Camber Variation and Cruise Efficiency for NACA X412 Aerofoils: A Conceptual Study in Aerofoil Curvature

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ABSTRACT: An aerofoil (British English) or airfoil (American English) refers to a cross-sectional structure in which its curvature provides the most favorable ratio between the coefficient of lift (C_L) and drag (C_D). In this particular study, the NACA *X*412 aerofoil will be used as its base model with the percent camber being the main variation, not just limited to 2% camber (NACA 2412). This paper will not discuss the relation of the distance of the maximum camber or the maximum thickness of the aerofoil as a percentage. The fundamental study will be based on the curvature of the aerofoil and how different percent camber impacts the cruise efficiency with respect to the ratio between the coefficient of lift (C_L) and drag (C_D). AoA (α) will also be considered throughout the process as its predominant contribution to the aerodynamics of an aerofoil. The results based on the study are arrived at which the optimum percent camber for a level cruise is at 2%. As the research pertains to examining the optimum percent camber, the 6% camber aerofoil also achieved a maximum C_L/C_D, requiring a typical AoA (α) for cruise conditions. This idea will remain to be further discussed in *Results and Discussion*, and *Conclusion*.

KEYWORDS: Engineering Mechanics, Aerospace and Aeronautical Engineering, Percent Camber, Coefficient of Lift and Drag, Aerodynamic Efficiency.

Introduction

History of NACA 4-digit series:

NACA (*National Advisory Committee for Aeronautics*) started its early research on aerofoils during the 1920s, centering on how aerofoil characteristics affect aerodynamic performance.[1] This led to the development of the first NACA 4-digit series of aerofoils, the first systematic approach to aerofoil designs. It was followed by a 4-digit number that represented the aerofoil's section's critical geometric properties, with each digit representing different characteristics of an aerofoil. The first digit describes the maximum camber as a percentage of the chord, while the second digit describes the distance of the maximum camber from the aerofoil leading edge in tenths of the chord. The last two digits indicate the maximum thickness of the aerofoil as a percentage of the chord.[2,3] With these in the foundation, the NACA 2412 aerofoil (Figure 2) has a maximum camber of 2% located 40% (0.4 chords) from the leading edge with a maximum thickness of 12% of the chord. Its balance of lift and drag, ease of use in design, and extensive documentation have made it a mainstay in both historical and contemporary aircraft designs.[4]

Aerodynamic Forces:

Aerodynamics stands as one of the most foundational disciplines within the realm of science. The word *Aerodynamics* is rooted in two Greek words: *aerios* and *dynamis*, they each mean 'concerning the air' and 'forces', respectively. Collectively, they denote the exploration of forces and the consequent motion of objects as they traverse through the air.[5]

For a typical aerofoil, aerodynamic forces acting on the body are the lift and drag forces with each being denoted with C_L and C_D respectively.[6] C_L is an expression of the lift force generated on a flying object with respect to the density and velocity of the fluid flowing around it and is the surface area over which this lift acts. It is defined as the perpendicular component of the force exerted by a surrounding fluid on an object due to the relative motion between them, which is defined as:

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

where, L is the lift force, ρ being the density of the fluid (air), V being the speed airspeed of the object relative to the surrounding fluid (air), and A being the relative plan area.[6,7] Alternatively, the C_D is an expression of the drag force generated on a flying object, also with respect to the density and velocity of the surrounding fluid, with S being the reference area, typically the wing area.[8] Fundamentally, it is equal to the drag force divided by the environmental effect of the aerofoil area, which is defined as:

$$C_D = \frac{D}{(\frac{1}{2})\rho V^2 S}$$

where, D is the drag force, with the remaining terms being the same as those used in the coefficient of lift equation.[6,9] It is also necessary to note that both values are non-dimensional values, allowing comparison of the aerodynamic performances between different setups and vehicles.[8] With these underdue, angle of attack noted as α is another fundamental component in aerodynamics to be understood. It is defined as the angle between a specified reference line on a body—commonly the

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chord line of an airfoil—and the vector representing the relative motion between the body and the surrounding fluid. Essentially, it quantifies the angle of the body relative to the oncoming flow, where the values obtained through Table 3 and Table 4 will be further discussed in *Results and Discussion*.[10]

Objectives:

It is distinctive that the designers have understood the significance of reducing drag and made extensive efforts to streamline design from early aerodynamic studies.[11] At the outset, It is of utmost importance to acknowledge that this research centers on the fundamental principles underlying the curvature of an aircraft wing configuration. Every calculation made throughout this paper will be held upon a model of Cessna 172, as the central focus of this study is the examination approaches of a NACA *X*412 aerofoil and its variation in camber, rather than merely analyzing the cruise efficiency of a Cessna 172. The objective of employing a Cessna 172 is because the aircraft itself is a symbolic carrier which implements the NACA 2412 aerofoil.[12]

This particular study will center on the aerodynamic efficiency and its performance on a series of aerofoils with the deviation in the percent camber. Not just limited to the NACA 2412 aerofoil, the maximum camber in percentage will be the main variation throughout the process (Figure 1), using a 1%, 2%, 4%, and 6% camber whilst maintaining 40% camber position and max thickness of 12%. Thus, the fundamental study will be based on the curvature of the aerofoil and how different percent camber impacts the cruise efficiency with respect to the ratio between C_L and C_D. To quantify the aerodynamic efficiency, the C_L/C_D ratio will be calculated using Airfoil Tools (XFOIL, Version 6.96) between different series of aerofoils (1412, 2412, 4412, 6412). Because C_L and C_D are both non-dimensional values as mentioned in *1.2 Aerodynamic forces*, the C_L/C_D ratio is an indication of the aerodynamic efficiency of an aircraft, where under cruise conditions, lift is equal to the weight of the aircraft.[13] Furthermore, interpretation/analysis will be applied to fully examine how a conventional wing curvature impacts its aerodynamic performance within the atmosphere. For consistency between aerofoils and therefore its primary concentration on the aerofoil curvature, the camber position and the thickness of the chord will be permanent throughout the process. The rest of the aerofoil characteristics that are represented through the second, third, and fourth digits of the 4-digit series will not be examined in the scope of this research.

The main goal of this study is to advance the contemporary research domains in the aerodynamics of flying objects and to provide the public with an opportunity to engage with this intricate field of aerodynamics.

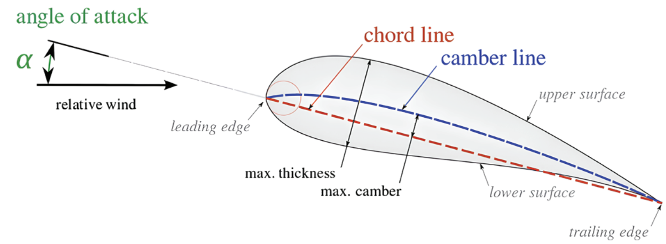

Figure 1: Schematic for an aerofoil section illustrating key features - chord line, camber, and angle of attack.[5]

Methods

Airfoil Tools/XFOIL for Parameter Calculation:

XFOIL is a two-dimensional aerodynamic modeling program, initially developed by Mark Drela at MIT in 1986.[14,15] Most of the calculations were held based upon Airfoil Tools, NACA 4 digit generator, which is a database for XFOIL, offering users to perform viscous and inviscid analysis of existing aerofoils. The primary purpose behind the use of Airfoil Tools was its easy access and convenient method of tracking data. The variables that were calculated through Airfoil Tools were the angle of attack (α), C_L, C_D, and C_L/C_D. The factors that were considered for the calculations are Reynolds number (Re), Mach number (M_∞), and Ncrit (N_{Crit}).[3] The values for the following are set alternatives during the entire calculation process which are shown below in Table 1.

Table 1: Airfoil Tools Calculation Parameters.

Reynolds number (*Re*)	200,000
Mach number (M_∞)	0.0
Critical amplification factor (N_{Crit})	9.0

The selection of these specific values serves a clear purpose. In the first place, the available Reynolds numbers (*Re*) for calculation via Airfoil Tools were constrained to 50,000, 100,000, 200,000, 500,000, and 1,000,000. Given that the Reynolds number (*Re*) for a Cessna 172 using a simple Reynolds number (*Re*) equation would exceed the maximum value offered by Airfoil Tools, all computations were performed at a Reynolds number of 200,000 (Table 1). This approach was conducted to maintain consistency and uniformity across all aerofoil, thereby minimizing the potential for substantial errors during calculations. The Mach number (M_∞), where higher cruise Mach number (M_∞) symbolizes near the speed of sound, was conducted with the value of 0.0 (Table 1) as the only value provided was 0.[16] In addition to this, N_{Crit}, referring to the critical amplification factor, is a factor used to control the laminar-turbulent transition phenomenon.[3] With Airfoil Tools also limited to exact values of 5 and 9, all aerofoil calculations were held based upon the N_{Crit} value of 9, also for consistency along with Reynolds number (*Re*).

Each NACA aerofoil profiles were also generated using the Airfoil Tools plots (Figure 2). It can be seen that the curvature of aerofoils is dependent on the percent camber, which is 1, 2, 4, and 6 from top to bottom.[17] With 1412 aerofoil being nearly symmetrical, the camber line (green line) is more approaching convex as shown below in Figure 2.

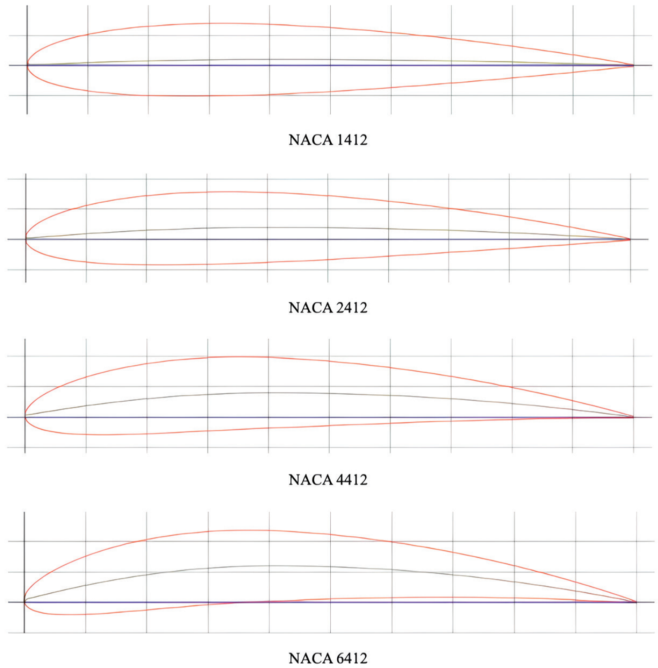

Figure 2: 4 NACA Aerofoil profiles at different camber percentages.

Calculations:

Before commencing the calculations through Airfoil Tools, it is necessary to work out the CL required to maintain a Cessna 172 in a linear flight level (Table 2). Given the simplicity of these calculations, they are primarily calculated manually. Considering that the lift of a Cessna 172 is equal to its weight during a stable flight, L in *Eq. 1* can be calculated by a simple $W = mg$ equation, where it is 11,350 N with approximation (Table 2). Correspondingly, C_L could be calculated using the values from Table 2 and L = 11,350 N, with Eq. 1 again. The table contains both the data provided by the POH, with the temperature and air density being calculated in alignment with the altitude (8500 ft).[18] The values of temperature and air density are evident as both have indirect proportionality with the altitude in the atmosphere.[19]

Extracting Data:

With C_L valued at 0.3615, calculations using Airfoil Tools have been conducted at this stage. With each aerofoil being plotted using Airfoil Tools and values from Table 2, the closest values to C_L = 0.3615 have been extracted from the Airfoil Tools' data table. The study's marginal limitation becomes apparent at this point. Because Airfoil Tools does not provide the exact value of C_D with a given C_L value, concise measurements could not be obtained in terms of their quantified measures. α in Airfoil Tools were provided in an increment of 0.25, for instance, C_L and C_D values anywhere between an α between 6.25 and 6.00 remained inaccessible throughout the data extraction procedure. Refocusing back to the data collection with Airfoil Tools, after determining the C_L with nearest proximity, corresponding α, and C_D have been acquired. This entire process has been repeated for all aerofoils illustrated in Figure 2, and the resulting data have been summarized in Table 3. Observable through Table 3, all C_L for aerofoils are not the definite value of actual C_L but are approximated. It is imperative to emphasize that Table 3 does not calculate the max C_L/C_D as this is separately shown through Table 4, which is going to be further discussed in *Results and Discussion*.

Table 2: *Data provided from POH.[18]

Maximum takeoff weight*	1157 kg
Wing area*	16.17 m^2
True air speed* (Cruise, 75% Power at 8500 ft)	63.79 m/s
Altitude*	8500 ft
Temperature	-1.8 °C
Air density	0.9544 kg/m^3

Table 3: Numerical data of C_L/C_D.[18]

	AoA (α)	C_L	C_D	C_L/C_D
1412	1.25°	0.3533	0.01012	34.91
2412	0.5°	0.3796	0.00985	38.54
4412	-1.0°	0.3583	0.01070	33.49
6412	-2.5°	0.3724	0.01517	24.55

Table 4: Numerical data of max C_L/C_D.

	AoA (α)	C_L	C_D	Max C_L/C_D
1412	5.25	0.7246	0.01258	57.59
2412	6.0	0.8911	0.01338	66.59
4412	7.0	1.2002	0.01536	78.14
6412	8.25	1.4878	0.01860	79.99

■ Result and Discussion

As outlined in *Objectives*, the primary objective of this study is to develop and examine a theoretical understanding of how variations in aerofoil curvature impact the aerodynamic efficiency of a typical aircraft. To meet the above requirements, it is essential to accurately interpret what these numbers represent with the numerical results collected through *Extracting Data*.

Effect in Angle of Attack with Camber Variation:

Figure 3 is a graph simply depicted with numerical data obtained in Table 3. For each percent, camber in each aerofoil (1412, 2412, 4412, 6412), the nearest achievable value of AoA (α) has been plotted with respect to the closest possible value established in 2.3 Extracting Data. It can be seen from the figure that as the percent camber increases, the AoA (α) required to produce the explicit value of C_L = 0.3615 decreases. Similar study has been carried out in ShuaiShauai Wang *et al.* where its CFD simulation results and analysis reveals that with increased AoA (α), the C_L of each airfoil increases

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gradually, where for this case, the aerofoils evaluated are 0412, 2412, 4412, 6412.[17] Besides, it is also noted that this theory applies from AoA (α) between -5.0° to 15.0° and as the AoA (α) reaches 20.0°, the value of C_L subsides.[17] In conjunction with research from ShuaiShauai Wang *et al.*, demonstration from Figure 3 verifies that as the AoA (α) increases, less C_L will be required to maintain an aircraft in a level flight as all values of AoA (α) collected in Table 3 are all within the range -5.0° to 15.0°.17 With 2% camber, aerofoil exhibits the highest C_L/C_D value in Table 3, deviating from the expected trend observed in Table 4, where the max C_L/C_D thoroughly increases as the percent camber increases. Also, this suggests that the AoA (α) is a critical factor in an aerofoil design.[1,2]

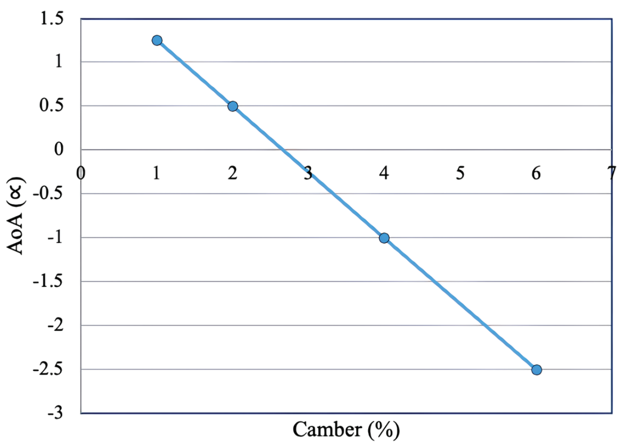

Figure 3: Camber (%) vs AoA (α).

Effect in Lift Coefficient with Camber Variation:

Given that prior data interpretation in *Effect in Angle of Attack with Camber Variation* implies that with an increase in percent camber amongst the NACA *X*412 aerofoil, minor degrees of AoA (α) are requisite to maintain the optimal C_L for a linear cruise for Cessna 172, it is vital to examine its effect in C_D. With numerical results from Table 3 plotted into a Camber (%) vs C_D graph, it can be seen that the C_D increases after the smooth line plots 2% camber in the graph. With 1412 aerofoil having a marginally higher C_D compared to that of 2412, it is apparent that the lift-to-drag ratio also decreases after it reaches its maximum in 2% camber (Table 3).

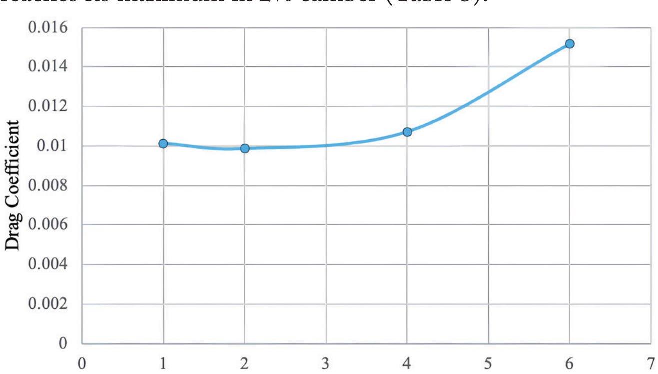

Figure 4: Camber (%) vs C_D.

Using the same data from Table 3, and plotting the camber percentage versus the lift coefficient shows an almost linear form from 1% to 4%. Upon passing 4% it is shown to suddenly increase in a likewise linear manner. If the y-axis values of the two figures are compared at camber percentages 4% and 6%, it is observed that upon entering a negative AoA, the drag coefficient starts to drift further away from 0.01; when the AoA value is -1, the drag coefficient is 0.01070. With the 1412 aerofoil having a marginally higher C_D compared to that of 2412, it is apparent that the lift-to-drag ratio also decreases after it reaches its maximum in 2% camber (Table 3).

The 2% camber showed maximum efficiency during a cruise with an appropriate α value of 0.5. Meanwhile, the 6% camber showed the highest C_L/C_D value 79.99, but its α value of 8.25 was not a typical AoA value for cruise conditions

■ Conclusion

A study carried out by Kondapalli Siva Prasad, Vonmi Krishna, and B.B. Ashok Kumar, unveils that their analysis using FLUENT and GAMBIT presents that enhanced pressure variation will result in better aerodynamic performance of the aerofoil.[1] Also, simulations were performed by Shivasharanayya Hieremath and Anandkumar. S. Malipatil affirms that induced drag accounts for approximately 33% of the total drag of the aircraft during the cruise, where it becomes even more pronounced at lower speeds.[10] Based on this information, and more on it is perceptible that aerodynamic analysis of aerofoil is a multifaceted aspect with extensive factors contributing or influencing it.[5]

This study highlights the critical role of an aerofoil curvature, specifically percent camber, in determining the aerodynamic efficiency of the NACA *X*412 aerofoil during cruise. Numerical simulations have been conducted to investigate the relationship between AoA (α), C_L, C_D, and C_L/C_D. The findings of the study show that as the curvature for NACA *X*412 aerofoil increases by percent camber, the AoA (α) required to maintain an undeviating level flight, typically for a Cessna 172 decreases. Despite that the study displays the concept that with an increase in percent camber, the max C_L/C_D will increase along with the AoA (α), the principal emphasis of this study is to examine the aerodynamic efficiency of the aerofoil during the cruise. Two conclusions could be made after due: 1. 2% camber aerofoil with the base of NACA 2412 aerofoil shows the maximized efficiency during the cruise. However, to obtain a precise measurement of percent camber, additional analysis with Figure 4 is required as percent camber for this study is executed with 1% / 2% interval with AoA (α) in 0.25° intervals. 2. 6% camber aerofoil also showed its maximum lift-to-drag ratio of 79.99 but with an AoA (α) of 8.25°, which is not a typical degree level for an aircraft during the cruise. To address this conclusion, additional research could investigate the integration of the aerofoil with the aircraft, as an AoA (α) of 8.25° appears to be optimal for cruise conditions.

This study serves numerical limitations using the Airfoil Tools software for its computations. Airfoil Tools itself is a two-dimensional aerodynamic modeling program as stated in *Utilisation of Airfoil Tools/XFOIL*. Innumerable research in the field of aerofoil aerodynamics have been studied, and are continuous these days. Adel Mushin Elewe has simulated with ANSYS Fluent for pressure contour concerning velocity.6 Study carried out by Cody Lafountain, Kelly Cohen, and Shaaban Abdallah utilizes XFOIL to increase aircraft performance with thickness-based camber-morphing technology.[14] It is essential to recognize that aerofoil aerodynamics is an intricate field with numerous factors influencing performance. For accurate results, all individual factors affecting an aerofoil's aerodynamic performance must be identified and incorporated into calculations. However, Airfoil Tools does not offer three-dimensional simulations for aerofoils, which may result in reduced accuracy in the outcomes compared to that of computations held with XFOIL or ANSYS. As mentioned in *Utilisation of Airfoil Tools/XFOIL*, the numerical values for each Reynolds number (*Re*), Mach number (M_∞), and Ncrit (N_{Crit}) were also limited to specific values. It is more than imperative to determine the precise numerical figures for aerofoil calculations.

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References

1. Siva Prasad, K.; Krishna, V.; Kumar, B. Aerofoil Profile Analysis and Design Optimisation. J. Aerosp. Eng. **2013**, 3, 1–10.
2. Sundram; Kumar, R. Investigation of Airfoil Design and Analysis. *Int. J. Res. Appl. Sci. Eng. Technol.* **2022**, *10*, 863–880. DOI: 10.37591/.v3i2.656
3. Ramanujam, G.; Ozdemir, H. Improving Airfoil Lift Prediction. In 35th Wind Energy Symposium; American Institute of Aeronautics and Astronautics: Grapevine, Texas, 2017. https://doi.org/10.2514/6.2017-1999.
4. Filippone, A. On the Benefits of Lower Mach Number Aircraft Cruise. *The Aeronautical Journal* **2007**, *111*, 531–542. DOI: 10.1017/S0001924000004772.
5. Chakraborty, M. A Computational Study on Two Horizontally Close Sequential Airfoils to Determine Conjoined Pressure Distribution and Aerodynamic Influences on Each Other, B.Sc. Eng. Thesis, Chittagong University of Engineering and Technology, Chittagong, Bangladesh, 2015.
6. Muhsin Elewe, A. Numerical Simulation of Surface Curvature Effect on Aerodynamic Performance of Different Types of Airfoils. *IOP Conf. Ser.: Mater. Sci. Eng*. **2020**, *928* (3), 032003. DOI: 10.1088/1757-899X/928/3/032003.
7. Triet, N. M.; Viet, N. N.; Thang, P. M. Aerodynamic Analysis of Aircraft Wing. *VNU Journal of Science: Mathematics - Physics* **2015**, *31* (2).
8. Sadraey, M. Drag Force and Drag Coefficient. In *Aircraft Performance*, 1st ed.; CRC Press, 2016; Chapter 3
9. Sharma, S. An Aerodynamic Comparative Analysis of Airfoils for Low-Speed Aircrafts. *Int. J. Eng. Res. Sci. Technol*. **2016**, V5. DOI: 10.17577/IJERTV5IS110361.
10. Wang, S.; Qiao, Y.; Zhang, Z. Influence of Camber on Aerodynamic Performance of Airfoil Based on CFD Technology. *J. Phys.: Conf. Ser.* **2022**, *2276* (1), 012027. DOI: 10.1088/1742-6596/2276/1/012027.
11. Sirenko, V.; Pavlovs'ky, R.; Rohatgi, Methods of Reducing Vehicle Aerodynamic Drag, In *Proceedings of the ASME 2012 Fluids Engineering Division Summer Meeting collocated with the ASME 2012 Heat Transfer Summer Conference and the ASME 2012 10th International Conference on Nanochannels, Microchannels, and Minichannels*, Puerto Rico, USA. July 8–12, 2012; Volume 1: Symposia, Parts A and B. pp. 97-102. DOI: 10.1115/FEDSM2012-72491
12. Hiremath, S.; S.Malipatil, Anandkumar. CFD Simulations of Aircraft Body with Different Angles of Attack and Velocity. *Int. J. Innov. Res. Sci. Eng. Technol.* **2014**, *03* (10), 16965–16972. DOI: 10.15680/IJIRSET.2014.0310077.
13. Saltzman, J.; Hicks, W. In-Flight Lift-Drag Characteristics for a Forward-Swept Wing Aircraft (and Comparisons With Contemporary Aircraft); NASA-TP-3414; NASA Hugh L. Dryden Flight Research Facility Edwards, CA, 1994. https://ntrs.nasa.gov/citations/19950012150 (accessed Aug 11, 2024).
14. Lafountain, C.; Cohen, K.; Abdallah, S. Use of XFOIL in Design of Camber-controlled Morphing UAVs. *Comput. Appl. Eng. Educ*. **2012**, *20* (4), 673–680. DOI: 10.1002/cae.20437.
15. Joo, J. J.; Marks, C. R.; Zientarski, L.; Culler, A. Variable Camber Compliant Wing – Design. In *23rd AIAA/AHS Adaptive Structures Conference*, Kissimmee, Florida, January 5–9, 2015. DOI: 10.2514/6.2015-1050.
16. Coder, J. Further Development of the Amplification Factor Transport Transition Model for Aerodynamic Flows. In *AIAA Scitech 2019 Forum*, San Diego, California, January 7-11 2019. https://doi.org/10.2514/6.2019-0039.
17. Bertin, J. J.; Cummings, R. M. *Aerodynamics for Engineers*; Cambridge University Press, 2021.
18. Cessna Aircraft Company. *Information Manual Skyhawk SP*. Cessna Aircraft Company, 2004. https://www.befa.org/wp-content/uploads/2019/12/POH-Cessna-172S.pdf (accessed Aug 18, 2024).
19. Federal Aviation Administration. *Pilot's Handbook of Aeronautical Knowledge*; United States Department of Transportation, Federal Aviation Administration, Airman Testing Standards Branch, 2023. https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/faa-h-8083-25c.pdf (accessed August 18, 2024)

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