Effect of Varying Reynolds Number On The Aerodynamic Design of Lifting Surfaces

Seshan Jayapregasham*

Embry-Riddle Aeronautical University, Daytona Beach, Florida, USA

The design of an airfoil section is a critical part of the performance of a lifting surface. Historically, airfoil designs have evolved based on the Reynolds number which encompasses the scale and the fluid momentum effects on airfoil behavior. From insect flight at low Reynolds numbers to supersonic jets at high Reynolds numbers, this review highlights the varying airfoil designs that maximize performance of the lifting surface. As humans move towards the exploration of planets using rotary winged vehicles, airfoil designs must accommodate for unexplored flow environments. Designs are discussed for compressible ultra-low Reynolds number flows in the Martian environment and Reynolds number flows several times higher than on Earth in the dense Titan atmosphere. The process for design and optimization of airfoils involves both computational and experimental approaches. The performance of future air vehicles depends on the ability to design airfoils for an expanding range of environments.

Nomenclature

Term	Description
Re	Reynolds Number
ρ	Density
V	Velocity
l	Section chord length
μ	Viscosity
C_L	Coefficient of Lift
C_{Lmax}	Maximum Coefficient of Lift
C_D	Coefficient of Drag
$NACA$	National Advisory Committee for Aeronautics

I. Introduction

Airfoil section design is driven by the aerodynamic forces developed as the lifting surface moves through the air. This depends on the shape and speed of the lifting surface as well as the viscosity and compressibility of the mass of the air going by the object. The Reynolds Number, which indicates the ratio of the mass forces to the viscous forces in aerodynamic applications, is ordinarily used as the criterion of similarity. Essentially, it allows us to categorize and compare the flow patterns around objects and the performance of lifting surfaces with different geometries and in different environments. This enables us to define the "Realm of Reynolds numbers" to represent the changing flow regimes and their significance to nature's and man-made attempts for efficient motion of solid bodies through fluids.[1] Fractional or extremely low Re numbers within 150, characterized by highly viscous flow and represented by falling particles of dust, smoke or pollen, are outside the realm of wing design.[2] The behavior of insects in flight falls in the range of 1000 and 10000 Re, where the flow is strongly laminar. Re numbers from 10000 to 200000, a typical range for birds, are well-studied for the design of model aircraft. This range represents a region that is actively being investigated for the design of

*Undergraduate Student, Aerospace Engineering, Embry-Riddle Aeronautical University

aerial explorers in the thin atmosphere of Mars. The data surrounding Re values of 1 to 3 million is extensive for powered flight and benefits from the vast catalog of NACA airfoil data. At these low Reynolds numbers, turbulent reattachment usually follows laminar separation, thereby forming the so-called laminar separation bubble.[3,4] As Re numbers approach 9 million, methods that ensure the turbulent boundary layer on the aft part of the wing can stay attached were developed and are typically seen in corresponding designs. From this point, thick airfoils ensure extensive laminar flow is maintained up to 40 million Re, and this is represented physically by designs of small torpedos and dolphins that fall in this range. Large, high speed aircraft in the high Re range of 40 million to 10^9 have less available supporting data due to the difficulty in replicating this environment with typical facilities. Beyond 10^9, turbulent friction drag dominates the performance of applications like large nuclear submarines. In hypersonic flight, aerothermal heating becomes significant. A plot of the Airfoil or section speed against the Re number adapted from literature demonstrates the various types of lifting surfaces, engineered and natural, that operate across this realm, as shown in Fig 1.

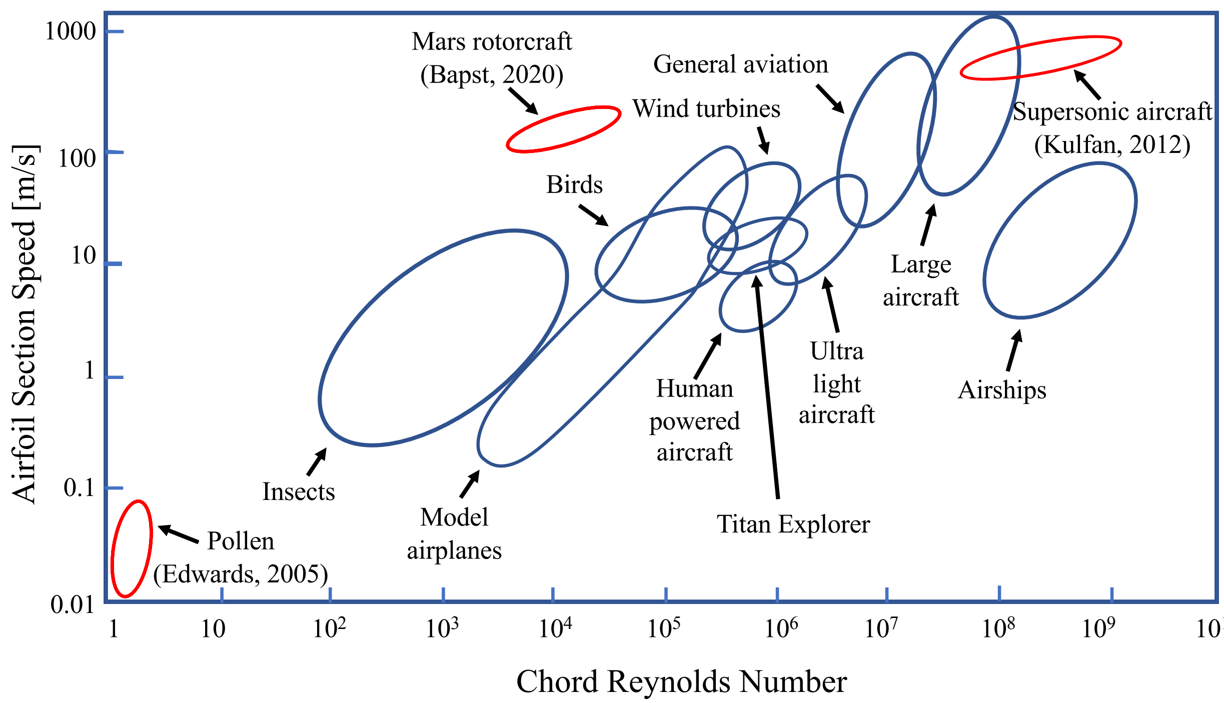

Figure 1: Section speed vs Reynolds number plot categorizing the various lifting surfaces according to type of operation adapted from literature[5,6] with added categories in red[2] including values for more recent aerial applications for planetary exploration such as the Mars helicopter.[7,8]

Mathematically, the Reynolds number is defined as

$$R = \frac{\rho V l}{\mu} \tag{1}$$

where ρ is the air density, V is the airspeed, l is a representative length scale such as the wing root chord and μ is the viscosity coefficient of the fluid.[9,10] Figure 1 focuses on the effect of the environment (ρ, μ) and speed (V)of the lifting surface Re number that dominates the operating categories of different types of lifting bodies. Re, as a similarity parameter, allows for the accurate testing of scaled models during design phase and the advancement of wind tunnel facilities that can provide the appropriate range of test environments for the success of the full scale air vehicle.[11] The classical design of airfoils, however, starts with the geometry of the airfoil and how it increases the lift efficiency of the body. The following sections will focus on the influence of these shapes and surface topologies on the design of airfoils for Low and High Reynolds numbers with the discussions of various applications or examples in engineering or nature. The impact of the operating environment and speed of the object on the design will be highlighted for each of these geometries with a special focus on recent advances in aerial vehicles for planetary exploration. Following this, approaches in experimental and computational methods to design lifting surfaces from the classical design strategy to newer inverse methods will be discussed with respect to narrowing down the vast design possibilities to establish optimal section properties for the various Re regimes.[12,13]

II. Airfoil shape as a function of Reynolds Number

Airfoil design is historically initiated by geometric considerations and guided by empirical study. This geometry or shape of the airfoil is defined by the camber, thickness distribution, leading edge radius, and trailing edge thickness.[14] The free-stream parameters that influence the flow dynamics are the Mach number, Reynolds number, and angle of attack. Extensive investigations using a variable density wind tunnel have been conducted to give information about certain important aerodynamic characteristics for each airfoil shape with Reynolds Number.[15] The effect of the airfoil shape on the lifting performance is represented by the aerodynamic coefficients of lift and drag. Re takes into account size or the scaling effect through the section chord which in turn affects these aerodynamic coefficients. This means that different sizes of airfoils require different shapes.[5] The coefficient of lift C_L relates the lift force to the angle of attack of the lifting surface. If the lift force is known at a specific airspeed, the lift coefficient C_L can be calculated from:

$$C_L = \frac{2L}{\rho V^2 S} \tag{2}$$

The maximum value of this coefficient at an angle of attack, known as the stalling point, is referred to as C_{Lmax}. The value of C_{Lmax} is a very important airfoil characteristic, because it determines the minimum speed at which the lifting body can fly. In order to understand how design of airfoil shape varies with Re, the flow separation with respect to variation in Reynolds numbers must be understood.[6] Fortunately, many different measurement techniques to investigate this separation have been developed, including particle image velocimetry (PIV), smoke flow visualization, and hot-wire turbulence measurement.[6] These measurements provide a visual insight into the effect of the Reynolds number, highlighting the difference between low- and high Re flows. The boundary layer characteristics are strongly related to the sensitivity of the airfoil performance at different Reynolds number ranges. The ratio of aerodynamic coefficients or the C_{Lmax} is generally presented with respect to the Re number to provide an indication of the lifting performance of the airfoil. Figure 2 shows the airfoil shapes of a range of sections illustrated including standard shapes and typical NACA sections with the addition of the Mars helicopter airfoil.[8,16,17]

At lower Reynolds numbers of 10^4 to 10^5, the lifting performance of smooth airfoils significantly deteriorates due to flow phenomena, including separation, transition and reattachment. At these ranges of Re, laminar separation bubbles play an important role in determining pressure distributions on the wing and aerodynamic characteristics.[3] The insect-inspired corrugated airfoil,[19] shows a maximum C_L value of 0.8 to 1.0. At high Re, boundary layer transition takes place before laminar separation. An interesting high lifting capability is seen in the gliding snake model, which outperforms several of the typical airfoils in the similar Re range.[16] Traditional airfoils, such as the NACA airfoils, were designed to operate at high Reynolds numbers, since they were mainly intended for full-scale aircraft. Thickness also appears to be an important characteristic that impacts stall angles.[20] Thicker flat plates tend to increase the pressure drag, resulting in poor aerodynamic performance compared with thin plates.[6] The Mars helicopter uses a clf5605 airfoil, which closely resembles the NACA4404 airfoil.[21] This is based on the knowledge that sharp leading edges and plate-like airfoils can out-perform conventional airfoil shapes at the low Re regimes associated with the Martian environment.[7] By optimizing the airfoil for camber and thickness variation of curved and polygonal thin airfoils with sharp leading edges, the final form of the airfoil shown in Figure 2 was developed to operate in the mostly unexplored Airspeed-Re region in Figure 1.[8,21] While not highlighted in Figure 2, it is noteworthy that multi-element airfoils with separate elements, like slats, vanes, or flaps significantly enhance lift and are typical on large transport aircraft[22] at higher Re. Details on the design of Low and High Re airfoils are discussed in the following sections.

A. Low Reynolds number airfoils

Although there is no fixed Reynolds number range that is defined as the limits of the low Reynolds number regime, the term low Reynolds number is usually defined where the chord Reynolds number is below approximately 500000.[4] The design of airfoil shapes at Low Reynolds numbers has gained much research interest and advancement due to the popularity of micro uninhabited air vehicles.[12,23] Even more futuristic designs of nano and pico air vehicles are also being developed. As a result, there is a vast amount of review

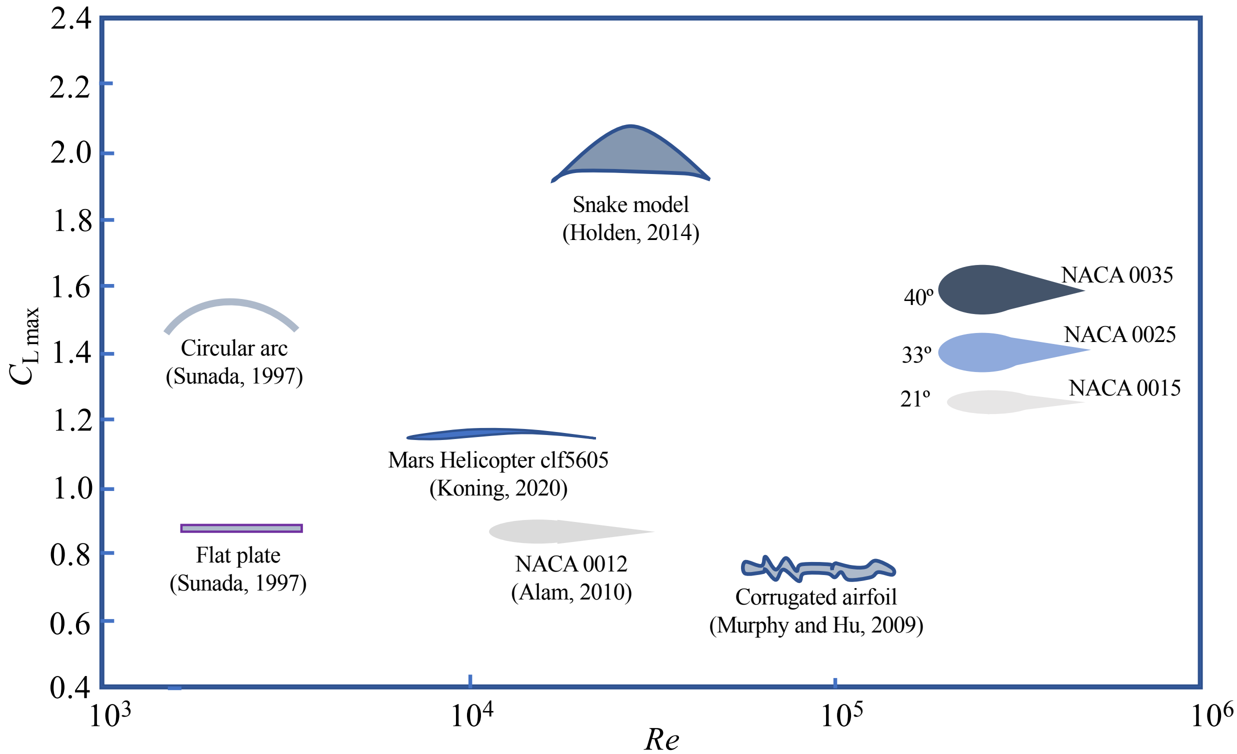

Figure 2: Maximum Coefficient of Lift vs Reynolds number plot with the stall angle listed categorizing some examples of lifting surfaces in the low Re region. This is adapted from literature[16] with the addition of data from airfoil geometries for more recent aerial applications for planetary exploration such as the Mars helicopter[7,8,18]

literature on the aerodynamic phenomena at low Reynolds numbers.[12] Since this regime falls within the category of natural flying objects including insects such as the dragonfly,[19] many of the designs have led to biologically inspired flight vehicles. It is also the operating range of small horizontal axis wind turbines.[4] At these low Reynolds numbers, there are very large viscous effects, which cause high drag and limit the maximum lift coefficient. The laminar separation bubble at low Re has been extensively documented and is characterized by separation of the laminar flow occurring near the nose.[3,24] To overcome these challenges and achieve high maneuverability there are traditional passive flow control measures such as slots and flaps as well as new concepts using material roughness, flexibility or partial flexibility of the airfoil.[24]

The design of the airfoil for the Mars helicopter is unique, because it addresses low Re at a higher airspeed, which is a region of the the Airspeed-Re plot that has not been very well explored, as seen in Figure 1. Various representative airfoil shapes at the relevant Re were highlighted in the initial airfoil consideration, as shown Figure 3. It is important to note that while these are in the similar Re range, the dragonfly and pigeon airfoils operate in a flapping configuration, and their applicability as inspiration for the initial design were limited. The Eppler 193 is a traditional low Re airfoil. The clf5065 Mars helicopter airfoil shown in Figure 3 was the result of computational optimization[8] and the camber compared to the Eppler 193 may have contributed to its improved performance. The design takes into account the fact that the vehicle must fly at relatively high speed to produce a lift enough to sustain its weight, as well as to ensure a stabile flight in gusty atmosphere. The flight Mach number reaches 0.4 to 0.7, because the sound speed is low in the CO_2-based Martian

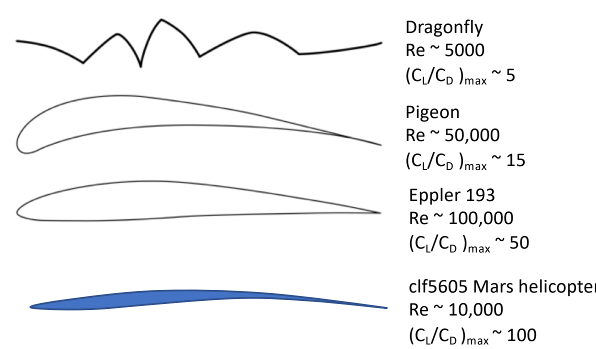

Figure 3: Typical cross-section shapes of low Re airfoil and efficiency from literature[5] adapted to include comparison with the Mars helicopter airfoil clf5605[8,18]

atmosphere at low temperature.[8] The effects of the specific heat ratio are also important, since its value is different in CO_2 and in air. Thus, it is expected that the flow field on a Mars aerial vehicle will become highly complicated, with a strong interaction of viscous effects and compressibility effects. A test facility to evaluate the aerodynamic performance of the Mars aerial vehicle wings at low Reynolds numbers and high subsonic Mach number, called the Mars Wind Tunnel (MWT), has been developed with modifications to allow the tunnel to be operated using CO_2, the main constituent of the Martian atmosphere.[11]

B. High Reynolds number airfoils

The term high Reynolds number is typically associated with turbulent flow above 10^6, and this regime is where most conventional airfoils perform well (Figure 1). Literature on the optimization of airfoils for high Reynolds number is somewhat limited. It seems there is a consensus for a need to expand this database, as well as the database for Reynolds number and Mach number effects on high-lift airfoils.[25] The challenge here, is to design an airfoil with fewer elements, that maintains high levels of maximum lift, while minimizing flow separation. The benefits are in reducing complexity and the cost of manufacturing, as well as achieving reduced noise. Supersonic flight presents complexities, since the airfoil will see different classes of flows while the aircraft operates. These include attached flow, shock/boundary layer induced separations and leading edge vortex flows.[26] In general, supersonic airfoils have a thin section with very sharp leading and trailing edges. The section is formed of either angled planes creating a diamond shape, or opposed arcs creating a double-curved or biconvex shape.[27] However, with the new designs of supersonic transport aircraft, which will operate in a wide range of Re, a subsonic leading edge is preferred. This is because supersonic airfoils do not have good subsonic performance, and more thrust will be required in addition to noise issues. Multipoint optimization studies have been aimed at minimizing the drag penalty at lower speeds without compromising the supersonic performance.[28]

The ongoing design for aerial exploration vehicles for Saturn's moon, Titan, will provide important new progress in high Re airfoil design. The high nitrogen-laden atmosphere (95%) of Titan is 4 times more dense than Earth, in addition to being colder. The low temperature means molecular viscosity is lower than on Earth. The combination of higher density and lower viscosity means that an airfoil of given size and speed is operating at a Reynolds number that is several times higher than on Earth.[29] This is expected to be a good environment for winged flight, due to its thick and dense atmosphere, which supports low wing or disc area required to generate a given amount of lift force, and for its low gravity, which reduces the required magnitude of lift force.[17] In Figure 1, the Reynolds numbers and average blade airspeed for Titan aerial explorers are seen at the intersection of human-powered aircraft, ultra-light aircraft, and wind turbines. This provides opportunities for Titan rotary-wing explorers being equipped with high-performance airfoils that are also fairly insensitive to changes in surface roughness over the vehicle lifetime in remote operation, since the environment is expected to be harsh.[29] For the Titan aerial vehicle, Dragonfly, a blade section more typically used in terrestrial wind turbines is being investigated.[30] For wind turbines operating in this similar Re range, many specific airfoils with a high lift coefficient, leading-edge roughness insensitivity, and good stall performance, including NACA64618 or NACA63421, have been developed to adapt the operational state of a wind turbine.[31]

III. Computational and Experimental approaches to airfoil design

With the great number of possibilities and permutations of airfoil designs for the growing range of conditions and requirements, it is necessary to have various approaches to generate all potential designs from which an optimized and practical solution can be selected. Due to the limitations in experimental wind tunnel testing facilities and difficulties in replicating all types of environments, computational methods have gained a much more significant role in airfoil design.

Figure 4 indicates the various methods used to optimize the airfoil design based on the parameters of shape, performance, boundary layer development, and velocity distribution. Direct design has been the historic approach to airfoil optimization, which uses shape as a starting point and involves continuous testing to control and improve aerodynamic performance in a loop. Here, using wind tunnel testing or computational methods, the velocity distribution and boundary layer development can be provided from an experimental airfoil. The overall performance of this airfoil can then be discerned. Rather than specifying the airfoil design, the inverse method, via velocity distributions, works by specifying the desired airfoil velocity distribution

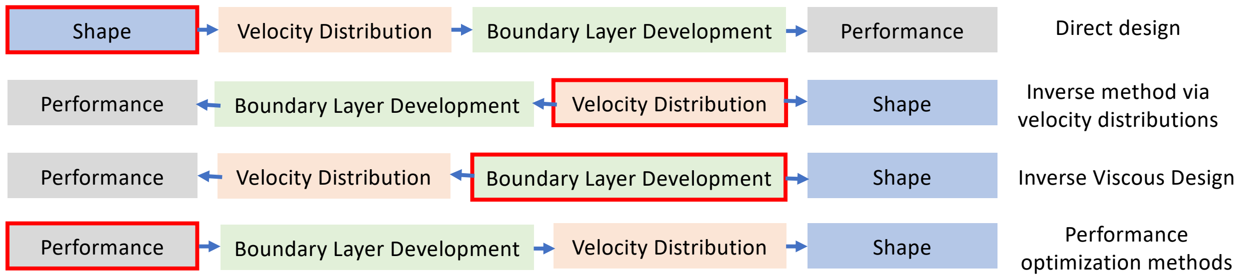

Figure 4: Comparison of approaches to Airfoil Design adapted from literature[13] and presented in flowchart form for one design cycle.

based on the boundary layer and consequently performance concerns, thus determining the shape of the airfoil. Inverse viscous design takes a similar approach, but emphasizes the boundary layer development in order to produce the desired result. The final design approach, known as the performance optimization method, works in the opposite direction of direct design by starting with the desired performance parameters. From this point, the boundary layer development and velocity distributions are computed, and the desired airfoil shape can be produced. This approach was used for the Mars helicopter airfoil design through a method known as genetic algorithms to perform the optimization.[21,32] Computational programs such as X-foil are better suited for this method since the translation from performance to design must be simulated. Both computational and experimental approaches provide benefits and contribute in their own way to advancing the design of airfoils. The effective design of these airfoils will therefore depend on the progress of techniques in both of these areas.

IV. Conclusions

The effect of Reynolds number on the design of airfoils was discussed broadly in this review. Examples of geometries of airfoils, from low and high Reynolds number applications, were provided with specific discussion on the influence of operating conditions, as well as the environment in the designs. A special focus on the airfoil design advances for the planetary aerial vehicles in Mars and Titan was presented, with consideration of the varying Re values posed by the different environmental conditions. Future advancements in research, design, and challenges in the field of aerial vehicles for planetary exploration, including fixed wing, rotary wing, and flapping wing vehicles will create new opportunities for unique designs inspired by various engineered or natural airfoil shapes in flight. New areas of the Airspeed-Re graph that are being explored with the thrust in applications for planetary exploration, urban air vehicles, supersonic and hypersonic flight, will be the motivation for more integration between computational and experimental efforts to design the best aerodynamic lifting surfaces for maximum performance and efficiency.

Acknowledgments

The author wishes to thank faculty at Embry-Riddle Aeronautical University for advice and opportunities that led to the ideas for the topic of this paper.

References

[1]Carmichael, B., “Low Reynolds Number Airfoil Survey,” Tech. rep., Low Energy Transportation Systems, NASA, 1981.

[2]Edwards, J., Whitaker, D., Klionsky, S., and Laskowski, M. J., “A record-breaking pollen catapult,” *Nature* , Vol. 435, No. 164, 2005.

[3]Horton, H., *Laminar Separation Bubbles in 2 and 3 dimensional incompressible flow*, Ph.D. thesis, Queen Mary College, University of London, 1968.

[4]Giguere, P. and Selig, M. S., “Low Reynolds Number Airfoils for Small Horizontal Axis Wind Turbine,” *Wind Engineering*, 1997.

[5]Lissaman, P. B. S., “Low-Reynolds-Number Airfoils,” *Annual Review of Fluid Mechanics*, Vol. 15, No. 1, 1983, pp. 223–239.

[6]Winslow, J., Otsuka, H., Govindarajan, B., and Chopra, I., “Basic Understanding of Airfoil Characteristics at Low Reynolds Numbers (104–105),” *Journal of Aircraft*, Vol. 55, No. 3, 2018, pp. 1050–1061.

[7]Withrow, S., Johnson, W., Young, L. A., Cummings, H., Balaram, J., and Tzanetos, T., *An Advanced Mars Helicopter Design*.

[8]Koning, W. J. F., Johnson, W., and Allan, B. G., “Generation of Mars Helicopter Rotor Model for Comprehensive Analyses,” *AHS Specialists’ Conference on Aeromechanics Design for Transformative Vertical Flight,*, 2018.

[9]Anderson, J. D., *Fundamentals of Aerodynamics*, McGraw Hill Education, 2017.

[10]Ackroyd, J. A. D., “The Aerodynamics of the Spitfire,” *Journal of Aeronautical History*, 2016.

[11]Anyoji, M., Nose, K., Ida, S., Numata, D., Nagai, H., and Asai, K., *Low Reynolds Number Airfoil Testing in a Mars Wind Tunnel*, 2010.

[12]Ukken, M. G. and Sivapragasam, M., “Aerodynamic shape optimization of airfoils at ultra-low Reynolds numbers,” *Sadhana*, 2019.

[13]Selig, M. S., “Low Reynolds Number Airfoil Design Lecture Notes,” Tech. rep., VKI Lecture Series Sponsored byNATO Research and Technology Organization (RTO) Applied Vehicle Technology (AVT) Panel, 2003.

[14]Balakumar, P., *Direct Numerical Simulation of Flows over an NACA-0012 Airfoil at Low and Moderate Reynolds Numbers*, 2017.

[15]Jacobs, E. N. and Sherman, A., “Airfoil Section Characteristics as affected by the variations of Reynolds number,” Tech. rep., Langley Memorial Aeronautical Laboratory, National Advisory Committee for Aeronautics, 1939.

[16]Holden, D., Socha, J. J., Cardwell, N. D., and Vlachos, P. P., “Aerodynamics of the flying snake Chrysopelea paradisi: how a bluff body cross-sectional shape contributes to gliding performance,” *The Journal of Experimental Biology*, 2014.

[17]Langelaan, J. W., Schmitz, S., Palacios, J., and Lorenz, R. D., “Energetics of rotary-wing exploration of Titan,” *2017 IEEE Aerospace Conference*, March 2017, pp. 1–11.

[18]Koning, W. J. F., “Airfoil Selection for Mars Rotor Applications,” Tech. rep., NASA Ames Research Center, Moffett Field, California, 2019.

[19]Levy, D.-E. and Seifert, A., “Simplified dragonfly airfoil aerodynamics at Reynolds numbers below 8000,” *Physics of Fluids*, Vol. 21, 2009, pp. 071901.

[20]Dongli, M., Yanping, Z., Yuhang, Q., and Guanxiong, L., “Effects of relative thickness on aerodynamic characteristics of airfoil at a low Reynolds number,” *Chinese Journal of Aeronautics*, Vol. 28, No. 4, 2015, pp. 1003–1015.

[21]Koning, W. J. F., Romander, E. A., and Johnson, W., “Performance Optimization of Plate Airfoils for Martian Rotor Applications Using a Genetic Algorithm,” *45th European Rotorcraft Forum, Warsaw, Poland, 17-20 September*, 2019.

[22]van Dam, C., “The aerodynamic design of multi-element high-lift systems for transport airplanes,” *Progress in Aerospace Sciences*, Vol. 38, 2002, pp. 101–144.

[23]*Uninhabited Air Vehicles: Enabling Science for Military Systems*, National Research Council, The National Academies Press, 2000.

[24]Genc, M. S., Koca, K., Demir, H., and Acıkel, H. H., *Autonomous Vehicles: Traditional and New Types of Passive Flow Control Techniques to Pave the Way for High Maneuverability and Low Structural Weight for UAVs and MAVs*, chap. 7, IntechOpen, 2020, pp. 129–162.

[25]Lin, J. C. and Dominik, C. J., “Parametric Investigation of a High-Lift Airfoil at High Reynolds Numbers,” *Journal of Aircraft*, Vol. 34, No. 4, 1997, pp. 485–491.

[26]Kulfan, B., *Reynolds Numbers Considerations for Supersonic Flight*, 2012.

[27]Yong, W., “Study on Aerodynamic Characteristics of Supersonic Airfoil,” *Modern Mechanical Engineering*, Vol. 9, 2019, pp. 13–19.

[28]Mangano, M. and Martins, J. R. R. A., “Multipoint Aerodynamic Shape Optimization for Subsonic and Supersonic Regimes,” *Journal of Aircraft*, 2019.

[29]Hassanalian, M., Rice, D., and Abdelkefi, A., “Evolution of space drones for planetary exploration: A review,” *Progress in Aerospace Sciences*, Vol. 97, 2018, pp. 61–105.

[30]Lorenz, R. D., Turtle, E. P., Barnes, J. W., Trainer, M. G., Adams, D. S., Hibbard, K. E., Sheldon, C. Z., Zacny, K., Peplowski, P. N., Lawrence, D. J., Ravine, M. A., McGee, T. G., Sotzen, K. S., MacKenzie, S. M., Langelaan, J. W., Schmitz, S., Wolfarth, L. S., and Bedini, P. D., “Dragonfly: A Rotorcraft Lander Concept for Scientific Exploration at Titan,” *Johns Hopkins APL Technical Digest*, Vol. 34, No. 3, 2018.

[31]Ge, M., Tian, D., and Deng, Y., “Reynolds Number Effect on the Optimization of a Wind Turbine Blade for Maximum Aerodynamic Efficiency,” *Journal of Energy Engineering*, 2014.

[32]Koning, W. J. F., Romander, E. A., and Johnson, W., “Optimization of Low Reynolds Number Airfoils for Martian Rotor Applications Using an Evolutionary Algorithm,” *AIAA SciTech Forum, Orlando, FL*, 2020.