Slotted, Natural-Laminar-Flow Airfoil: A Revolutionary Technology for Fuel Efficiency

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The slotted, natural-laminar-flow (SNLF) airfoil is a revolutionary technology projected to contribute to a 70% decrease in fuel and energy consumption. The SNLF is designed to allow favorable pressure gradients to extend further aft, which increases the extent of laminar flow it can achieve to about 90% of the entire airfoil. These high amounts of laminar flow decrease streamwise instabilities, which in turn reduces the wing profile drag of the airplane wing. In addition, the SNLF airfoil also exhibits the dumping-velocity effect and achieves an off-surface pressure recovery, both of which are highly critical for achieving large extents of laminar flow and are major limitations of single-element airfoils. Therefore, the SNLF is unique in its design and is considered a novel concept that could lead to more fuel-efficient aircrafts. To further optimize the SNLF airfoil and prepare the concept for incorporation with a commercial vehicle, the National Aeronautics and Space Administration (NASA) University Leadership Initiative (ULI) funded the Advanced Aerodynamic Design Center for Ultra-Efficient Commercial Vehicles at the University of Tennessee Knoxville (UTK). The central goal of this ULI team is to combine the S207, SNLF airfoil with advanced methods and technologies to create a more aerodynamically efficient aircraft wing.

I. Introduction

The current need for improved aircraft fuel efficiency is unprecedented and more urgent than ever before. In 2018, the United States commercial aircraft industry consumed over 23 billion gallons of fuel, a 5.88% increase from the previous year [1]. The data from the Federal Aviation Administration's (FAA) yearly Aerospace Forecast reports for the fiscal years of 2019 and 2020 indicates that the aerospace industry's demand will only continue to increase, as demonstrated by the projected rates of passengers flying through the United States and total fuel usage by U.S. commercial aircrafts, as illustrated in Fig 1 [1] [2]. While the COVID-19 pandemic has significantly impacted the airline industry, the FAA optimistically predicts minimal long-term ramifications on travel projections and that current passenger traffic levels will increase once vaccinations are more widespread and infection rates are under control [2]. Therefore, even upon accounting for the pandemic, air travel is still considered to be vital and will continue to grow in the future, making fuel efficient aircraft design a necessity. This need in the aircraft industry prompted NASA to create N+3 goals, which essentially builds on a baseline 'N' aircraft to create advanced solutions that lead to reductions in fuel consumption, nitrous oxide emissions, and noise levels. This challenge encompasses many conflicting requirements including accommodating the continuous increase of commercial airplane passengers, while simultaneously protecting the environment and preparing for a diminishing supply in fuel and associated rapid increase in fuel costs [3]. With this multitude of complexities, temporary fixes and incremental advancements will not adequately address these issues. Instead, the development of revolutionary new operations and aircraft technologies will enable long-term sustainability and cost benefits for the aerospace industry.

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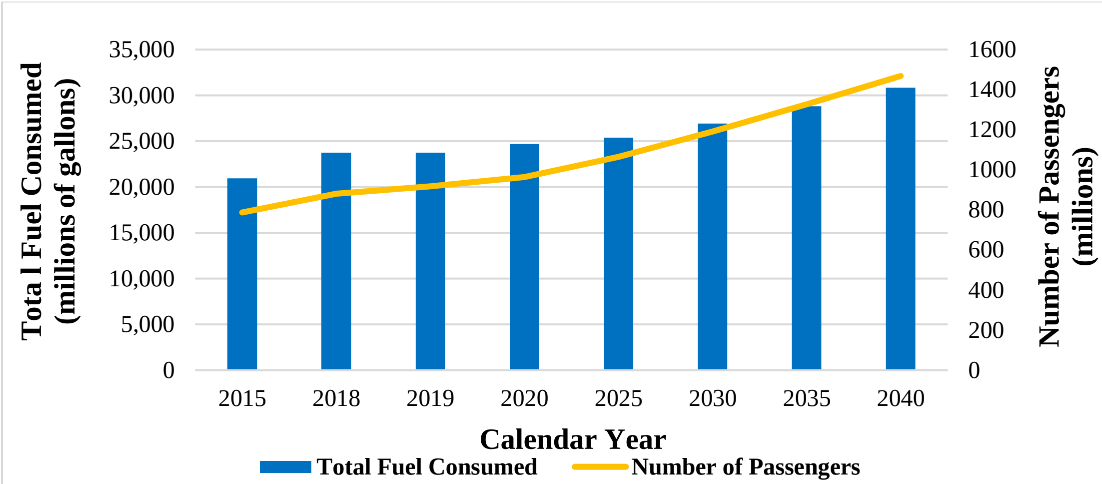

Fig. 1 Total Domestic and International U.S. Passenger Traffic for U.S. Commercial Air Carriers; Historical and Projected Jet Fuel and Aviation Fuel Consumption by U.S. Civil Aircraft [1]

Foundational research illuminating the necessity of aircraft optimization was performed by Boeing [3] and the Massachusetts Institute of Technology (MIT) [4] and funded through NASA's pursual of revolutionary technologies for future aircraft designs. As they undertook a systemic approach to evaluate future projections and needs, Boeing and MIT both cited natural laminar as a factor in their models and designs. Both concept studies concluded that achieving increased laminar flow through different configurations helps to reduce drag and thus improve fuel efficiency [3] [4]. However, there remain barriers that still must be crossed for this technology to reach its full potential, such as NLF merely contributing a 2.54% reduction of PFEI in MIT's study, as well as being a high-risk technology according to Boeing's risk analysis. Therefore, these studies clearly demonstrates that the current NLF technology needs further development to contribute more to NASA's fuel burn goals while also keeping in mind the need to integrate this technology favorably into future aircraft designs.

One potential solution to improve fuel efficiency is the implementation of the slotted, natural-laminar-flow airfoil (SNLF) in the production of future aircraft. The SNLF airfoil is specifically designed to improve cruise performance by increasing the extent of natural laminar flow (NLF), thus achieving a higher lift-to-drag (L/D) ratio during flight. The patent for the SNLF airfoil, held by Dan Somers of Airfoils Inc, states that the SNLF airfoil consists of a fore airfoil element, an aft airfoil element, and a slot region in between [5]. This two-element design and configuration of the SNLF airfoil, as shown in Fig. 2, is a revolutionary concept that contains the potential to improve an aircraft's aerodynamic performance. By including a slot between the fore and aft elements, the fore element has a lower trailing edge pressure than the freestream. This creates a higher velocity at the trailing edge of the fore element, an effect known as dumping velocity [6]. The slot helps achieve a higher dumping velocity, thereby allowing the element to carry more load before separation, and additionally, the aft element interacts with the fore element to sustain the dumping velocity, which permits the airfoil to achieve increased lift [7].

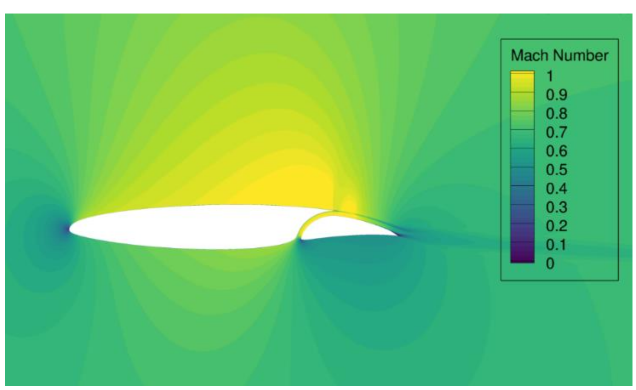

Fig. 2 CFD image of S207, slotted, natural-laminar flow airfoil

Therefore, this aerodynamically efficient wing-design is an essential contribution in achieving the N+3 goal of a 70% decrease in fuel and energy consumption [8]. Attainment of this goal would substantially impact environmental sustainability while addressing many of the aircraft industry's aforementioned issues. To better investigate an avenue to improve aircraft fuel consumption, several organizations have explored the potential of NLF technology and investigated avenues for continued development and implementation of an SNLF airfoil. This paper will discuss these contributions as well as the current efforts of the National Aeronautics and Space Administration (NASA) through the Advanced Aerodynamic Design Center for Ultra-Efficient Commercial Vehicles funded through a University Leadership Initiative (ULI). This SNLF ULI team has shown remarkable progress in advancing this airfoil concept for fixed-wing commercial air vehicles to meet the N+3 goal in fuel and energy consumption [8]. However, to achieve this goal, it is critical to gain a detailed understanding of the various past and current technologies in optimizing aircraft performance to determine the future pathways towards incorporating laminar flow technologies into existing aircrafts. Therefore, this paper aims to examine the mechanisms of laminar flow in aerodynamics and trace the succession of laminar-flow airfoils, using this information to frame and assess the NASA ULI team's current efforts in improving and advancing the SNLF airfoil.

II. Achieving Laminar Flow

In essence, the fundamental basis of the SNLF airfoil is a configuration that allows for a greater amount of laminar flow as compared to a traditional airfoil. Laminar flow occurs when air particles move in smooth layers that allow for uninterrupted flow, which is the opposite of turbulent flow, a more unsteady, mixed flow that produces drag. The occurrence of laminar flow under the surface of an airplane wing primarily depends on the state of the boundary layer. Additionally, a study by the National Advisory Committee for Aeronautics (NACA) in 1945 found that boundary layers and consequently the airfoil's overall behavior are influenced strongly by the surrounding pressure gradient [9]. An extended gradient of decreasing pressure is favorable as it reduces streamwise instabilities on the boundary layer, allowing for increased amounts of laminar flow on the surface. This provides stability to the boundary layer, greatly reducing the airfoil's skin friction drag. However, at some point, an adverse pressure gradient forms and destabilizes the laminar flow, causing a transition to turbulent flow. The onset of turbulent flow increases the previously reduced instabilities, causing boundary layer separation and increasing the skin friction drag. In summary, increasing the favorable pressure gradient and the extent of laminar flow on the airfoil is essential to reducing drag coefficients of the wing surface and improving overall aircraft performance.

However, maintaining laminar flow is extremely challenging because the airfoil must simultaneously fulfill multiple flight conditions, such as high Mach numbers, high Reynolds numbers, and increased section lift conditions. If the Reynolds number is very high, then the favorable pressure gradient must also extend along the entire length of the airfoil to stabilize the flow and maintain the laminar boundary layer [10]. Additionally, accounting for the various range of instabilities is crucial to prevent the boundary layer from transitioning from laminar to turbulent. For wings with relatively large sweep angles, the predominant instability is crossflow; however lower swept wings have primarily Görtler instabilities [11]. This presents a conflict as reducing the wing sweep could lower crossflow instabilities (CFI), but wing sweep is also crucial for increasing the critical Mach number, which is desirable for better aircraft efficiency [12]. Therefore, due to the various issues presented by the transition from laminar flow to turbulence flow, researchers are investigating approaches to reduce this wing profile drag to allow for more laminar flow and higher lift coefficients.

While such a solution may appear to be straightforward, examining the technical details reveals certain issues. For example, one approach to achieve reduced wing profile drag is to utilize a mechanical high-lift system to increase the maximum lift coefficient; however, such a complex structure tends to be heavy and expensive and could strain the system to the point of potential failure [13]. An ideal solution would not need extreme additions of materials and would be easily integrated into the existing framework of the aircraft.

Another attempt to decrease wing profile drag is via passive laminar flow by designing the shape of a single element to provide an increased extent of natural laminar flow (NLF) on the surface. Utilizing such a natural-laminar-flow (NLF) airfoil allows for a higher achievable maximum lift coefficient while also decreasing the profile drag coefficient. While many such airfoils have been designed and developed, single-element NLF airfoils have certain design limits that cannot be overcome through mere airfoil shaping. For instance, the extent of laminar flow along the aft and leading-edge sweep of the airfoil is limited to around 70-percent chord. Additionally, once the adverse pressure gradient reaches a certain point, trailing edge separation occurs [13]. The separation decreases the maximum lift coefficient, further reducing the L/D ratio of the aircraft.

One example of a single element, NLF airfoil is the NASA Common Research Model (CRM), specifically the CRM.65 model. It has been heavily researched and developed, and while the airfoil has been able to reach a higher level of laminar flow than standard airfoils, analyses show that there is also a 25 percent increase in total profile drag due to an early transition to turbulent flow on the lower surface [6] [14]. This indicates that the benefits that NLF provides to the CRM.65 are counteracted by the increased drag, and this specific design cannot sustain large extents of laminar flow while also preventing early transition.

In contrast, the slotted design of the SNLF airfoil overcomes the technical barriers that make laminar flow difficult to maintain. The SNLF airfoil provides an elegant solution while still allowing for a remarkable amount of increased fuel efficiency and airplane performance. While there has traditionally been a limited amount of naturally produced laminar flow for any aircraft wing, the two-element SNLF airfoil redefines those limits past any that is achievable by a single-element airfoil, solely through its slotted design [15]. This slot configuration allows for laminar flow across multiple parts of the airfoil. By including a slot that is always open between the fore and aft elements, the favorable pressure gradient can extend further aft and along both surfaces of the fore elements. This allows the fore element to be entirely laminar, while the aft element also achieves 60 percent on the upper surface and 100 percent on the lower, which results in the entire SNLF airfoil reaching around 90 percent laminar flow on its surface [4] [16]. Thus, the SNLF airfoil concept brings about lower wing profile drag coefficients and higher maximum lift coefficients through revolutionary wing design while simultaneously preserving the conventional airfoil shape.

III. The SNLF Airfoil Development Timeline

While airfoils have always been an immensely critical aspect of aeronautics, the leap towards optimizing airfoils to gain a more desirable extent of laminar flow predominantly began with Eastman Jacobs, a research engineer at NACA Langley Research Center, who published a preliminary report of laminar-flow airfoils in the late 1930s. Jacobs inverted the airfoil analysis method to derive an airfoil shape that would produce the desired pressure distribution [11]. In doing so, he created a unique procedure for obtaining the optimal boundary-layer characteristics that continues in today's research of airfoil design. Thus, this newfound procedure to design laminar-flow airfoils helped NACA in developing and verifying a variety of low-speed airfoils such as the NACA 6-series airfoils, which showed lower drag characteristics and higher critical Mach numbers than its predecessors [9]. A couple of decades later, NASA transitioned to supercritical, turbulent-flow airfoils such as the one developed by Richard Whitcomb in 1965 [12]. However, upon seeing higher lift coefficients but no improvements in the cruise drag coefficients from its predecessor, NASA decided that the best path would be to create a NLF airfoil that combined low drag from the NACA 6-series airfoils with the high lift from the supercritical airfoils [13]. One such airfoil, entitled the NLF (1)-0115, was designed for general aviation applications and the report on its design procedure and theoretical analysis was published by Dan Somers, Mark Maughmer, and Michael Selig in 1995 [14]. The philosophy behind the design was to incorporate a greater extent of the favorable pressure gradient on the lower surface to produce lower drag coefficients and improve maximum lift. Therefore, these philosophies were essential to creating NLF airfoils such as the NASA low-speed airfoils that had high lift and the NACA 6-series airfoils with low drag characteristics that Somers was attempting to build on in his studies [14].

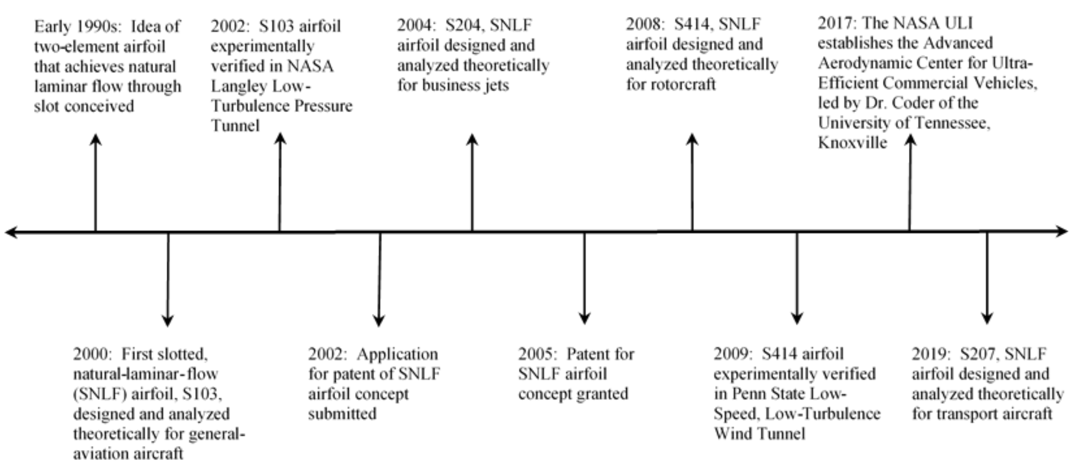

Figure 8: Timeline of the various specialized SNLF airfoils [15]

While Somers spent most of his career working on perfecting laminar-flow airfoils, he was actually working on a project on tilt-wing configurations when he conceptualized a two-element airfoil to reduce drag and increase laminar flow without nested configurations. He hypothesized that an open-ended slot would allow for a greater extent of laminar flow between the fore and aft elements and proceeded to submit a patent in 2002. The patent was granted in 2005 and describes how the pressure distributions from the fore and aft element interactions along with the slot would provide NLF over a greater region than with an airfoil without a slot, thereby generating additional lift due to the shape of the airfoil alone, as shown in Fig. 7 [5]. As displayed in Fig. 8, there have been 4 models of the SNLF airfoil so far. Figure 4 depicts all four of the airfoils' shapes, while table 1 summarizes their general designations and theoretical analyses.

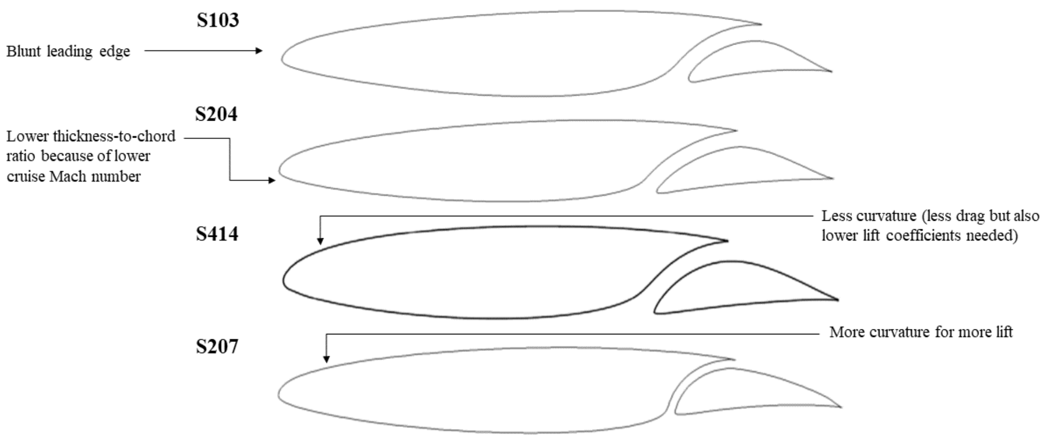

Figure 9: Compilation of the SNLF airfoil images with design annotations [15]

Table 1: Summary of Theoretical Analysis of all SNLF airfoil models

Airfoil	Designated Aircraft	Maximum Lift Coefficient	Mach Number	Reynolds Numbers Range
S103	General aviation applications	1.92	0.10	3.0 x 10^6
S204	Business jet	2.10	0.10	3.0 x 10^6
S414	Rotorcraft	2.01	0.10	1.0 x 10^6
S207	Low-speed transport aircraft	2.23	0.20	16.0 x 10^6

A. S103, SNLF Airfoil

Somers then dedicated years of design, research, and experimentation to the SNLF airfoil concept. The first SNLF airfoil was the S103, as shown in figure 6, and it was designed and analyzed theoretically in 2000. In 2002, it was later experimentally verified through wind-tunnel tests conducted in NASA's Langley Low-Turbulence Pressure Tunnel. Created with general-aviation applications in mind, specifically low-speed aircraft, the S103 had to meet the primary objectives of high maximum lift and low profile drag coefficients while also meeting the pitching moment and airfoil thickness constraint [16]. The goals were to reach a maximum lift coefficient of at least 1.72 at a Reynolds number of 3×10^6, as well as to achieve low-profile drag coefficients, from the range of a cruise lift coefficient of 0.20 at a Reynolds number of 9×10^6 to a climb lift coefficient of 1.00 at a Reynolds number of 6×10^6 [16]. The results of the theoretical analyses, as shown in table 2, for all four SNLF airfoils were predicted using the method outlined in Mark Drela's paper on a design and optimization method for multi-element airfoils. The paper describes a design/optimization method that breaks down the process into smaller optimization cycles, allowing the designer to isolate different functions and observe how the flowfield responds to design changes [17]. Using the MSES code as the underlying analysis solver and implemented through the LINDOP program, this method permits the designer to generate both least-square problems and general optimization problems to gather linear sensitivity information and then predict the needed design changes to continue to the next cycle [17]. Through both computational analysis and wind tunnel testing, the experimental data collected, as summarized in table 3 demonstrates that the airfoil exhibits favorable pressure distributions and section characteristics that fulfill the design objectives. However, the S103 exhibits a rapid stall, which indicates that the aircraft's angle of attack exceeds to the point where the lift decreases rapidly. Thus, the S103 does not meet the airfoil's goal of having minimal and docile stall characteristics [16]. In comparison with the baseline, NASA NLF (1)-0215F airfoil, the S103 has lower drag coefficients for higher lift coefficients, including a 12 percent higher maximum lift coefficient and a 7 percent lower drag coefficient. Therefore, even despite the rapid stall characteristics, the S103, SNLF airfoil achieved the two primary design objectives through both theoretical analysis and experimental verification.

Table 2: Theoretical and Experimental Results for the S103 and S414 SNLF airfoils

Airfoil	Mach #	Reynolds #	Transition State	Maximum Lift	Drag Range
S103 - Theoretical	0.10	1.00 x 10^6	Transition free	1.916	0.0397 – 0.2312
S103 - Theoretical	0.10	1.50 x 10^6	Transition free	2.269	0.0321 – 0.2449
S103 – Experimental	0.10	3.0 x 10^6	Transition free	1.969	0.0502– 0.2349
S103 - Experimental	0.10	6.1 x 10^6	Transition free	2.156	0.0454 – 0.2362
S414 - Theoretical	0.07	0.70 x 10^6	Transition free	1.940	0.087 – 0.231
S414 - Theoretical	0.10	1.00 x 10^6	Transition free	2.010	0.069 – 0.245
S414 - Theoretical	0.16	1.50 x 10^6	Transition free	2.095	0.140 – 0.247
S414 - Theoretical	0.17	1.50 x 10^6	Transition free	2.115	0.139 – 0.246
S414 - Experimental	0.07	0.70 x 10^6	Transition free	1.7464	0.0071 – 0.0552
S414 - Experimental	0.10	1.00 x 10^6	Transition free	1.8546	0.0059 – 0.1398
S414 - Experimental	0.16	1.50 x 10^6	Transition free	1.9944	0.0057 – 0.1305
S414 - Experimental	0.17	1.50 x 10^6	Transition free	1.9319	0.0095 – 0.0642

B. S204, SNLF Airfoil

The succeeding SNLF design is the S204 airfoil, as shown in figure 7. It was conceptualized and analyzed theoretically for business-jet applications in 2004. The S204 had the same design objectives as the S103 — high maximum lift and low profile drag — however, the S204 design also aimed for relative insensitivity to roughness [18]. Specifically, the objectives were to reach a maximum lift coefficient of at least 1.55 at a Mach number of 0.10 and a Reynolds number of 3×10^6 (which is the tip chord at a minimum velocity), and to obtain low profile-drag coefficients from a lift coefficient of 0.20 at a Mach number of 0.65 and a Reynolds number of 12×10^6 (the root chord at cruise condition) to a lift coefficient of 0.40 at a Mach number of 0.30 and a Reynolds number of 12×10^6 (the root chord at climb condition). Ideally, the design of the S204 would prevent the maximum lift coefficient from decreasing with fixed transition near the leading edge, while also displaying docile stall characteristics. Even though there was a constraint for the airfoil thickness to equal 15-percent chord, the final design was 14 percent to account for the lower cruise Mach number of business jets [18].

While the S204 has not undergone experimental testing to date, it was theoretically designed and verified. The design analysis and computational analysis was conducted using the single-element, Eppler Airfoil Design and Analysis Code as well as the multi-element, MSES code. The theoretical results show that the laminar flow extends to the trailing edge on both surfaces of the fore element, 60 percent chord on the upper surface of the aft, and to the trailing edge on the lower surface of the aft [18]. As for the section characteristics, generally the lift-curve slope, minimum drag coefficient, the width of the low-drag range, and magnitude increase of the pitching-moment coefficient all increase as the Mach number increases. The maximum lift coefficient increases with an increase in Reynolds number, while the minimum drag coefficient and width of the low drag decrease with increasing Reynolds number. Additionally, when considering the effect of roughness, there was only a decrease of approximately 1 percent in maximum lift coefficient from the airfoil that was transition-free, indicating that the design objective pertaining to roughness insensitivity is fulfilled [18]. Therefore, the S204, SNLF airfoil design successfully met its main design objectives through theoretical analysis.

C. S414, SNLF Airfoil

Soon after the patent for SNLF airfoils was granted to Somers in 2005, he began designing and analyzing a third airfoil. As illustrated in figure 8, the S414, SNLF airfoil design was intended to reduce blade profile drag for helicopters and rotorcraft and was initially theoretically analyzed in 2008 [19]. The overall goal was to maximize rotor

L/D ratio by increasing the section maximum lift coefficient for the retreating blade while reducing the cruise section profile-drag coefficient. A higher lift coefficient delays the stall-flutter on the retreating blade while a lower section profile-drag coefficient leads to a decreasing drag on the advancing blade [19]. These desirable characteristics, paired with the benefit of greater favorable pressure gradients in the same manner as the other SNLF airfoils, allows the overall aircraft to achieve more efficient flight. Additionally, the two primary design objectives were to achieve a maximum lift coefficient of 1.25 at a Mach number of 0.23 and a Reynolds number of 0.97×10^6, and to obtain low profile-drag coefficients from a lift coefficient of 0.10 at a Mach number of 0.70 and a Reynolds number of 22.6×10^6 to a lift coefficient of 0.65 at a Mach number of 0.45 and a Reynolds number of 1.45×10^6. The design specifications mainly require that the airfoil should not exhibit strong stall characteristics, the thickness should equal approximately 14 percent chord, and the maximum lift coefficient should not experience a significant decrease with transition fixed on the leading edge on both surfaces [19]. The S414 underwent theoretical analysis, the results of which are summarized in table 4, using the Eppler Airfoil Design and Analysis Code for designing the initial fore and aft elements. While the lower limit of the low-drag, lift-coefficient range was higher than expected, the remaining results yielded by the theoretical analysis align with the specified objective and constraints [19].

A mere year after it was theoretically verified, the S414 airfoil reached yet another milestone. In 2009, the S414, SNLF airfoil was successfully tested and experimentally verified through a series of wind-tunnel tests in the Pennsylvania State University Low-Speed, Low-Turbulence Wind Tunnel (LSLTT) [17]. These results led to a second paper, written by James Coder of Pennsylvania State University as well as Somers and Maughmer, which combines the theoretical analysis previously conducted for the S414, SNLF airfoil with experimental results, shown in table 5, from Pennsylvania State University's wind tunnels to uncover the potential benefits of the airfoil [17]. Many of the experimental results are provided with results measured at other well-established wind tunnel facilities such as NASA Langley Research Center and Delft University to increase confidence in the Pennsylvania State facility's qualifications [17]. The experimental methods yielded pressure coefficients, section normal, chord-force, and pitching-moment coefficients, and profile-drag coefficients. Uncertainties were also calculated based on the operating conditions, with the general trend being that uncertainty increases as the angle of attack increases [17]. Additionally, to better pinpoint the locations of transitions and where the flow separated, as well as to verify the two-dimensionality of the tests, the researchers conducted flow-visualization studies using fluorescent oil.

For the section characteristics, the results display that the lift-curve slope and maximum lift values are directly proportional to the Reynolds number, whereas the extent of the low-drag range is inversely proportional to the Reynolds number [17]. However, tests have shown the occurrence of unusual shapes at the lower Reynolds numbers. Namely, at the lowest Reynolds number, laminar-separation-bubble effects cause a higher drag than expected in the low-drag range. Additionally, at the lower limit of the low-drag range, the drag coefficient drops significantly when the Reynolds number is 0.7 x 10^6. This drop, or "horn," is likely to be caused by an interaction between the wake of the fore element and the laminar separation bubble on the upper surface of the aft element [17]. As for the pressure distributions, the comparisons of estimated and measured results are in very close agreement for the first element but show some small discrepancy at the slot entrance. Nevertheless, their overall consistency is an achievement while also providing validation for the computational fluid dynamics approach for analyzing the SNLF airfoil [17]. All in all, the modelling of the airfoil and the experimental results from wind tunnel testing yielded a large amount of data on the airfoil, allowing the authors to gain more analytical insight on how the airfoil may behave when installed on an aircraft. Therefore, the S414, SNLF airfoil successfully achieved the main objectives of low drag and high lift coefficients.

D. S207, SNLF Airfoil

The latest SNLF airfoil design conceptualized by Dan Somers is the S207 SNLF airfoil, as shown in figure 9, and was designed specifically for a transport aircraft. As with the previous designs, the core goal revolves around the reduction of wing profile drag, which is responsible for a third of the total drag for transport aircraft. A preliminary report of the airfoil states that the design specifications were initially derived from the Boeing SUGAR study and further refined by the members of the Configuration Technical Sub-Group of the NASA ULI team, as this design is specifically being tailored to the ultra-efficient aircraft that NASA aims to develop [7]. The primary objectives are to achieve a maximum lift coefficient of 2.30 at a Mach number of 0.225 and a Reynolds number of 16.0×10^6, as well as to obtain low profile-drag coefficients over the range of lift coefficients from 0.39 to 0.65 at a Mach number of at least 0.660 and a Reynolds number of 13.2×10^6 [7]. The base philosophy behind a two-element airfoil with a slot is to ensure that the entire fore element is laminar, and the aft element can achieve significant laminar flow with lower Reynolds numbers, thus satisfying the design goals. As with the S103, S204, and S414, the S207 airfoil design was also executed using the Eppler Airfoil Design and Analysis Code for the MSES code for successful theoretical analysis of the element shapes and the airfoil configuration [7].

In terms of the pressure distributions, around the lower limit of the low-drag, lift-coefficient range, the pressure gradient is favorable along the upper surface of the fore element while on the lower surface, the pressure gradient is quite adverse [7]. Additionally, within the low-drag range, the pressure gradient remains consistently favorable along the entire lower surface of the fore element whereas the distribution on the aft element does not experience much change. As for the boundary-layer transition, when within the low-drag range, the airfoil achieves almost complete laminar flow on both surfaces of the fore element, 55 percent laminar flow on the aft element's upper surface, and all the way to the trailing edge on the lower surface of the aft element [7]. There is also next to no wave drag in the low-drag range. As expected, as the Mach number decreases, the lift-curve slope and the pitching-moment coefficients do so as well. One thing to be noted is that the method for theoretical analysis does not account for Görtler instabilities that may occur on the boundary layer. According to the report, the airfoil was preliminarily evaluated, and the Görtler instabilities could influence boundary-layer transition and cause it to occur in the concave region of the fore element's lower surface [7].

IV. Current SNLF Research

As demonstrated by the NASA studies, the LamAiR report, and the development of the SNLF airfoil, laminar flow is rapidly gaining recognition as an advanced solution that can be incorporated into existing aircraft designs. Considering the findings that emerged from the Boeing and MIT studies, as well as the need to meet increasing demand and costs in the aircraft industries, NASA chose to invest in laminar flow technologies further as a part of their University Leadership Initiative (ULI). The NASA ULI program was initiated to encourage partnerships with university researchers and aims to seek innovative ideas that support the goals and interests of the NASA Aeronautics Research Mission Directorate (ARMD) and the overall United States aeronautics community. As previously mentioned, the NASA ULI program was created to build bridges between the NASA Aeronautics Research Mission Directorate (ARMD) and various universities and industry members by connecting them through multidisciplinary aeronautics research [20]. Upon ARMD's designation of various strategic thrusts for research, NASA ULI then accepts applications from universities and industry partners across the nation and awards the finalists with funding and resources to address their respective thrusts. In the first round of ULI awardees, James Coder of the University of Tennessee was chosen the Principal Investigator of the Advanced Aerodynamic Design Center for Ultra-Efficient Commercial Vehicles to focus on the ARMD strategic thrust of developing ultra-efficient commercial vehicles [20]. Through further developing an SNLF airfoil specific to the type of commercial vehicles NASA is seeking to optimize and successfully integrating it into existing aircraft designs, the NASA ULI team at UTK hopes to prove the value of investing in the unique airfoil design. The current design that the NASA ULI group is focused on is the S207, SNLF airfoil, and while the design is finalized and has been successfully analyzed theoretically, the project itself is still ongoing.

The core goal of the Advanced Aerodynamic Design Center for Ultra-Efficient Commercial Vehicles centers around developing the SNLF airfoil so that it can be integrated with Boeing's Truss-Braced Wing Aircraft to create a more efficient aircraft. To achieve this goal, the ULI team at UTK divided their project into three phases: Technology Development, Technology Integration, and Technology Demonstration. The initial focus will be technology development, involving using the baseline SNLF design and tailoring it to the Boeing design specification, along with optimizing the airfoil and exploring other newer technologies that could further enhance maximum lift [21]. Later, the technology integration stage will aim to take the newly developed SNLF airfoil and ensure that it integrates perfectly with the Boeing Truss-Braced Wing airplane through computational and experimental analysis. Finally, with technology demonstration, the optimized SNLF airfoil will be experimentally verified in the NASA Ames 11ft Transonic Wind Tunnel to test that it satisfies the goals of wing profile drag and noise reduction, thereby successfully demonstrating the advanced technologies included in the airfoil [21].

Since the commencement of the Advanced Aerodynamic Design Center for Ultra-Efficient Commercial Vehicles, the ULI researchers have chosen to analyze various aspects of the SNLF airfoil's performance, methods of analysis and optimization, and advanced technologies that would be integrated into the airfoil to better improve fuel and energy efficiency. These parallel strategies refine the airfoil's shape and behavior to better match the Boeing airplane, while also exploring cutting-edge technologies that would greatly enhance multiple aspects of the airfoil's performance, such as aerodynamics, structures, propulsion, stability, and acoustics [21].

The ULI research centered around aerodynamics is two-fold; while some researchers focus on optimizing the design and geometry of the S207, SNLF airfoil and how it affects its behavior, others investigate different methodologies and technologies that can enhance the S207's aerodynamic benefits. One method of analyzing the S207's aerodynamic behavior is utilizing computational fluid dynamics (CFD) to make high-lift predictions. ULI researchers Coder and Ortiz-Melendez, along with Shmilovich from Boeing, conducted a study on the most suitable configuration of the aft element of the SNLF airfoil (in this case, the S204 airfoil was used a baseline) in order to satisfy the high-lift target for commercial aircraft [22]. The study aimed to explore two different configurations of the aft element of the SNLF airfoil, the first being micro-flapped aft element or instead, making the aft element a Fowler flap. In total, the four combinations that these versions produce is a baseline S204 aft element, a deflected aft element, a deflected micro-flap, and both a deflected aft element and micro-flap [22]. The computational approach chosen was a Reynolds-Averaged Navier-Stokes (RANS) procedure, which is used to calculate the flow near maximum lift by integrating the lift-forces of the system, as shown in figure 10 [22]. Through the use of CFD in the design and verification process, the required costs and efforts for preliminary wind-tunnel testing have been greatly reduced. meshes of the S204 airfoil were also generated with the use of NASA's Chimera Grid Tools, and multiple grid systems were produced to incorporate the two flap configurations being studied [22]. By the conclusion of the study, results depicted that the S204 airfoil micro-flap (when deflected downwards) and the Fowler flap have provided a greater maximum lift than the airfoil without the flap [22]. Thus, this research is paving the way for future studies that investigate these configurations in more depth and in conjunction with the use of an active flow control device to further optimize the SNLF airfoil's performance in terms of high lift.

Another example of the methodologies that explore ways to better improve the S207's performance is by identifying and decomposing the types of aircraft drag to inform the SNLF's design and optimization process. While multiple methods for drag decomposition exist, maintaining a consistent methodology is extremely important, especially when the design deviates from traditional aircraft configurations, as in the case of Boeing's Truss-Braced Wing design. Therefore, one facet of the NASA ULI project is to explore an alternative methodology based on partial-pressure fields in compressible flow calculations, which provides more insight into pressure drag and could also present more resolved surface-pressure contours that would better guide the high-performance adjoint-based optimization in the future [23].

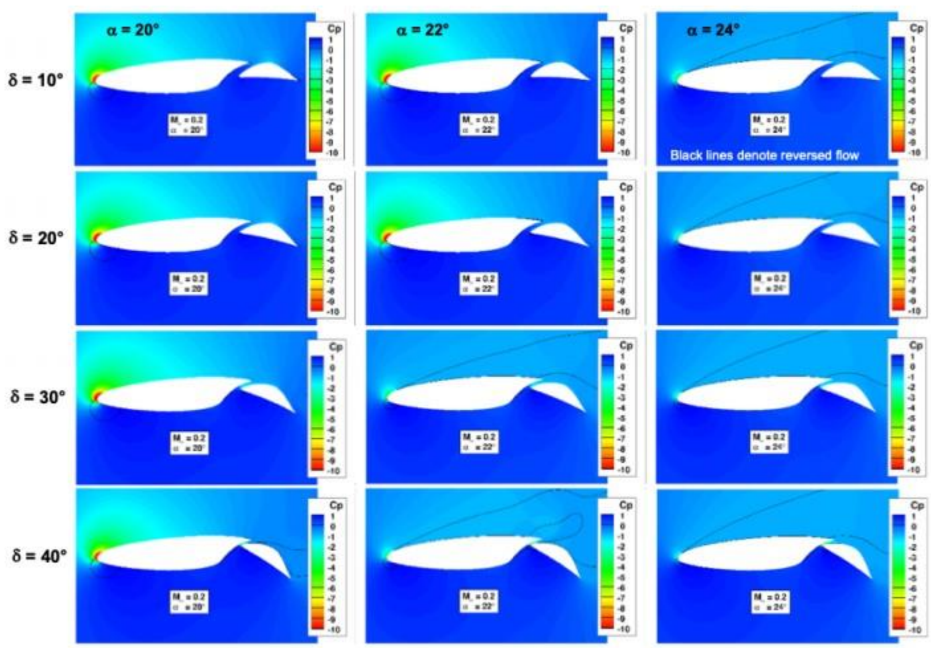

Figure 10: Effect of Flap Deflection on the Flow Structure near Maximum Lift [22]

Studying the structure of the airfoil section, especially given the slot separating the fore and aft elements for the SNLF airfoil, is crucial to the aerodynamic performance and overall integrity and efficiency of the wing. One aspect of the ULI's structures research is aimed at structurally optimizing different parts of the airfoil through conducting damage tolerance predictions for hybrid materials [24]. Essentially, hybrid composites allow for a greater range of benefits from different individual materials, thus improving the overall structure's performance while minimizing the weight added. This strategy would be very desirable when considering the needs of an ultra-efficient airfoil design. Therefore, one goal of the ULI team at the University of Tennessee is to use an integrated approach of combining computational simulation, sensitivity analysis, and experimental testing to study the various damage mechanisms of the composite and identify the most influential inputs on the damage tolerance [24]. The results from this study helps in informing the development of the high-fidelity model, which in turn is currently being used to design joint connectors for the SNLF airfoil, which are critical, as the connectors will be the sole source of support between the fore and aft elements that are separated by the slot.

When looking into various advanced technologies that the NASA ULI is exploring, one example is the experimental research being conducted with inclined fluidic oscillators for active flow control to improve boundary layer separation control and heat transfer, among other aspects [25]. Fluidic oscillators are devices that generate a continuous stream of oscillations without the use of moving parts. In the main chamber of the oscillator, the supplied flow enters through the inlet and passes through towards the outlet, but through a narrow feedback channel, small amounts of the stream pass back through to the other side of the mixing chamber and switch sides, thus causing the flow to have an oscillating frequency as it recirculates [26].

V. Conclusion

As previously discussed, the NASA ULI team is currently in the process of optimizing the S207's shape and geometry to best fit the dimensions of the target vehicle, the Boeing Truss-Braced Transonic aircraft, while also investigating other enabling technologies to further reduce drag and enhance maximum lift on the wing. Upon completing the phases of technology development and integration, which consists of the computational research that will enhance the wing's performance, the final design of the SNLF airfoil will be finalized. Shortly after, the SNLF airfoil will be experimentally verified by conducting wind tunnel experiments at the NASA Ames 11ft Transonic Wind Tunnel in order to prove the technology's efficiency and functionality. The wind tunnel testing will be the final step in the NASA ULI team's five-year project, and if successful, will conclusively demonstrate the SNLF airfoil's viability as a revolutionary wing design and will most likely lead towards a permanent incorporation into the Boeing Transonic Truss-Braced Aircraft.

In summation, the need for advancing aircraft optimization by finding solutions to global aircraft issues that can be incorporated into existing structures is very dominant in the aerospace industry. In the area of reducing wing profile drag and optimizing the lift-to-drag ratio, the SNLF airfoil is an ideal solution as it requires no additional technology development and, by allowing almost 90% of its surface to achieve laminar flow, can contribute to the N+3 goal of reducing fuel consumption by 70%. In addition, the NASA ULI team is continuing to work towards improving and refining the airfoil in order to integrate it with the Boeing Transonic Truss-Braced aircraft. Therefore, the paper accomplishes its core aims of tracing the need for laminar flow technology, detailing the developments on the novel SNLF airfoil design, and surveying recent developments of the NASA ULI's research on the SNLF airfoil and their progress towards incorporating NLF technology in commercial aircraft.

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