a smart technology across the clean sky program', *Chinese Journal of Aeronautics*, Vol. 34, No. 7, pp.13–28, <https://doi.org/10.1016/j.cja.2020.08.004>.
- Prasad, K.S., Krishna, V. and Kumar, B.B.A. (2013) 'Aerofoil profile analysis and design optimisation', *Journal of Aerospace Engineering and Technology*, Vol. 3, No. 2, pp.1–10 [online] <https://www.researchgate.net/publication/279186627> (accessed 27 January 2023, 10:29:33).
- Raibole, K.V. and Deshmukh, S.R. (2024) 'Applications and limitations of additive manufacturing techniques for manufacturing components of aerospace industry', *Advances in Materials and Agile Manufacturing CPIE 2023*, pp.11–19, Springer, Singapore, https://doi.org/10.1007/978-981-99-6601-1_2.
- Rajendran, R. et al. (2020) 'Analysis of morphing airfoil structures and fabrication of the wing using the concept of additive manufacturing', *International Journal of Engineering Research and Technology*, Vol. 9, No. 6, pp.1–5 [online] <https://www.ijert.org> (accessed 29 January 2023, 21:04:08).
- Şahin, H.L. and Yaman, Y. (2018) 'Synthesis, analysis, and design of a novel mechanism for the trailing edge of a morphing wing', *Aerospace*, Vol. 5, No. 4, pp.1–20, <https://doi.org/10.3390/aerospace5040127>.
- Şahin, İ. and Acir, A. (2015) 'Numerical and experimental investigations of lift and drag performances of NACA 0015 wind turbine airfoil', *International Journal of Materials, Mechanics and Manufacturing*, Vol. 3, No. 1, pp.22–25, <https://doi.org/10.7763/ijmmm.2015.v3.159>.

- Srinath, R. et al. (2022) 'Streamline effect improvement of additive manufactured airfoil utilizing dynamic stream control procedure', *Advances in Materials Science and Engineering*, <https://doi.org/10.1155/2022/1252681>.
- Suzuki, H., Rinoie, K. and Tezuka, A. (2010) 'Laminar airfoil modification attaining optimum drag reduction by use of airfoil morphing', *Journal of Aircraft*, Vol. 47, No. 4, pp.1126–1132, <https://doi.org/10.2514/1.46152>.
- Vale, J. et al. (2011) 'Aero-structural optimization and performance evaluation of a morphing wing with variable span and camber', *Journal of Intelligent Material Systems and Structures*, Vol. 22, No. 10, pp.1057–1073, <https://doi.org/https://doi.org/10.1177/1045389X11416031>.
- Wilcox, D.C. (1993) *Turbulence Modeling for CFD*, DCW Industries Inc., Glendale.
- Yeong, S.P. and DoI, S.S. (2016) 'Aerodynamic optimization of micro aerial vehicle', *Journal of Applied Fluid Mechanics*, Vol. 9, No. 5, pp.2111–2121, <https://doi.org/10.18869/acadpub.jafm.68.236.25522>.

Nomenclature

AOA	Angle of attack
CL	Coefficient of lift
CD	Coefficient of drag
CL/CD	Lift-to-drag ratio
CFD	Computational fluid dynamics
SLE	Scissor like elements
SSM	Scissor-structural mechanism
UAV	Unmanned aerial vehicle
