Lift, drag and pitching moment performances of different wing profiles for MAV wings

N I Ismail¹, H Yusoff¹*, H Sharudin¹, S Suhaimi² and S K Hamdan¹

¹Faculty of Mechanical Engineering, Universiti Teknologi MARA, Cawangan Pulau Pinang, 14000, Permatang Pauh, Pulau Pinang
²Faculty of Mechanical Engineering, Universiti Teknologi MARA Shah Alam, 40450, Shah Alam, Selangor

*hamidyusoff@ppinang.uitm.edu.my

Abstract. The wing profile for Micro Air Vehicle (MAV) can be easily developed through the polynomial equation method which is proven in generating good aerodynamic performances. However, the study demands more studies in profile configurations to provide more evidence which interrelated with its aerodynamic performances. Thus, in this works, an aerodynamic study on different wing profiles configurations has been carried out. Profile 1, Profile 2 and Profile 3 were developed through the 3rd order polynomial equations have analyzed based on simulation works by using ANSYS-CFX. Based on the lift distribution analysis, it shows that Profile 3 has a huge advantage in generating better lift distribution (C_L) among the wing profiles. Profile 3 able to produce at least 20% to 22.9% better maximum lift coefficient (C_Lmax) and C_L magnitude compared to the other wing profiles. Despite its benevolent in C_L performances, Profile 3 has induced the highest drag (C_D) penalty among the wing profiles. Profile 3 has consistently produced at least 57.5% higher C_D magnitude compared to other wing profiles. However, in terms of moment coefficient (C_M) performances, Profile 3 has shown a promising ability in providing better wing stability compared to the other wing profile due to steeper C_M slope.

1. Introduction

Micro air vehicle (MAV) is a small and portable flying vehicle which designed to specific mission similar to Unmanned Aerial Vehicle (UAV)[1]. MAV has been defined to have a maximum length is 6 inches[2] with the gross takeoff weight at 200 gram or less[3]. MAV fly in the low Reynolds Number regime which is 10³ or less[4]. Due to the low Reynolds number ranges, the airfoil for such MAV applications should be thin and well-cambered. MAV needs a thin airfoil in order to produce higher lift coefficient, C_L and consequently better lift to drag ratio[5]. A thin cambered plate airfoil with Zimmerman wing planform is the most suitable wing for such MAV application since it can induce better lift coefficient (C_L) compared to the flat plate airfoil configurations[6]. Generally, a thin and cambered airfoil geometry can be design based on a certain polynomial order. This polynomial order method provides freedom for airfoil designer in choosing suitable airfoil shape for MAV. In fact, the 3rd order polynomial airfoil has been proven in generating a good performing MAV airfoil for low Reynolds number operation[7]. However, the wing profile design demands more configuration studies to provide more evidence which interrelated with its aerodynamic performances. Thus, in this works, an aerodynamic study on MAV wing configurations with different wing profiles configurations (based
on 3rd order polynomial equations) has been carried out. The study focuses on the aerodynamics performances (lift coefficient, $C_L$, drag coefficient, $C_D$, and moment coefficient, $C_M$) of three proposed wing profiles (known as Profile 1, Profile 2 and Profile 3) designed with difference 3rd polynomial order equations. The performances of each wing profiles are analyzed through the virtual wind tunnel simulation works by using ANSYS-CFX. The $C_L$, $C_D$, and $C_M$ results for each wing profile is compared and the optimal wing profile is determined at the end of study based on the aerodynamic performances.

2. Methodology

2.1. CFX computation method
In this works, Ansys-CFX simulation method was fully utilized to analyze the aerodynamic performance of each wing profile. Here. The 3D RANS equations coupled with SST k-ω turbulent equations were employed. The flow was assumed to be viscous, steady and incompressible.

2.2. MAV wing modeling
Based on the previous work[2], Zimmerman wing planform with thin airfoil profile was chosen for this study as shown in Figure 1. This is because Zimmerman wing planform has already shown its compatibility for MAV applications[6]. For configuration study, three different profiles (known as Profile 1, Profile 2 and Profile 3) produced by three difference 3rd polynomial order equations are proposed here. Figure 2 shows the thin wing profiles for Profile 1, Profile 2 and Profile 3. The main characteristics for each wing profile are given in Table 1. Basically, all wing has almost similar wing characteristics in terms of the chord length, wing area and aspect ratio. Every wing was tested at similar velocity input of 10.074 ms$^{-1}$ (equivalent to Reynold Number = 100,000 at root chord). The main differences between the wing are the profile equation (the 3rd polynomial order equations) to develop the wing profile. Resulting from the profile equation differences, each wing profile induced a difference in camber percentage (shown in Table 1).

![Figure 1. Zimmerman airfoil shape.](image-url)
Figure 2. Thin airfoil profile in 2D drawing.

Table 1: The main characteristics of each wing profile

| MAV Design | Profile 1 | Profile 2 | Profile 3 |
|------------|-----------|-----------|-----------|
| Equation   | $y = 0.00703x^3 - 0.1266x^2 + 0.0563x - 2 \times 10^{-16}$ | $y = 0.1405x^3 - 0.2531x^2 + 0.1126x - 5 \times 10^{-16}$ | $y = 0.281x^3 - 0.5062x^2 + 0.2252x + 9 \times 10^{-16}$ |
| Chord Length | 150 mm | 150 mm | 150 mm |
| Wing Area | 35640 mm$^2$ | 35254 mm$^2$ | 36610 mm$^2$ |
| Reynolds Number (Re) | 100 000 | 100 000 | 100 000 |
| Velocity | 10.074 ms$^{-1}$ | 10.074 ms$^{-1}$ | 10.074 ms$^{-1}$ |
| Aspect Ratio | 0.6313 | 0.6382 | 0.6146 |
| Camber percentage | 3.8% | 7.5% | 15.0% |

2.3. Domain sizing and mesh generation
In this work, Ansys-CFX has been fully utilized for the virtual wind tunnel simulation. To ease the solving process, the symmetrical wing condition for each wing design has been manipulated by slicing each wing CAD design into half. The airflow domains were built surrounding each wing based on the chord sizing as shown in Figure 3. An unstructured tetrahedral mesh of Ansys Solid 187 3D element type has been generated for each wing domain. The optimized mesh for the flow domain achieved at 535,379 elements as shown in Figure 4. The growing prism inflation layer option has been implemented on wing-airflow boundaries with the first cell above the wall is set at $y+ \leq 1$.

2.4. MAV wing boundary conditions
Figure 3 also shows the boundary conditions imposed on the air domain for the simulation works. The symmetrical wall and side wall were assigned as symmetrical and slip surface boundary conditions, respectively. In a virtual wind tunnel test, the ideal air with standard sea level air properties was used. Zero pressure boundary condition is enforced at the outlet with the inlet velocity magnitude $V = 10.074$ m/s (or equivalent to $Re \approx 100,000$) imposed at the inlet. The Angle of Attack (AoA) was set to
be varied between -10° to 42°. The wing surface itself was assigned as a non-slip surface. The turbulence was set at 5% with the automatic wall function was fully employed to solve the viscous effect on the wing surface. The simulation was run based on Reynolds Average Navier-Stokes equations (RANS) at steady state and incompressible flow conditions. The simulation convergence control was used to ensure the simulation results are reliable with momentum residual magnitude was used and kept below 1.0 x 10⁻⁵. The convergence monitoring also applied to the magnitude of lift coefficient (C_L) and drag coefficient (C_D) value.

![Figure 3](image1.png) Figure 3. The geometrical of computational airflow domain (Enclosure).

![Figure 4](image2.png) Figure 4. The optimized mesh and inflation layer for ANSYS-CFX solver.

### 3. Aerodynamic simulation results

The aerodynamic simulation results for the three wings profiles are discussed in this section. The results presented here focused on the main aerodynamics performances are known as lift coefficient (C_L), drag coefficient (C_D) and moment coefficient (C_M). The comparative study between the three wing profiles was carried out in each aerodynamics performances.

#### 3.1. Lift coefficient (C_L) distribution

Figure 5 shows the results of the lift coefficient (C_L) performance for all wings profiles. Generally, each wing induced almost similar C_L trend throughout the AoA increment. The C_L magnitude for each profile increase with AoA increment up to the maximum AoA incidence angle which also known as stall angle (AoA_{stall}). Each profile induced the maximum C_L magnitude (C_{L,\text{max}}) at AoA_{stall} before it tends to degrade its magnitude at the post-stall angle region.

Based on the C_L magnitude analysis taken at the pre-stall angle (0° to 30°), the result clearly shows that Profile 3 produced the highest C_L magnitude among the wing profiles. Profile 3 induces averagely 20% higher C_L magnitude compared to Profile 2 produced. While Profile 1 induced the lowest C_L magnitude among the wing profiles with averagely two times lower than the Profile 2 produced. In terms of AoA_{stall} magnitude, Profile 2 has the most delayed stall angle at AoA_{stall}=35°. This is followed by Profile 1 and Profile 3 at AoA_{stall}=32° and AoA_{stall}=30°, respectively. Based on these AoA_{stall} magnitude, it means that Profile 2 has at least 8.6% better stall angle compared to the other...
wing profiles. Analysis of the $C_{L_{\text{max}}}$ magnitude shows that Profile 3 has the highest $C_{L_{\text{max}}}$ magnitude among the wing profiles at $C_{L_{\text{max}}}=0.7478$. Profile 3 induced at least 22.9% higher $C_{L_{\text{max}}}$ magnitude compared to Profile 2 ($C_{L_{\text{max}}}=0.6085$) and Profile 1 ($C_{L_{\text{max}}}=0.2678$). Based on the analysis of the overall $C_L$ and $C_{L_{\text{max}}}$ magnitudes, it clearly shows Profile 3 has promising advantages in generating better $C_L$ distribution among the wing. Despite a slight disadvantage in AoA_stall performance, Profile 3 shows huge advantages in producing better $C_{L_{\text{max}}}$ and $C_L$ magnitude. Such benevolent performances are expected due to the higher camber percentage found in Profile 3.

3.2. Drag coefficient ($C_D$) distribution

The result of the drag coefficient ($C_D$) for each wing profile is shown in Figure 6. Generally, the result shows that each wing profile produced almost similar $C_D$ trend throughout AoA increment. The $C_D$ magnitude for each wing profile slightly decreases at early AoA ($\text{AoA} \approx -5^\circ$ to $0^\circ$). The $C_D$ magnitude reaches its lowest point at the minimum $C_D$ magnitude ($C_{D_{\text{min}}}$) before the $C_D$ value increase monotonically with AoA increment ($\text{AoA} \approx 0^\circ$ to $42^\circ$).

The $C_D$ result clearly shows each wing profiles reach the $C_{D_{\text{min}}}$ magnitude at nearly the same incidence angle of AoA $\approx 0^\circ$. By comparing the $C_{D_{\text{min}}}$ magnitude, it shows that Profile 1 has produced the lowest $C_{D_{\text{min}}}$ among the wing at $C_{D_{\text{min}}}=0.000027$. This is followed by Profile 2 and Profile 3 at $C_{D_{\text{min}}}=0.00719$ and $0.025753$, respectively. This means that Profile 1 induces almost two times lower $C_{D_{\text{min}}}$ compared to the other wing profiles.

Based on comparative analysis on the $C_D$ magnitude (conducted at AoA$\approx 0^\circ$ to $30^\circ$ or known as pre-stall angle), the results show that Profile 3 has consistently produced at least 57.5% higher $C_D$ magnitude compared to Profile 2. While Profile 2 has induced 80.9% higher $C_D$ magnitude compared to Profile 1. It clearly shows that Profile 3 has induced the highest drag penalty among the wing. Such condition is expected due to larger camber percentage found on Profile 3. Despite its benevolent $C_L$ performance due to larger camber configuration (Profile 3), it also contributes to a larger frontal area (additional form drags) and greater induce drag components.

![Figure 5. The $C_L$ performances for all three profiles.](image-url)
3.3. Moment coefficient ($C_m$) distribution

Figure 7 shows the $C_m$ results measured at the leading edge of each wing profile. The $C_m$ magnitude has been intentionally plotted against $C_m$ with a view to measure the $C_m$ curve slope ($\Delta C_m/\Delta C_l$) magnitude. In the aerodynamic study, the $\Delta C_m/\Delta C_l$ magnitude has been initially used to indicate the level of aircraft longitudinal stability. Steeper $C_m$ curve slope (lesser value of $\Delta C_m/\Delta C_l$ magnitude) means better wing stability. To ensure the consistency of comparative study, the analysis on $\Delta C_m/\Delta C_l$ magnitude was conducted only at the linear $C_l$ portion (in pre-stall region). For the current case study, the $\Delta C_m/\Delta C_l$ magnitude was analyzed at AoA 2° to 18°. The result from the $\Delta C_m/\Delta C_l$ analysis shows that Profile 3 has induced the steepest $C_m$ slope at $\Delta C_m/\Delta C_l = -0.296$. This is followed by Profile 1 and Profile 2 at $\Delta C_m/\Delta C_l = -0.256$ and -0.251, respectively. Based on these magnitudes, it means that Profile 3 has at least induced 13.4% better $C_m$ slope than the other wing profile. While Profile 1 only managed to produce about 2.1% better $C_m$ slope compared to Profile 2. Thus, based on these $\Delta C_m/\Delta C_l$ results, one can presume that Profile 3 has shown a promising ability in providing better wing stability compared to the other wing profile considered here. However, further study need to be conducted in the future to ensure the stability condition achieved in lateral and directional axes.

Figure 7. The $C_m$ performances for all three profiles.
4. Conclusion
In this work, an aerodynamic study on different wing profiles has been carried out. Profile 1, Profile 2 and Profile 3 which were proposed through the 3rd order polynomial equations have analyzed based on simulation works by using ANSYS-CFX. Based on the $C_L$ analysis, it shows that Profile 3 has a huge advantage in generating better $C_L$ distribution among the wing profiles. Profile 3 able to produce at least 20% to 22.9% better $C_{L_{\text{max}}}$ and $C_L$ magnitude compared to the other wing profiles. Despite its benevolent $C_L$ performances, Profile 3 has induced the highest drag penalty among the wing profiles. Profile 3 has consistently produced at least 57.5% higher $C_D$ magnitude compared to other wing profiles. The deficiency is expected due to larger camber percentage which theoretically contributed into a larger frontal area (additional form drags) and greater induce drag components. However, in terms of $C_M$ performances, Profile 3 has shown a promising ability in providing better wing stability compared to the other wing profile due to steeper $C_M$ slope. Profile 3 able to produce at least 13.4% better $C_M$ slope compared to the other wing profiles.

Acknowledgment
Authors acknowledge technical and financial support from Universiti Teknologi MARA Cawangan Pulau Pinang and the Government of Malaysia.

References
[1] Ismail N I Tasin M A Talib R J Zulkifl A H Basri M H and Mahadzir M M 2016 A review on MAV design challenges Aust. J. Basic Appl. Sci. 10, 7 p. 84–90.
[2] Ismail N I Zulkifl A H Abdullah M Z Basri M H and Abdullah N S 2013 Computational aerodynamic analysis on perimeter reinforced (PR)-compliant wing Chinese J. Aeronaut. 26, 5 p. 1093–1105.
[3] Hassanalian M. Quintana A. and Abdelkefi A. 2018 Morphing and growing micro unmanned air vehicle : Sizing process and stability Aerosp Sci Technol. 78, 1 p. 130–146.
[4] Ismail N I Zulkifli A H Abdulllah M Z Basri M H Mat S C and Noor R M 2012 Review of monoplane fixed wing micro air vehicle design progress in 4th International Conference On Science & Application In Industry And Education (ICSTIE2012) 4, p. 14–26.
[5] Ismail N I Zulkifli A H Abdulllah M Z Basri M H and Abdulllah N S 2014 Optimization of aerodynamic efficiency for twist morphing MAV wing Chinese J. Aeronaut. 27, 3 p. 475–487.
[6] Hassanalian M and Abdelkefi A 2016 Design, manufacturing, and flight testing of a fixed wing micro air vehicle with Zimmerman planform Meccanica 52, 1 p. 1265–1282.
[7] Hassanalian M Throneberry G and Abdelkefi A 2017 Wing shape and dynamic twist design of bio-inspired nano air vehicles for forward flight purposes Aerosp Sci Technol. 68, 1 p. 518–529.