Paper ID #25535

Numerical Investigation of Flow Characteristics of a Slotted NACA 4414 Airfoil

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Abstract

This paper focuses on enhancing the critical thinking and problem solving skills of an undergraduate Mechanical Engineering student. This is accomplished via an independent study where the student is tasked with a real life challenge and has to utilize the basic theory acquired during a traditional classroom setting to aid in solving it. To achieve this, the flow characteristics of a slotted NACA 4414 airfoil has been numerically investigated in this paper. When the airfoil angle of attack exceeds a critical value, boundary layer separation occurs which results in a sudden reduction in lift and an increase in pressure drag due to the larger wake zone. Mitigation of boundary layer separation is critical in improving airfoil performance and delaying stall, and this is the assigned task.

After a thorough literature review, the student chose a passive technique to aid in minimizing boundary layer separation and improve airfoil stability. The proposed passive airfoil design is unique since the slot does not fully separate the trailing edge from the airfoil (unlike Fowler or Slotted Flaps), thus reducing the mechanical complexity. The study was constructed in such a manner that exposed the student to the comprehensive problem solving cycle which aided in enhancing the critical thinking skills. The student's performance was tracked throughout, and at certain places questions were asked to force the student to think out of the box. At the conclusion of the study, the student was highly appreciative of the project as it applied fundamental concepts to solve real world challenges, sharpened the critical thinking, and motivated the student to further engage in research by pursuing graduate studies.

Introduction

Sharpening the critical thinking ability of an undergraduate student remains a challenging task for many instructors in a traditional classroom setting. The requirement to cover a large volume of material in a semester with the proper balance of theory, derivation, and solving sample theoretical problems is a major cause. As a result, the students find it increasingly challenging to apply their theoretical knowledge to solve practical problems. For example, for flow over immersed bodies (a chapter in Fluid Mechanics), boundary layer separation is a major topic of interest. While students are able to comprehend the theory adequately, they are often unable to form a nexus between the theoretical and practical worlds. This problem was very evident when they were asked to apply their basic theory to aid in mitigation of boundary layer separation. Unfortunately, this ripple effect can be felt at the graduate level where even graduate students lack critical thinking. Involving the undergraduate student in a research project that connects the dots between theory and application is a proven way to enhance critical thinking and force the student to think out of the box. However, introducing such an in-depth research project in a traditional classroom setting may not be feasible. A solution to this is where the student does an independent study and interacts one-on-one with the faculty member. While independent studies are widely used, many of them are conducted in a manner where the student does not get the maximum exposure or challenge possible. The independent study needs to be chosen carefully such that the student is exposed to the comprehensive problem solving cycle (empathize, define, ideate, prototyping, and results) and is able to utilize his/her basic theory to aid in practical application. This paper provides an example of such an independent study done by an undergraduate Mechanical Engineering student. It involves numerically investigating the flow characteristics of a slotted airfoil for enhanced stability while also utilizing certain basic concepts learned in the traditional lecture to optimize the design. The entire project has been constructed in a manner to challenge the student by giving maximum exposure to the above mentioned five stages of a problem solving cycle.

Background

The interaction between a fluid and a body's surface is a major concept to understand before being able to design a body for a specific aerodynamic application. The boundary layer is a region where a velocity gradient exists due to the no-slip boundary condition. The vertical distance from the surface to the point where local velocity is 99% of free stream velocity is defined as thickness of the boundary layer. For flow over an airfoil, the incoming fluid (air) will reach a maximum velocity at a certain point, and according to Bernoulli's principle, this also corresponds to the point with the lowest pressure. Therefore, till this point is reached, the fluid is said to have encountered a favorable pressure gradient (high to low pressure). Beyond this point, the fluid has to return to its original ambient pressure and will have to encounter an adverse pressure gradient (low to high pressure) [1]-[3]. Even though air has a low viscosity, viscous forces will still exist near the airfoil surface due to the large velocity gradients, a result of boundary layer. These forces will result in a reduction in momentum for fluid layers immediately adjacent to the airfoil. If these fluid layers do not have sufficient energy to overcome the adverse pressure gradient, they will reverse in direction (see Fig. 1). The reverse streams will then collide with the oncoming streamlines causing them to separate from the body and create a wake region rich in vortices as shown in Fig. 2. The point of separation is called the boundary layer separation point.

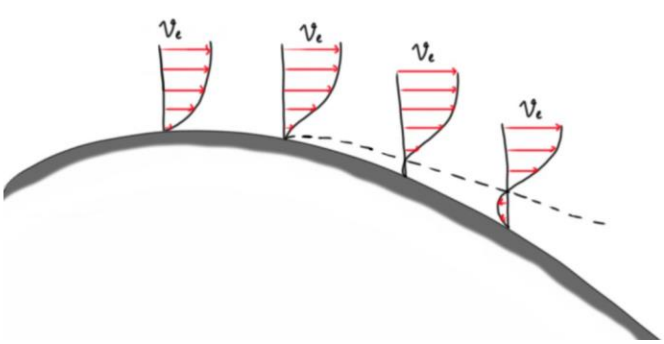

Figure 1: Velocity profile along airfoil

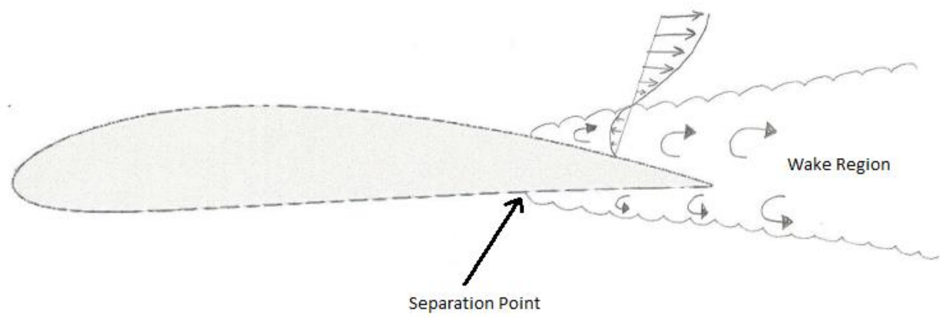

Figure 2: Illustration of vector reversal and creation of wake zone

Boundary layer separation for an airfoil becomes significant at high angles of attack. As the angle of attack is increased, the maximum velocity magnitude also increases thus increasing the velocity gradient and the viscous shear forces near the airfoil. Beyond a certain angle, the reduction in pressure is too large and the fluid adjacent to the airfoil does not have sufficient energy (momentum loss due to increased viscous forces) to combat the adverse pressure gradient resulting in boundary layer separation and creation of a wake region. This results in a reduction in lift and an increase in drag both of which are unfavorable. The airfoil is said to have undergone stall, and the critical angle of attack at which this happens is known as the stall angle. Figure 3 shows the variation of lift coefficient with angle of attack for a Clark-Y airfoil. The critical angle of attack is around 12 degrees. The above background information forms the empathize stage of the problem solving cycle and was given during both the traditional Fluid Mechanics lecture and independent study session. The student was asked to refer to other books and articles to further strengthen the basic concepts.

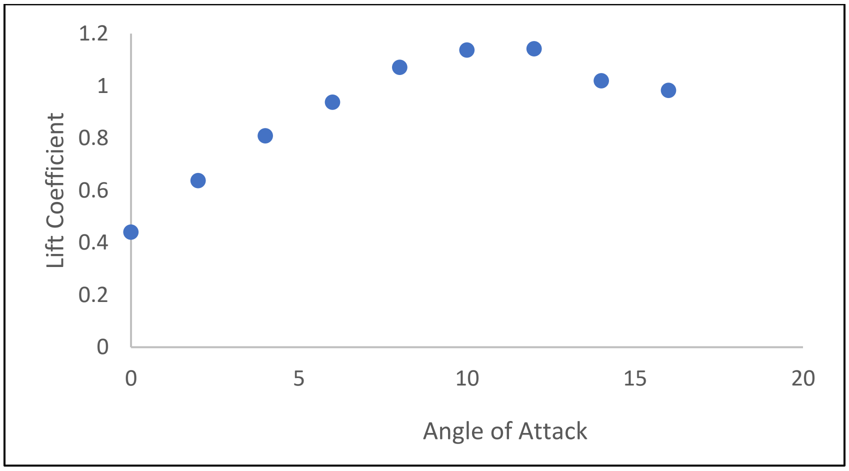

Figure 3: Experimental results for lift coefficient with angle of attack for Clark-Y airfoil

A decrease in lift performance is highly undesirable. The student's task is to device a method to improve the lift performance and stability of the airfoil by utilizing theoretical knowledge gained from prior stage. This is the problem statement (define) which stage 2 of the cycle is. Following this, the student proceeded to stage 3 which involves research (ideate). For the ideate phase of the study, the student was asked to conduct a detailed literature review and identify possible mitigation techniques while adhering to three requirements: (i) the project duration was to be no more than two months, (ii) the selected design should be such that the numerical simulation would not be cumbersome, and (iii) the idea of future potential experimental testing should not be discounted. Selection of a novel/custom design was heavily encouraged. The following is a condensed literature review conducted by the student.

Improving the airfoil performance and stability has been researched for several years and many different methods exist. One way to improve the lift of the airfoil is to decrease the size of the wake region, thus allowing the airfoil to operate at higher angles of attack (prolonging stall). This can be done by energizing the fluid prior to separation. The fluid will now have sufficient energy to fight the adverse pressure gradient and delay boundary layer separation by pushing the separation point further downstream. Techniques to achieve this can be classified as either active or passive [4]. Active forms include wall heating, synthetic jet usage, acoustic excitations, and pulsed blowing, while passive forms include vortex generators, surface roughness, and uniform suction/blowing [5]. Passive techniques do not require auxiliary power or a control loop. Vortex generators and mechanical flaps are examples of passive flow control solutions.

A large amount of research is available in the understanding of boundary layer separation reduction and the re-lamination of the airflow to the airfoil via the use of flaps [6]-[9]. Such airfoils are termed as high lift airfoils. Figure 4 shows the major basic types of flap configurations that exist. Plain flaps are obtained by bending the trailing edge, usually on a hinge, to increase the camber of the airfoil. A spilt flap is a device where the lower portion of the trialing edge is hinged downward while the upper portion of the trailing edge is locked in place. Although the efficiency of the spilt flap is low, it is popular due to its simplicity. Slotted flaps are similar to plain flaps except that as the flap's angle changes, the slot exposed between the main airfoil and the flap also changes. The exposed slot forces high pressure air from the lower portion of the airfoil to the top. This is a very simply yet effective technique. Boundary layer separation occurs due to a serious adverse pressure gradient and lift exists due to the pressure difference between the suction (low pressure) and pressure (high pressure) sides. If air was able to be drawn from the pressure side to the suction side, the adverse pressure gradient will be reduced on the suction side and the boundary layer separation point can be pushed further downstream of the airfoil. A fowler flap is slightly different compared to the slotted flap. Instead of the flap moving on a hinge, the flap on a fowler flap would actuate in a linear downward motion while the flap changes its angle. Not only is the camber changing, but also the chord length of the airfoil. To further improve the lift of a fowler flap, an additional flap can be incorporated into the design to create a double slotted flap.

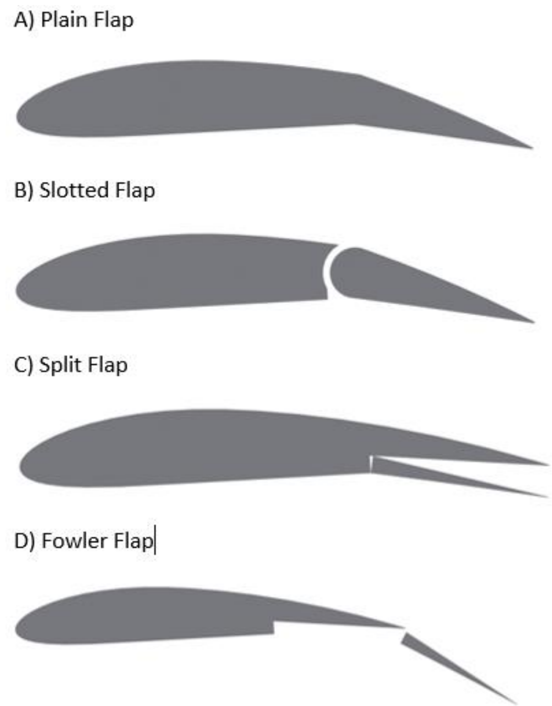

Figure 4: Trailing edge flap configurations.

Overall, trailing edge devices show an upward shift in the lift curve compared to the original airfoil [9]. However, due to the complexity of multi-element high lift airfoils, they are costly. Multi element high lift systems are costly due to the time required to design and test an airfoil, the complexity of the actuation system to deploy the high lift airfoil, weight of the system, and the maintenance of the system. About six to eleven percent of a transport aircraft's expense goes into the design and implementation of a high lift airfoil [10]. While the initial focus of high-lift design was mainly on improving the lift of the aircraft, the current focus has switched to reducing the complexity, cost, and maintenance on the airfoil [11].

The student proposed a simple fixed slotted idea to improve airfoil stability and performance. The proposed passive airfoil design is unique since the slot does not fully separate the trailing edge from the airfoil (unlike Fowler or Slotted Flaps) thus reducing the mechanical complexity. The airfoil camber and chord length remain unchanged. The slotted airfoil allows for bleeding of a small quantity of air from the pressure side of the airfoil to the suction side which energizes the flow thereby delaying boundary layer separation. This concluded stage 3, the research (ideate) phase. Once the general design idea was fixed, the student was then approved to proceed to stage 4 (numerical design). Typically, this stage is known as the prototyping stage, but since our study was purely numerical, we had to modify this part to suit our needs. This phase involved selection of a numerical software, learning the setup, and following certain protocols such as results validation and grid independence studies. Once the cases were setup in 2-D and 3-D, the student began the final stage (results) which involved parametric investigation of slot parameters. The following section was written by the student.

Numerical Setup

A custom NACA 4414 airfoil was selected and the profile (fig. 5) was generated using the GUI available at Airfoil Tools [12]. The maximum camber was 4.3% located 40% chord length from airfoil leading edge, airfoil thickness was 14% chord length, and number of points generated in space was 200. The points were then exported directly to ANSYS DesignModeler for the 2-D case or to SolidWorks for the 3-D case. All numerical analyses were done using ANSYS FLUENT, a commercially available CFD (Computational Fluid Dynamics) software.

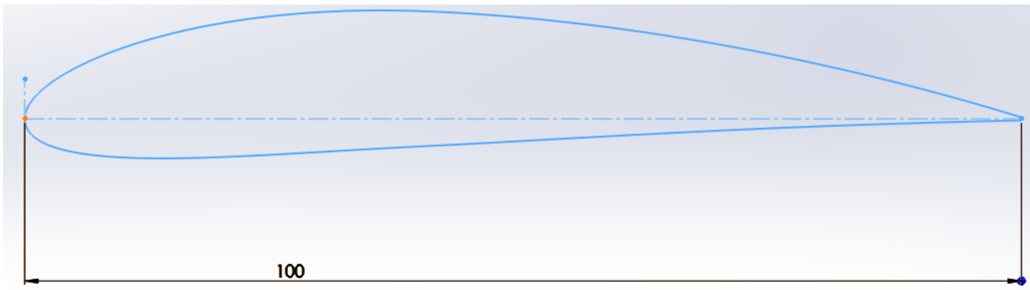

Figure 5: 2-D view of NACA 4414 airfoil

The first step in any numerical analysis is to validate the setup. For this procedure, simulations were conducted in 2-D for the well-established Clary-Y airfoil since data were readily available. Figure 6 shows the excellent agreement between CFD and experimental results at Re = $2x10^5$ thereby validating the setup. Following this, the NACA 4414 was analyzed in 2-D. Figure 7 shows the boundary conditions. A grid independence study was conducted and an optimal mesh sizing was selected when the lift coefficient values varied by less than 1%. For all analyses, an unstructured tetrahedral mesh was selected. In order to capture the detailed flow near the airfoil surface, an inflation layer consisting of 16 layers and a growth rate of 1.2 was added as shown in fig. 8. Table 1 provides the list of important CFD parameters.

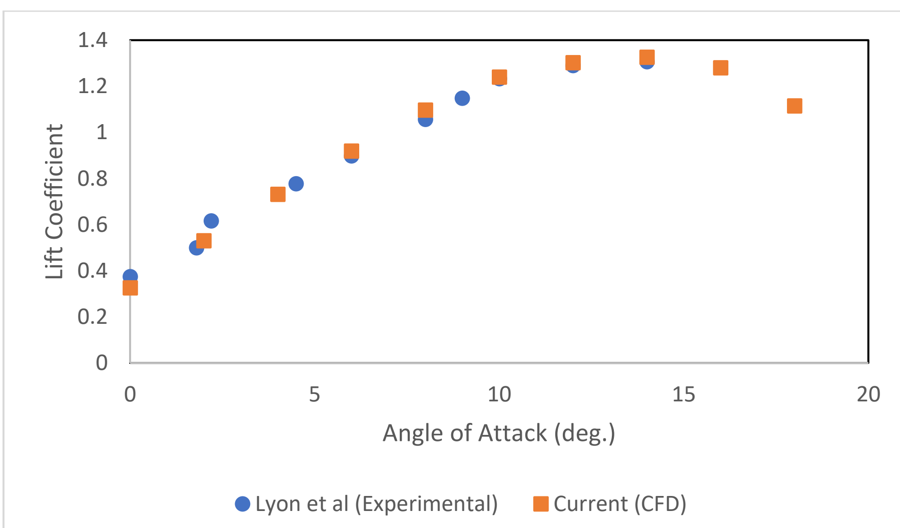

Figure 6: Experimental [13] and numerical comparison of lift coefficient for a Clark-Y airfoil

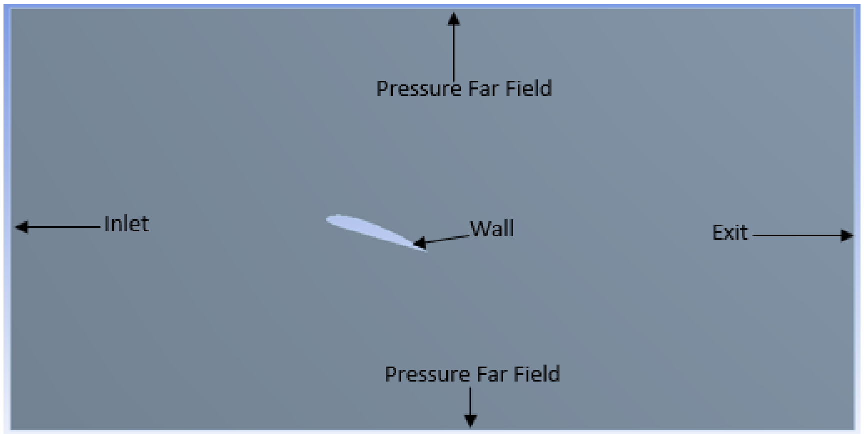

Figure 7: Boundary conditions

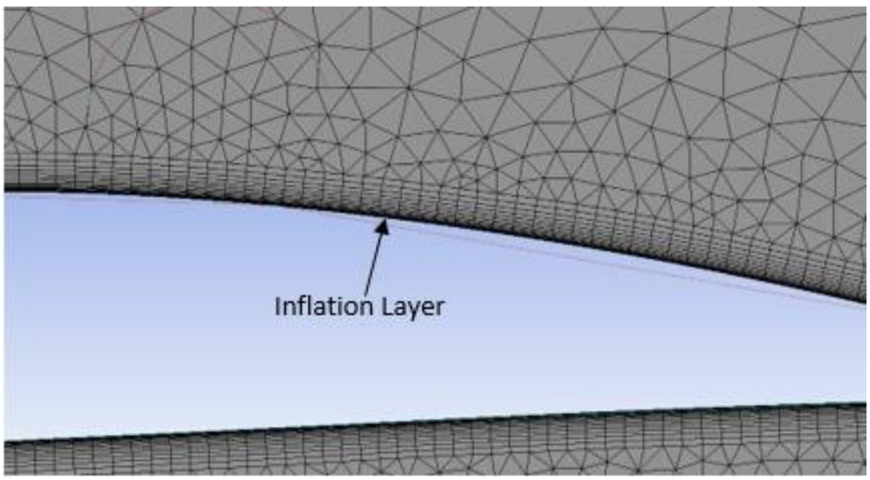

Figure 8: Zoomed in view for inflation layer

Table 1: CFD Parameters

Chord Length	100 mm
Turbulence Model	Spalart Allmaras
Momentum	Second Order Upwind
Pressure-Velocity Coupling	Simple
Inlet Velocity	30 m/s
Air Temperature	300 K
Air Density	1.225 Kg/m^3
Air Viscosity	1.7894×10^{-5} Kg/(m*s)
Outlet gauge Pressure	0 Pa
Wall	No Slip

The 3-D setup simply involved extruding the airfoil profile in SolidWorks to a finite length of 18 mm (fig. 9). The extra two planes created (front and back) were symmetric planes. The extruded airfoil with boundary conditions can be seen in fig. 10. The 3-D results of Clark-Y airfoil were compared to the 2-D ones and the 3-D case was also validated since the results were almost identical.

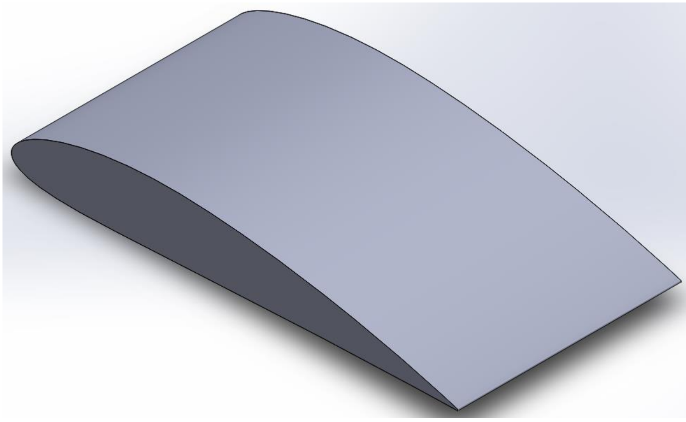
Figure 9: 3-D view of NACA 4414 base airfoil

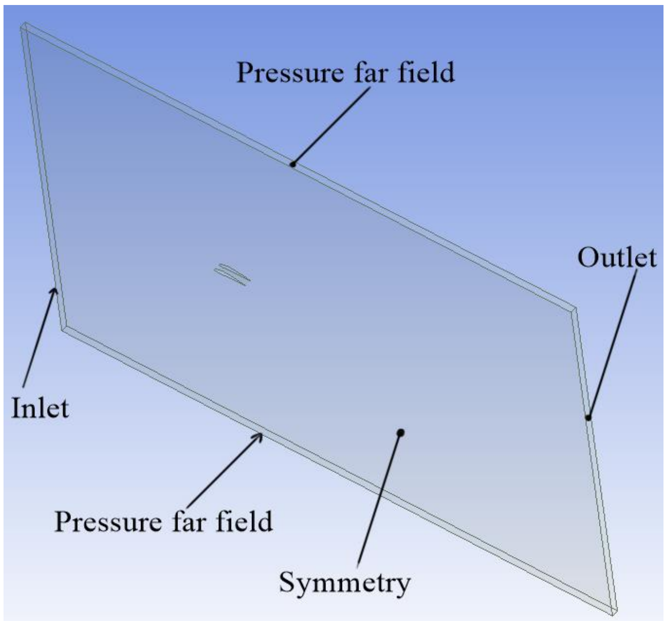

Figure 10: Boundary conditions for 3-D case

Results and Discussion

This section addresses the fifth and final stage (results) of the problem solving cycle which involves the student's ability to critically analyze the problem. Once the 2-D validation was completed using the Clark-Y airfoil, the baseline NACA 4414 airfoil was analyzed in 2-D and the lift coefficient at various angles of attack was computed. Figure 11 shows the trend with a stall angle of 14^0. The 3-D baseline NACA 4414 results are not shown in this paper since they were almost identical to the 2-D results. Figure 12 shows a close up view of the velocity contours for angles of 0^0 and 14^0.

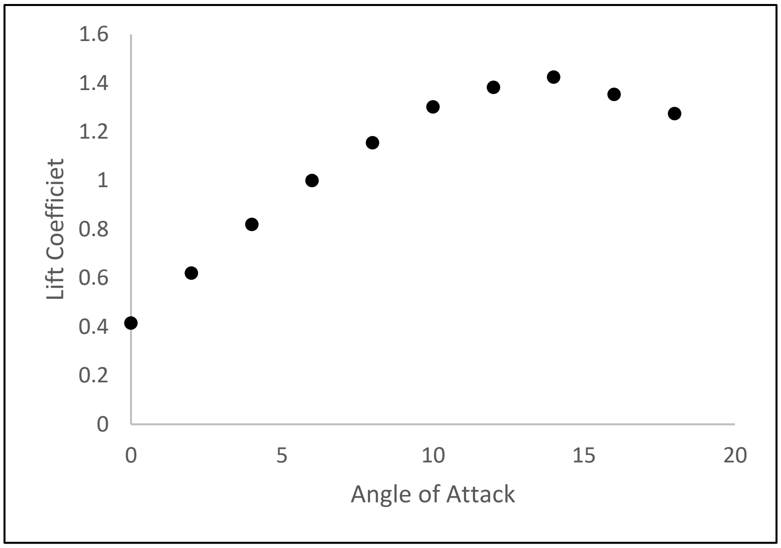

Figure 11: NACA 4414 baseline airfoil lift coefficient variation

As expected from theory, the velocity is highest on the suction side resulting in lower pressure and generation of lift. At 14^0, the stall angle, the wake region is large giving rise to increased drag and reduced lift. The student was able to successfully explain the CFD results at both angles and connect them to the theory learned during lecture. It was noted that the separation point (first vector reversal along airfoil) occurred at roughly 43% of chord length downstream of airfoil leading edge.

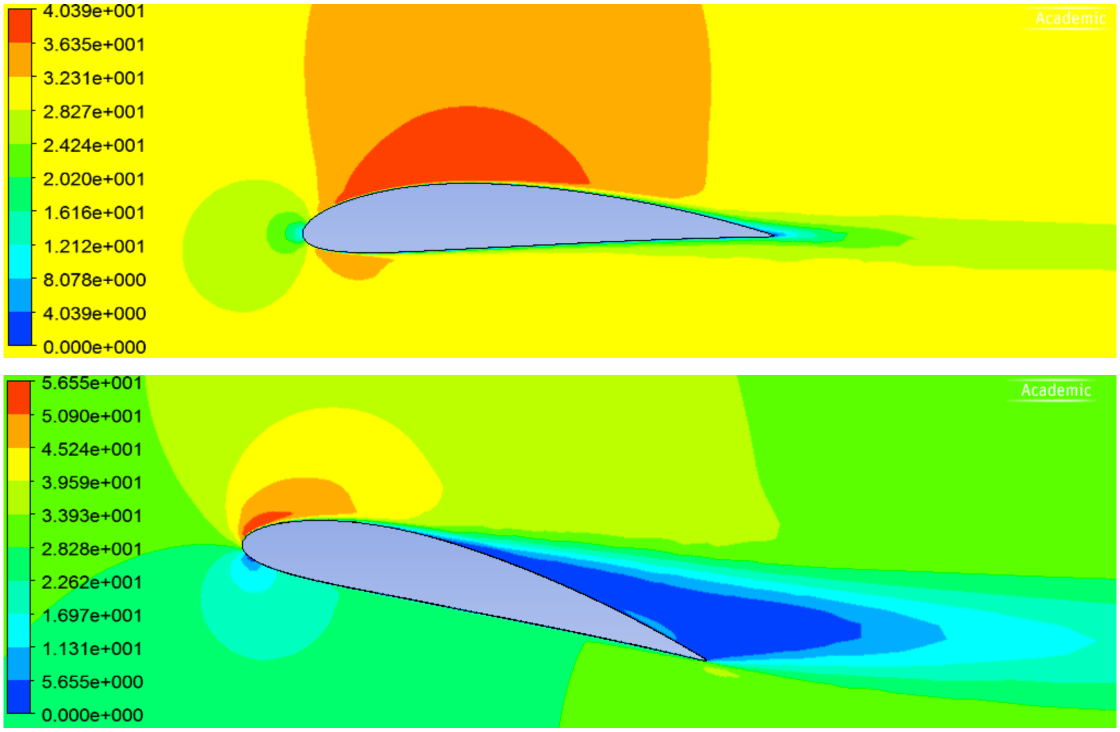

Figure 12: Close-up view of velocity contours for 0^0 (Top) and 14^0 (Bottom)

Next, the student began designing the slotted airfoil in 2-D and conducting a parametric investigation. The design of the slot hinged upon four major parameters, namely A) angle of slot relative to the horizontal, B) draft angle of slot, C) slot width on suction side, and D) position of slot in terms of chord length percentage. The four parameters can be seen in fig. 13.

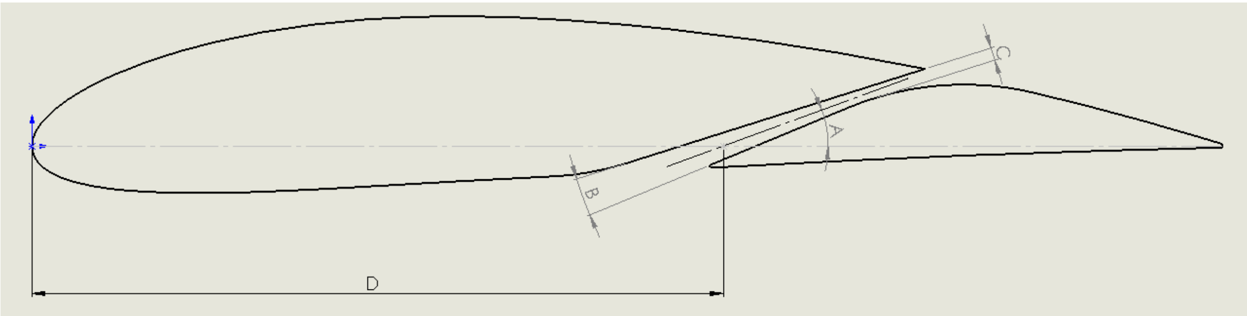

Figure 13: 2-D view of slotted airfoil with geometric parameters. A: Slot angle to horizontal. B: Draft angle of slot. C: Slot width on suction side. D: Slot position in percent chord length

The student suggested that since the baseline airfoil stalled at 14^0, the various slotted configurations will be initially only tested 14^0 and 16^0 since lift enhancement was the major focus. This would clearly indicate if stall was delayed thus minimizing run time. Once the optimal slot configuration was identified, the angle of attack can then be varied. The student was then asked to clearly reason out the parametric investigation procedure since there are no established guidelines for slot selection in the literature. The thought process of the student is outlined below.

Since the flow separation point was around 43% chord length, the slot opening on the suction side was positioned just before this point. The idea was to use the exiting high pressure flow to reattach the separated boundary layer. A constant slot width (C) of 1 mm was assumed and parameters A and D were varied. First, an arbitrary value of 50^0 was set for parameter A, and parameter D was then varied to identify the location that gave the best lift coefficient value. The slot angle (A) was then reduced incrementally by 5^0 and the best value was noted. It was observed that if the slot were positioned before 43% chord length, the lift performance was affected negatively. The velocity vectors for each run were observed carefully to predict the necessary location trends for A and D. For greater geometric accuracy, parameter D was varied by 1% chord length. In addition, fillets were added to the inlet and exit of the slot to help guide the fluid and decrease localized swirl inside the slot. The lift coefficient was maximum (1.668) at 14^0 angle of attack when parameters A and D were 20^0 and 58% chord length, respectively.

Subsequently, parameters B and C were then varied. Utilizing basic fluid mechanics concepts, the addition of a draft angle (B) and reduction in slot area on suction side (C) will result in an increase in jet exit velocity which will further aid in energizing the flow. It was found that a draft angle of 5^0 and a slot exit area of 0.5 mm on suction side further increased the lift *coefficient to 1.810 for a 14^0 angle of attack. This a 27% increase in lift coefficient compared to the baseline case. The results for selected configurations can be found in Table 2; the optimal configuration of 20-5-0.5-58 (A-B-C-D) is highlighted. Figure 14 illustrates the velocity vector plot for a few different configurations. The dependence of wake size and flow separation point along airfoil on slot geometry can be clearly seen. Figure 14A is for a uniform slot width of 1mm and flow reversal can be seen upstream of the slot resulting in a very large wake zone. The flow ejection angle is too steep thus creating a wall of high pressure stream which hinders the oncoming suction side flow. Reducing the slot angle and adding fillets greatly helped the flow field. The velocity and pressure contours and vector plots for the finalized configuration can be found in figures 15-17. There was no separation of flow noticed for the final slot configuration. Logical reasoning and simple fluid mechanics concepts were used in designing a slot for enhanced lift performance.*

The next step involved testing the above configuration of 20-5-0.5-58 at various angles of attack. An interesting behavior was noted at the lower end of the angle of attack spectrum; the lift performance was significantly reduced. For example, the lift coefficient was 0.279 at an angle of attack of 0^0 while the baseline case at the same condition had a lift coefficient of 0.415, a 33% reduction. All the slotted configuration variations were revisited and analyzed at an angle of attack of 0^0 as shown in Table 2. A reduction in lift was noticed for all of them. The student was able to realize that bleeding of the air from high to low pressure side will result in reduced lift due to lower vertical pressure difference. There is no boundary layer separation for very low angles of attack, therefore, the slot will only impact performance negatively. The configuration 20-5-0.5-58 was still chosen as the best configuration even though it did not have best lift value at 0^0 angle of attack. The student was able to realize that always testing of the airfoil at both extremes of the angle of attack spectrum and the ability to explain any unexpected behavior is very important. The slotted airfoil was then tested in 3-D and the results were almost identical. Figure 18 is a 3-D view of the selected slotted airfoil configuration.

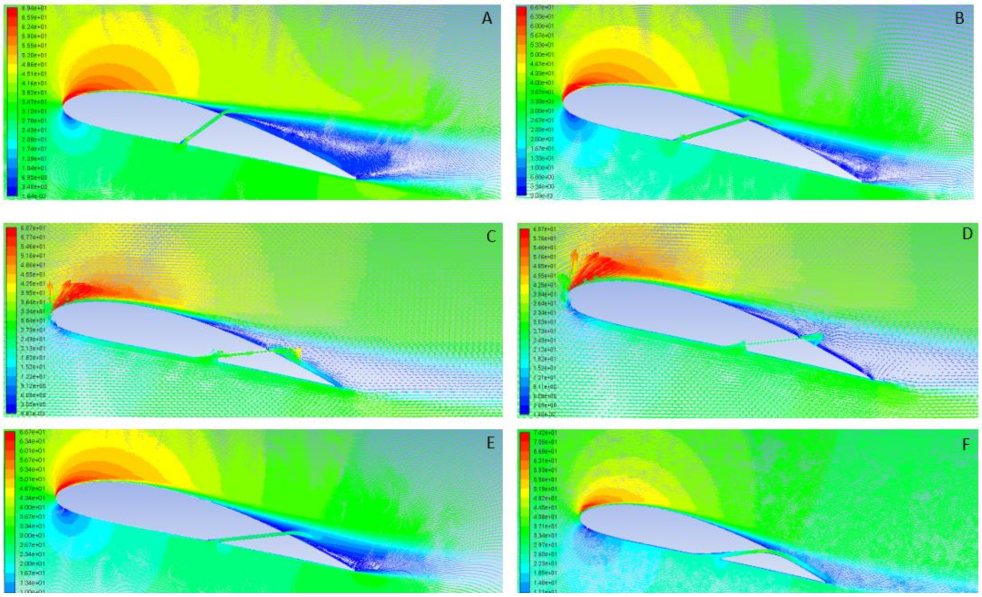

Figure 14: Velocity contours for A) 50-0-1-43, B) 30-0-1-43, C) 20-0-1.25-25, D) 20-0-0.75-58, E) 20-0-158, and F) 20-5-0.5-58 at 14^{0} angle of attack

Table 2: Lift data at 0^{0} and 14^{0} angles of attack for various configurations

Configuration	Angle of Attack	
	0	14
	Lift Coefficient	
50-0-1-43	0.271	1.129
40-0-1-43	0.269	1.273
30-0-1-43	0.275	1.402
30-0-1-46	0.262	1.241
30-0-1-50	0.271	1.443
30-0-1-55	0.254	1.309
20-0-1-55	0.181	1.663
20-0-1-60	0.197	1.574
20-0-1-58	0.253	1.668
20-0-1-57	0.255	1.666
20-0-1-59	0.204	1.588
15-0-1-58	0.178	1.620
15-0-1-60	0.192	1.668
20-0-0.75-58	0.306	1.329
20-0-1.25-58	0.308	1.404
20-5-0.7-58	0.255	1.709
20-5-0.5-58	**0.279**	**1.810**
20-5.5-0.7-58	0.213	1.731
20-5.5-0.5-58	0.217	1.727

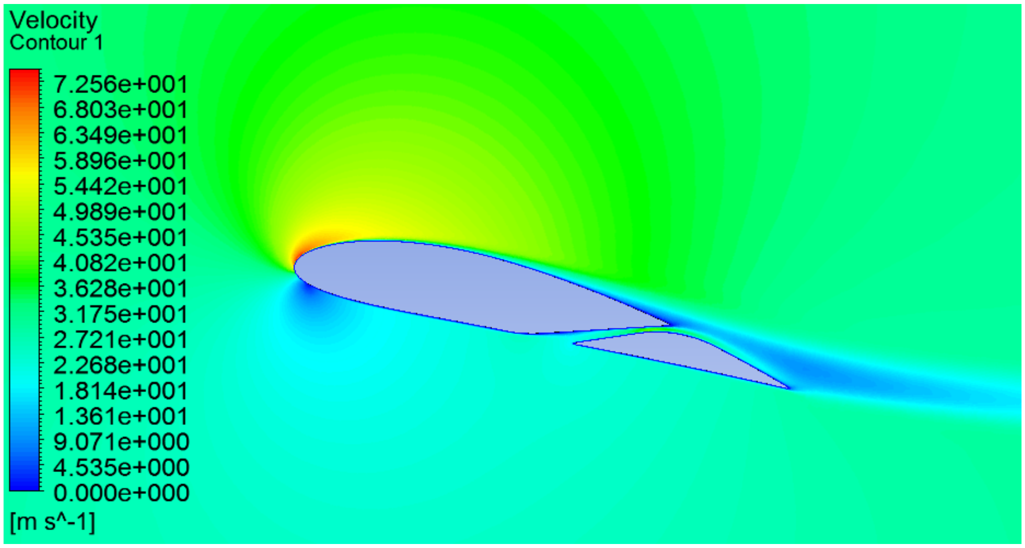

Figure 15: Velocity contour for NACA 4414 slot 20-5-0.5-58 at 14^0 angle of attack

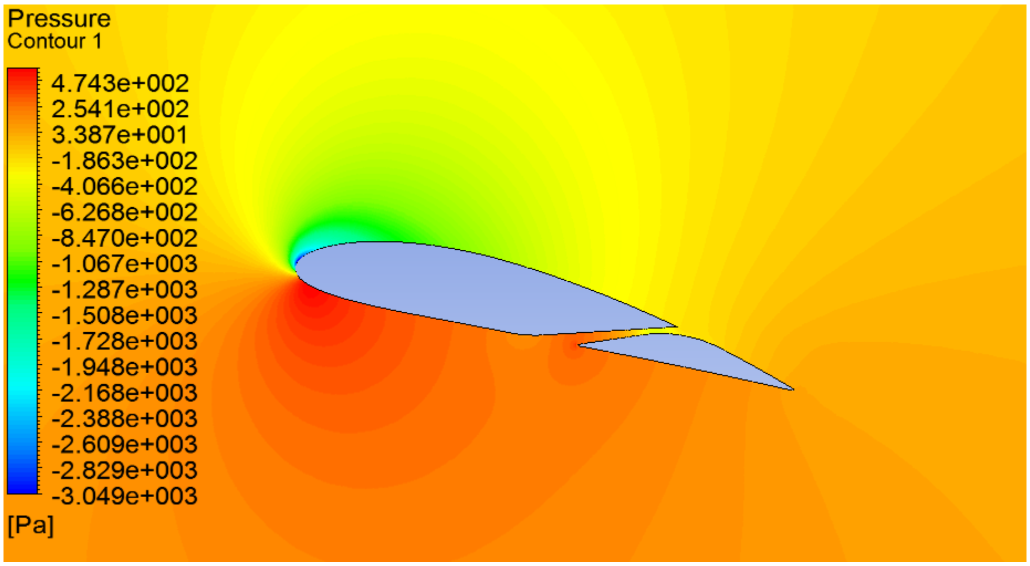

Figure 16: Velocity contour for NACA 4414 slot 20-5-0.5-58 at 140 angle of attack

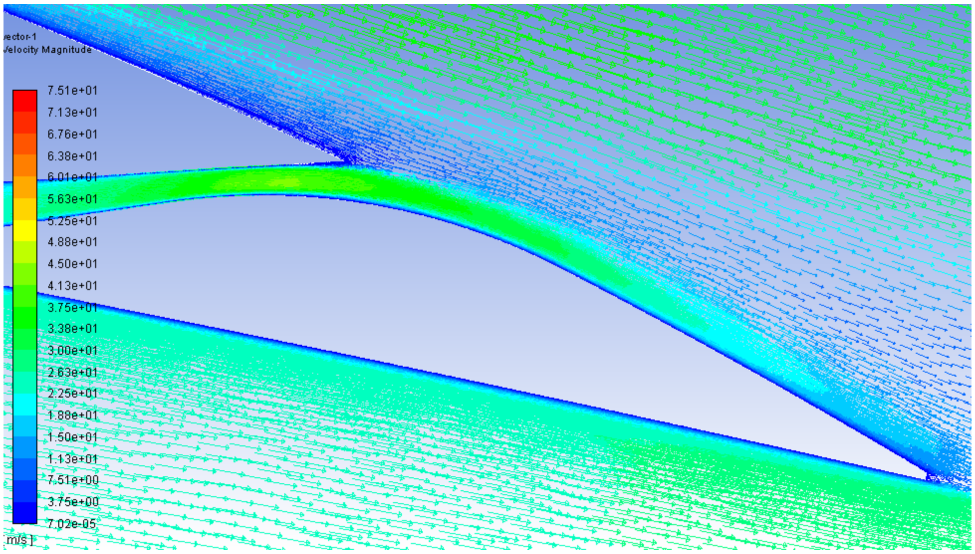

Figure 17: Zoomed in view of velocity contours of 20-5-0.5-58 at 14^0

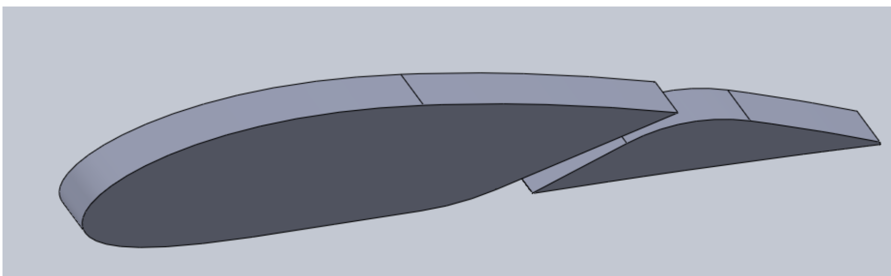

Figure 18: 3-D view of slot 20-5-0.5-58

Figure 19 provides the lift coefficient at various angles of attack. It can be clearly seen that the stall angle has been delayed by 2^0 and there is a significant increase in lift performance at higher contact angles. The airfoil is more stable in this region. At an angle of attack of 6^0, the slotted airfoil matches its counterpart and thereafter surpasses it. The slot becomes effective only at angles of attack greater than 6^0. Below this, it is clear that a simple control system to open and close the slot should be implemented. This concludes the results stage.

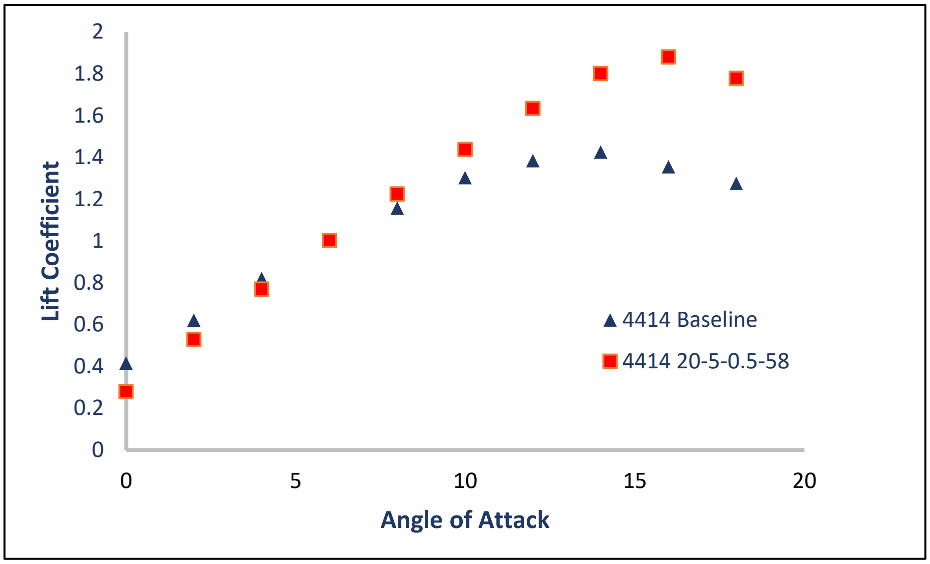

Figure 19: Comparison of lift data for NACA 4414 baseline and slot 20-5-0.5-58

This independent study exposed the student to the five different stages of problem solving while challenging the student's critical thinking ability. The student was allowed two months for the entire project (including the steep CFD learning curve) and was able to complete it well in advance. At the conclusion of the project, the student was appreciative of the fact that the project was able to: 1) tie in the concepts learned during lecture and apply it to solve a practical problem, 2) force the student to think out of the box, 3) always question CFD results and be able to analyze them correctly, 4) explain any unexpected behavior, and 5) approach a problem in a more holistic manner. This project has also sparked the research interest of the student who is now determined to pursue graduate studies; this in itself is a huge success. The CFD results are being used to manufacture a slotted airfoil to be tested against the baseline in a wind tunnel. Furthermore, the student will also be giving a presentation to the upcoming Fluid Mechanics class to encourage new students in participating in such studies.

Certain parts of this independent study can also be incorporated into the traditional Fluid Mechanics lecture to stimulate discussions. For example, the slotted airfoil geometry along with the lift curve could be presented to the class, and the students can be asked to reason out the design choice and explain why lift is poor at low angles of attack. Due to the steep learning curve associated with the software, such a study cannot be conducted as is during a regular lecture semester.

Conclusion

This study focuses on numerically analyzing the flow characteristics of a NACA 4414 baseline and slotted airfoil. The slot was a fixed one with no mechanical complexity. This was conducted as an independent study in an effort to expose the student to the five stages of a comprehensive problem solving cycle to sharpen the critical thinking ability. Following a geometric parametric investigation, a slot configuration was identified. During the process, the student applied many fundamental concepts learned during the Fluid Mechanics lecture to mitigate boundary layer separation and improve airfoil performance. The slotted airfoil increased maximum lift coefficient by 27%, eliminated the separation point, and delayed stall angle by 2^0. However, it performed poorly for angles of attack less than 6^0 due to the vertical pressure gradient being compromised. The student greatly benefitted from this study and has already taken it to the next step by utilizing the CFD results to manufacture a slotted airfoil for experimental analysis.

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