CFD Final Project Report

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Section 1: Problem Description

High Lift devices:

Part 1 of the project explored how a slat can be used in an airfoil to generate more lift and help an aircraft take off and land. In addition to slats, flaps are commonly used for the same reason. The first part of part 2 of the project will examine how flaps further increase the lift generated by an airfoil. Using Hyper Mesh software, the coefficient of lift and coefficient of drag will be calculated for an airfoil geometry with a slat and flap. The simulations will be run at 12 degrees angle of attack (aoa) and 45 mps and 90 mps. The values will then be compared to the values of a plain airfoil and an airfoil with a slat that was found in part 1. The study aims to evaluate the effects of slat and flap implementation on aerodynamic efficiency under steady, turbulent (45 mps (Re = 7.83e5) and 90 m/s (Re = 1.57e6)), and incompressible flow conditions in a quasi 2D simulation with a chord length of 0.254m (10in). The chord length of the slat and flap is 0.3c = 0.072 m. The slat and flap airfoils are also NACA 0015, and the material input is air at sea level at 15 deg Celsius with a density of 1.225 kg/m^3 and a viscosity of 1.781e-5 Pa·s.

Transient zoom analysis of Slat behavior

Building on the findings from the midterm report, the second part of this study focuses on a transient zoom analysis to investigate the dynamic flow behavior around the slat of the NACA 0015 airfoil. The initial steady-state analysis in Part 1 revealed significant flow variations in the region between the slat and the airfoil. Specifically, at 12° AoA flow was faster and better developed compared to 0° AoA. The transient analysis compares how flow changes over time at 90 mps for both 0° and 12° AoA. The study helps highlight the importance of the slat design for take off and landing phases of an aircraft where flow is volatile and stability is crucial. Stability was evaluated through HyperGraph. Similar properties of air were used as the flap analysis.

Section 2: Problem Setup

Study of flaps:

The boundary conditions include a no-slip condition applied around the airfoil, slat, and flap geometry with a wall velocity of 0, where a wall-resolved approach is used for near-wall treatment with a roughness height of 0. A slip condition is applied to the ±z surfaces for the 2D simulation. A far-field boundary condition is applied to the circular rim with freestream velocities of 45 m/s and 90 m/s. The physics of this study involves a steady-state simulation with incompressible turbulent flow assumptions. The turbulence model used is Spalart-allmaras.

Study of Slats, Zoomed in for Transient Analysis:

The boundary conditions include a no-slip condition applied around the airfoil and slat geometry with a wall velocity of 0, where a wall-resolved approach is used for near-wall treatment with a roughness height of 0. A slip condition is applied to the ±z surfaces for the 2D simulation. An inlet boundary condition is applied to the circular rim with freestream velocity of 90 m/s at 0 degrees and 12 degrees AOA relative to the x direction . The physics of this study involves a transient simulation with incompressible turbulent flow assumptions. Its time step size was 0.005675 s and the total time was 1.816. Longer timescales with smaller timesteps were attempted but far too computationally expensive to be analyzed with the hardware on hand. The Turbulence model was Laminar, and the solver wrote results every 4 timesteps, for 80 frames in total to analyze.

Section 3: Numerical Scheme and Meshing

Numerical Scheme:

All default settings from Acusolve were used for all meshes and solutions

Slat and Flap Mesh:

For 0015 airfoil with slat and flap 12 degree cases the following mesh setup was used:

- Edge mesh with average element size set to c/128 = 1.984375e-3 m on the airfoil, and a similar edge mesh on the slat with element size set to c/128 = 5.95e-4 m
- Edge layer with parent surface as the +z face. First layer thickness is set to c/300,000 = 8.4667e-7, with 20 layers. Constant growth method at a rate of 1.2 and termination policy set to truncate.
- For slat/ flap Edge layer with parent surface as the +z face. First layer thickness set to c/300,000 = 0.000000254, with 8 layers. Constant growth method at a rate of 1.2 and termination policy set to truncate.
- A box refinement zone was made with x,y,z measurements of 0.65 m, 0.6c = 0.1524 m, and 0.3c = 0.0762 m. The average element size was set to c/128 = 1.984e-3 m. For the 12 deg cases, the box was rotated 12 deg ccw around the z axis and translated up 0.005m. The box refinement zone covered both the airfoil, the slat, and the flap
- Two circular refinement zones were used at the leading edge and trailing edge. The leading edge refinement zone has a radius of c/32 = 7.9375e-3 m and an element size of c/1024 = 2.48e-4 m. The trailing edge refinement zone has a radius of c/128= 1.984e-3 m and the same element size as the leading edge zone.

- A surface mesh was ran on +z face with maximum mesh element size set to c = 0.254 m
- Extrusion performed with +z face as the source. Element size along extrusion was set to c/10 = 0.0254 m, and element type was set to quads
- Volume mesh was ran with maximum element size as c = 0.254 m

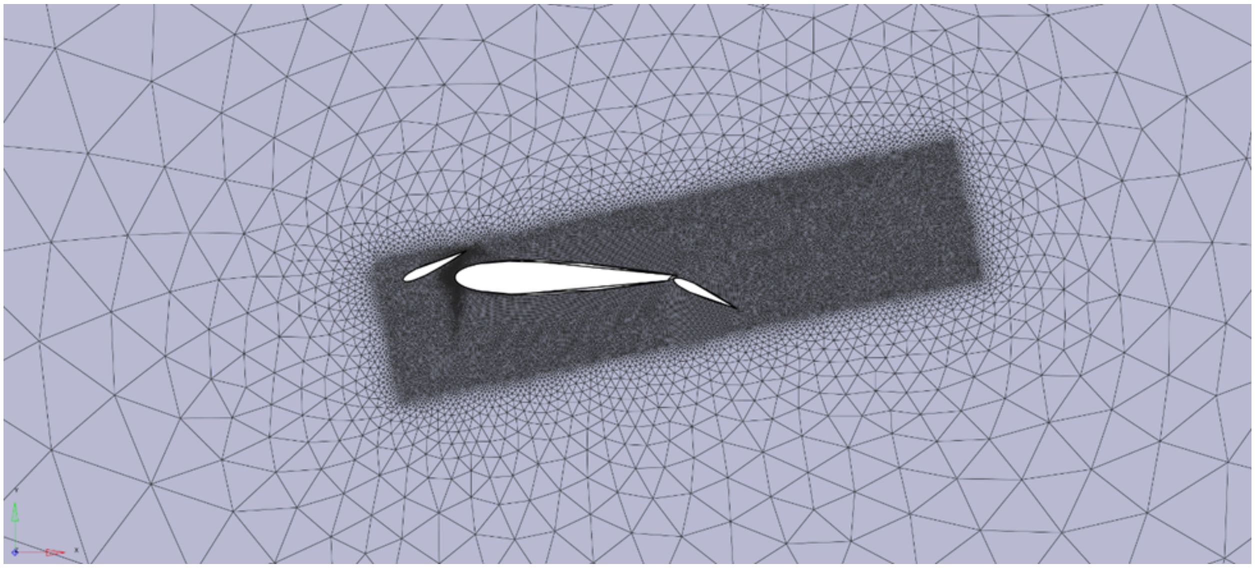


Figure 1: Flap Geometry Mesh

Mesh Quality Report

Mesh Check Type
- Count
- Surface Mesh Checks
- Volume Mesh Checks

	Type	Count
1	Nodes	185877
2	Surface mesh elements	232388
3	Volume mesh elements	230482
4	Triangles	215026
5	Quadrilaterals	17362
6	Tetrahedral elements	0
7	Hexahedral elements	15456
8	Pyramid elements	0
9	Prism elements	215026

Figure 2: Flap Geometry Mesh Quality Report

Zoomed in Slat-Airfoil Mesh for Transient analysis (Mesh 2):

As stated above, the purpose of this zoomed analysis was to provide both transient results as well as focus on how flow develops in the region between the slat and the airfoil. During the first report, this region was Identified as a major point of interest for both angles of attack, as flow was considerably faster and better developed in this region at 12 degrees aoa.

For 0015 airfoil with slat at 12 degree aoa, the following mesh setup was used:

- The geometry of the entire imported CAD is significantly smaller to be set up for transient analysis. Its new x and y dimensions are 0.76 and 1.14 m, respectively. This was done to save computational resources.
- Edge mesh with average element size set to c/128 = 1.984375e-3 m on the airfoil, and a similar edge mesh on the slat with element size set to c/128 = 5.95e-4 m
- Edge layer with parent surface as the +z face. First layer thickness set to c/300,000 = 8.4667e-7, with 43 layers. Constant growth method at a rate of 1.2 and termination policy set to truncate. More layers were chose to accurately define flow conditions along the slat
- 5 refinement zones were established.
    - A box around the main airfoil with elm size c/128 = 0.002, a width through the whole object, and a x and y size of 0.30m and 0.075 m respectively. This ensures enough height to capture flow conditions at both angles of attack and ensuring the region between the major features is well refined
    - A box around the slat with elm size = 0.001, at an angle of 25 degrees with the x axis and x and y dims While not following the c/128 ratio, this refinement still allowed for a high resolution solve while not sacrificing too much computational resources during transient analyses
    - Leading edge cylinders refinement zones were used on both features. The slat had an elm size of 0.000025 and a radius of 0.00482 m, and the airfoil had an elm size 0.00025, and a radius of 0.008m. Both radii were set larger to help capture the behavior of the fluid between the surfaces in this region, as it was the goal of this analysis.
    - The airfoil trailing edge had a cylinder refinement zone as well, this had the same elm size as the leading edge, and had a radius of 0.004m. This helped ensure flow behavior on the trailing edge had better resolution to help refine results from the midterm.
- A surface mesh was ran on +z face with maximum mesh element size set to c = 0.254 m
- Extrusion performed with +z face as the source. Element size along extrusion was set to c/10 = 0.0254 m, and element type was set to quads
- Volume mesh was ran with maximum element size as c = 0.254 m
- In terms of Mesh changes, there was some iteration with the mesh for the zoom analysis to achieve better resolution in the region of interest (the region between the airfoil and the

slat) thus two meshes were made and run. The 1st mesh lacked refinement in the focus region and yielded a poor resolution of flow condition. The 2nd mesh added new larger refinement zones about the slat to ensure a higher resolution in that region. Sample frames of the velocity plots for each mesh are provided below each respective mesh.

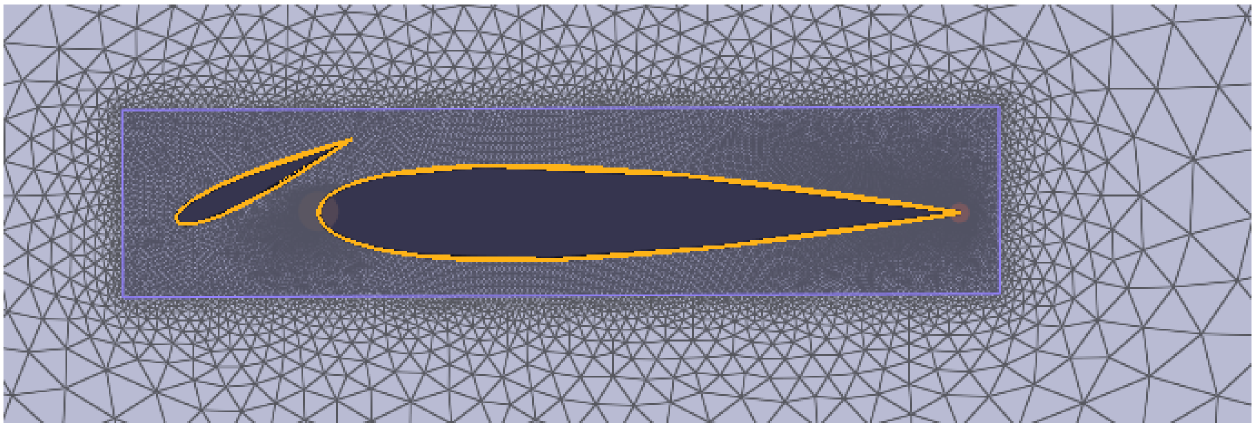


Figure 3: Mesh Iteration 1: Yielded poor resolution on velocity flow development over time in the region of interest

Mesh Quality Report

Mesh Check Type
- Count
- Surface Mesh Checks
- Volume Mesh Checks

	Type	Count
1	Nodes	54006
2	Surface mesh elements	72012
3	Volume mesh elements	70804
4	Triangles	70804
5	Quadrilaterals	1208
6	Tetrahedral elements	0
7	Hexahedral elements	0
8	Pyramid elements	0
9	Prism elements	70804

Figure 4: Mesh 1 Quality Report

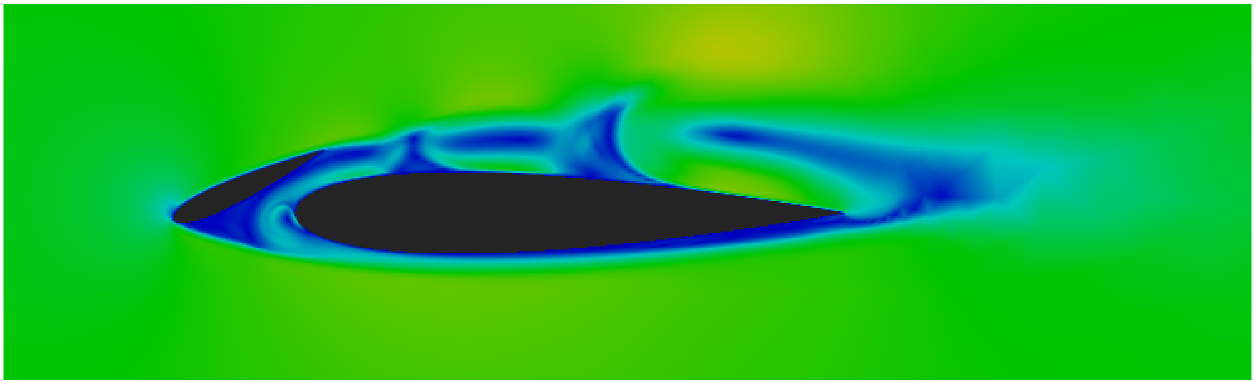


Figure 5: Sample Velocity plot for 1st mesh without further refinement zones. (frame 70)

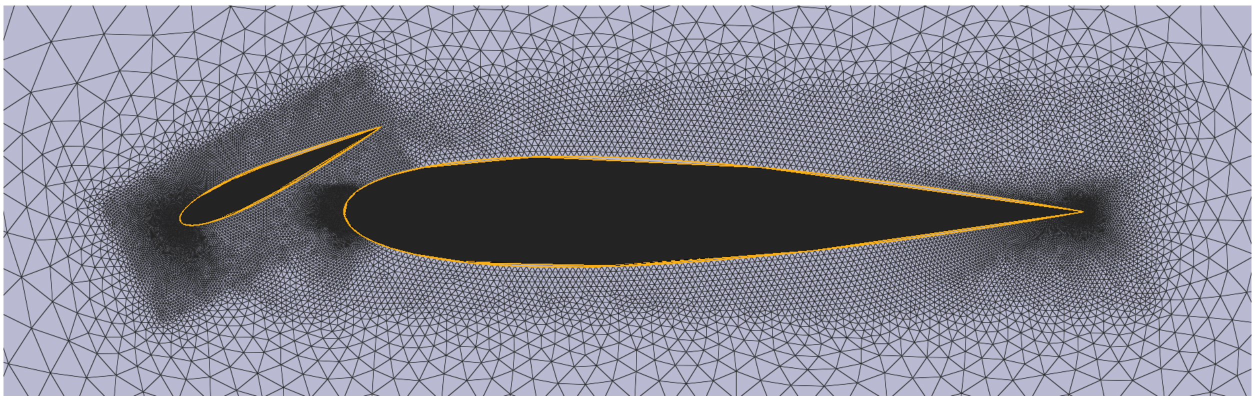


Figure. 6: Mesh Iteration 2

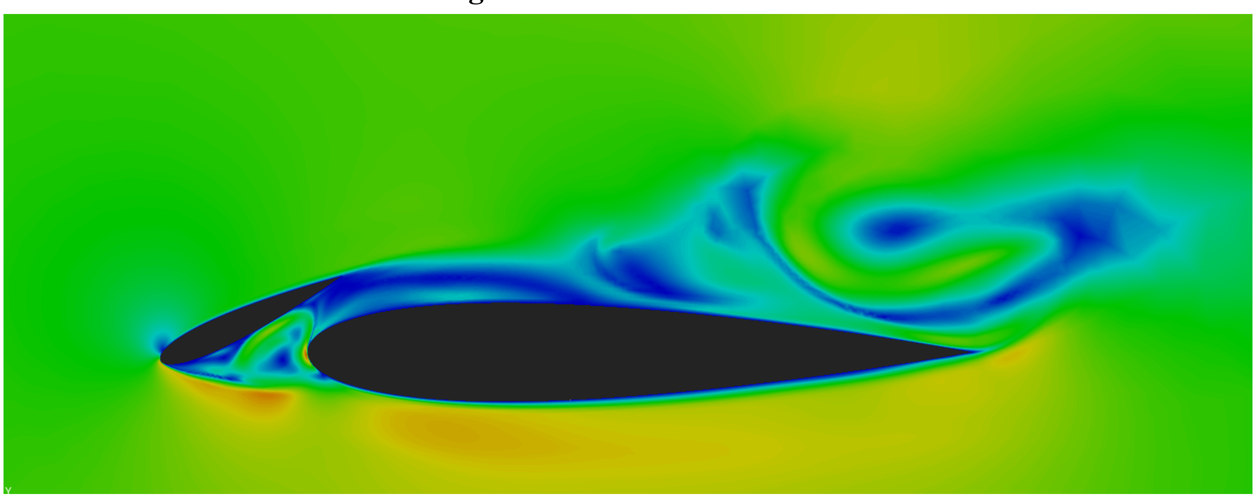
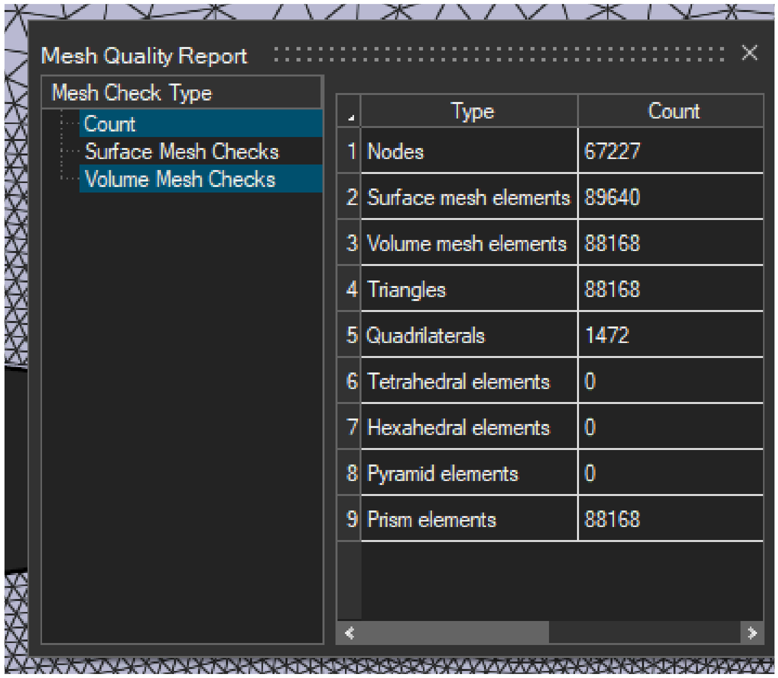


Figure 7: Sample Velocity Plot for 2nd mesh (frame 70)



	Type	Count
1	Nodes	67227
2	Surface mesh elements	89640
3	Volume mesh elements	88168
4	Triangles	88168
5	Quadrilaterals	1472
6	Tetrahedral elements	0
7	Hexahedral elements	0
8	Pyramid elements	0
9	Prism elements	88168

Figure 8: 2nd Mesh Quality Report

This mesh has fewer elements compared to the steady state analyses because the CAD was zoomed in by a massive amount to make transient solutions reasonable with the hardware on hand. Overall there is still a very high resolution as the additional refinement zones fix that issue

Iteration 2 focuses on flow development around slat and in the region of interest, yielded better resolution on changes in velocity over time! Also allows for a "1 mesh fits all" for the 2 angles of attack tested, as the region of interest is refined at an angle which is relevant for both cases.

Section 4: Other details and issues

Additional details:

-For the 12 deg cases, solver controls were modified:

- The steady state update factor was changed to 0.8
- The steady maximum steps was increased to 200

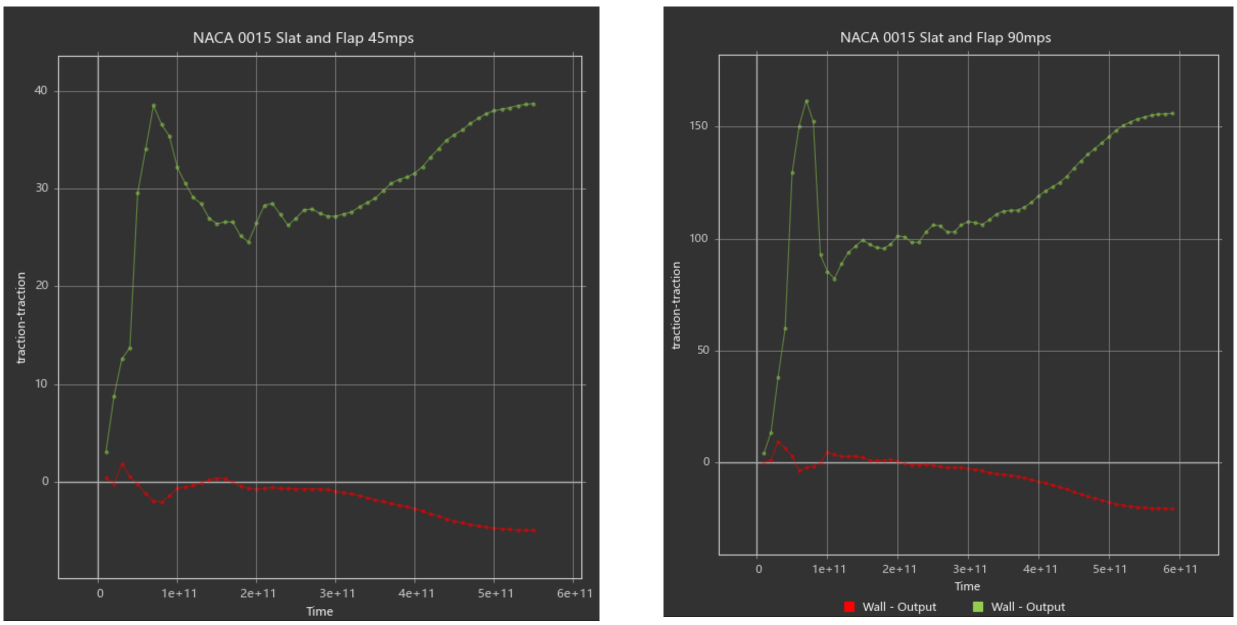
-All other settings are default

-For the flap geometry, due to the proximity of the flap and airfoil, adding additional mesh refinement zones was difficult, and the computers used to run the simulation did not have sufficient computing power to calculate and run these complex solutions. Adding boundary layers to both the slat and flap also lead to meshing issues. Due to this problem, small surface y plus values couldnt be used for the slat and flap geometry however the airfoil geometry has optimal surface y plus values The mesh used has around 230,000 volume mesh elements, which is sufficient for our study

-For transient cases, a longer time scale than 1.8 seconds was desired, but created too much data and had acusolve failing and yielding errors.

Section 5: Results

Effect on lift and drag of flaps:



A.) **B.)**

Figure 9: Lift (green) and Drag (red) forces for slat and flap geometry at 45 mps(A) and 90 mps(B)

From these plots, the drag and lift forces were found. The values were taken after a long time (i.e. stable slope of the plot), to capture the most realistic forces the wings would experience at each condition. To find the lift, drag, and coefficients of each, the following methodology was used:

Lift and drag forces were pulled from traction force plots when the forces approached steady state. Through these and keeping standard air conditions in mind ($\rho = 1.23 kg/m^3$), then dynamic pressure (q) is calculated as:

$$q = \frac{1}{2}\rho V^2$$

Where V is the freestream velocity (45m/s or 90m/s). Through dynamic pressure, the Lift coefficient (C_L) and Drag coefficient (C_D) given by

$$C_L = \frac{L}{qS}$$

$$C_D = \frac{D}{qS}$$

Where S is the area of the 2D airfoil given as the product of the chord * span length. The table with the C_L and C_D values is given in the table below

Case	Lift (N)	Drag (N)	C_D	C_L
Slat and Flap 45 mps	38.733	4.9878	0.143	1.11
Slat 45 mps	19.959	3.2298	0.11	0.681
Basic 45 mps	18.462	3.15	0.131	0.769
Slat and Flap 90 mps	155.93	20.456	0.146	1.11
Slat 90 mps	81.642	13.467	0.115	0.697
Basic 90 mps	75.709	13.43	0.14	0.788

Table 1: Lift and drag comparison of geometries at 12 deg aoa

Section 6: Conclusion

The effect of high lift devices:

The data demonstrate the significant aerodynamic benefits of incorporating high-lift devices—specifically slats and flaps—into an airfoil design for takeoff and landing phases. At a freestream velocity of 45 m/s, the configuration with both slats and flaps produced a lift force of 38.733 N and a corresponding lift coefficient(C_L) of 1.11. In contrast, the slat-only and basic configurations yielded substantially lower lift values of 19.959 N (C_L=0.681) and 18.462 N (C_L=0.769), respectively. This represents nearly a twofold increase in lift with the use of flaps.

A similar trend is observed at a higher velocity of 90 m/s. The slat and flap configuration again achieved the highest lift at 155.93 N with a C_L of 1.11, while the slat-only and basic configurations produced 81.642 N (C_L=0.697) and 75.709 N (C_L=0.788), respectively.

Although the addition of flaps and slats does result in a modest increase in drag, as indicated by the slightly elevated drag coefficients, the corresponding enhancement in lift, particularly at low speeds, demonstrates their effectiveness. These findings confirm that high-lift devices are essential for improving lift performance during critical flight operations, such as takeoff and landing, where low-speed lift augmentation is vital for safety and efficiency.

It is important to note that these values are only accurate for the mesh and simulation that the group ran. More powerful computing power is needed to run more precise and accurate simulations, and these values should only be considered under the utilized physics model.The appendix includes velocity, and surface y plus figures for the slat and flap geometry.

To better understand and potential validate the flow conditions causing these unique drag and lift effects, applying transient analysis and refining the regions of interest was very useful.

An important finding from the midterm report was of the slat's efficacy at high angles of attack, and low efficacy in level flight. This was assumed to be due to a lack of flow separation near the slat at 12 degrees. At 0 degrees AoA, the areas of low velocity and high pressure near the front of the wing caused a loss of lift and high drag. It was theorized that the slat was inducing vortices above the airfoil that caused a down force further pushing the lift into a negative force.

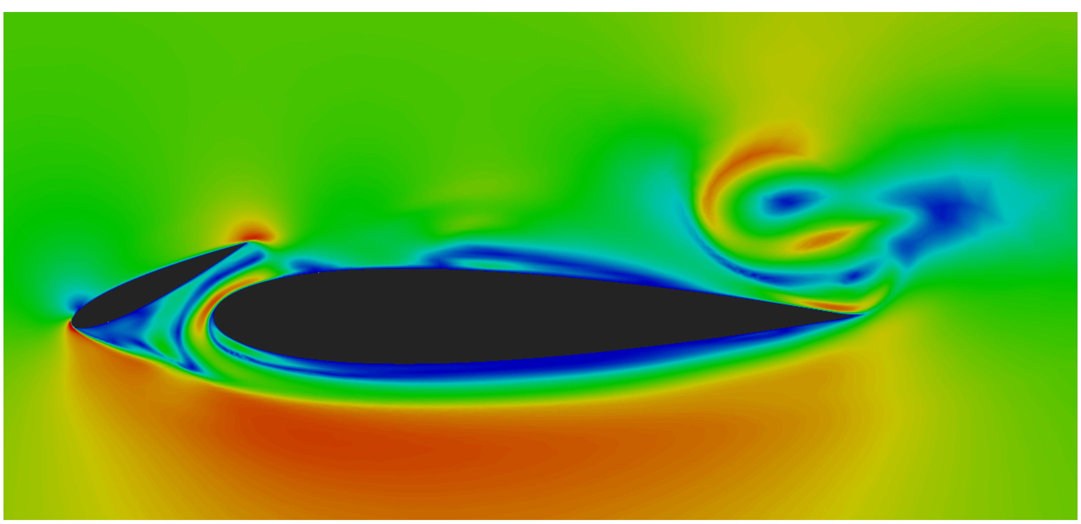


Figure 10: NACA0015 w Slat at 0 AoA 90m/s (Frame 71)

This assumption was validated during transient analysis (see figure 10), as the formation of vortices above the airfoil were observed several times over the course of the 1.8 second simulation at 0 AoA. An example of this is in frame 71 of the 0 AoA transient analysis with the slat, where there is a large vortex above the airfoil. Throughout the simulation, vortices appear there, and in the region between the slat and the airfoil.

While this does confirm earlier findings and conclusions drawn from the steady-state analysis at 0 AoA, the true test is whether the region between the slat and airfoil has a higher velocity and more stable/developed flow at 12 degrees AoA. In earlier analyses, there was significantly less flow separation under the slat at this AoA, and thus had less drag and more lift than at 0 AoA by a huge margin.

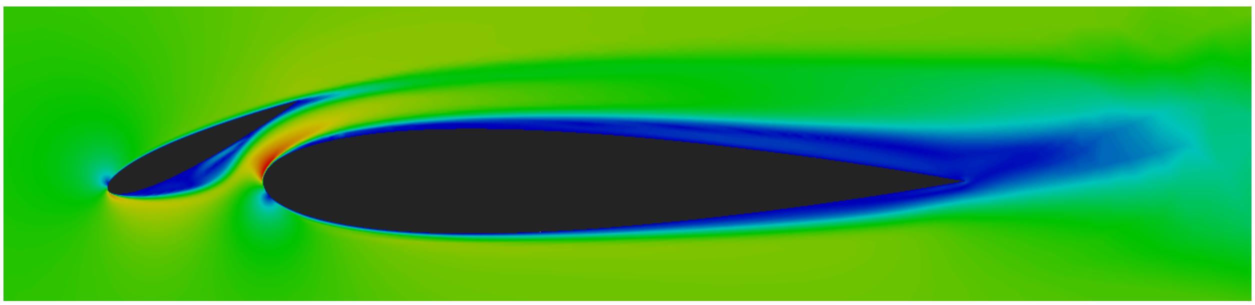


Figure 11: Transient NACA0015 w Slat at 12 AoA 90m/s (Frame 60)

In transient analysis this conclusion remains true(see figures 10 and 11), as flow remains well developed (generally) and fast under the slat at 12 degrees AoA. As stated previously, this is because when the system is at 12 degrees AoA, the effective AoA of the slat is out of the Stall range and begins to generate lift as intended.

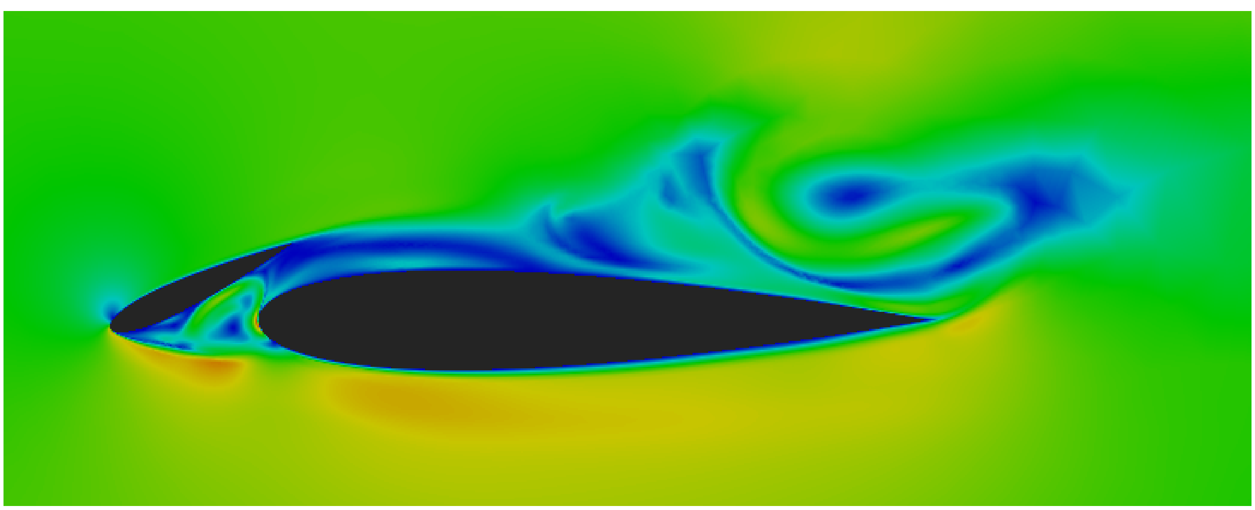


Figure 12: Transient NACA0015 w Slat at 0 AoA 90m/s (Frame 71)

Like as Steady state predicted, drag is still higher with the slat than without at 12 degrees AoA. This is likely due to moments like this, where a large (but less severe) vortex is present (see figure 12). However because flow isn't separated for much of the time, the forces of these high pressure regions and vortices have less influence on the forces experienced by the wing.

The existence of this momentary separation begs the question: how do slats affect stability? And is the rapid changing of these forces enough to discourage their use in takeoff and landing? This is where hypergraph comes in.

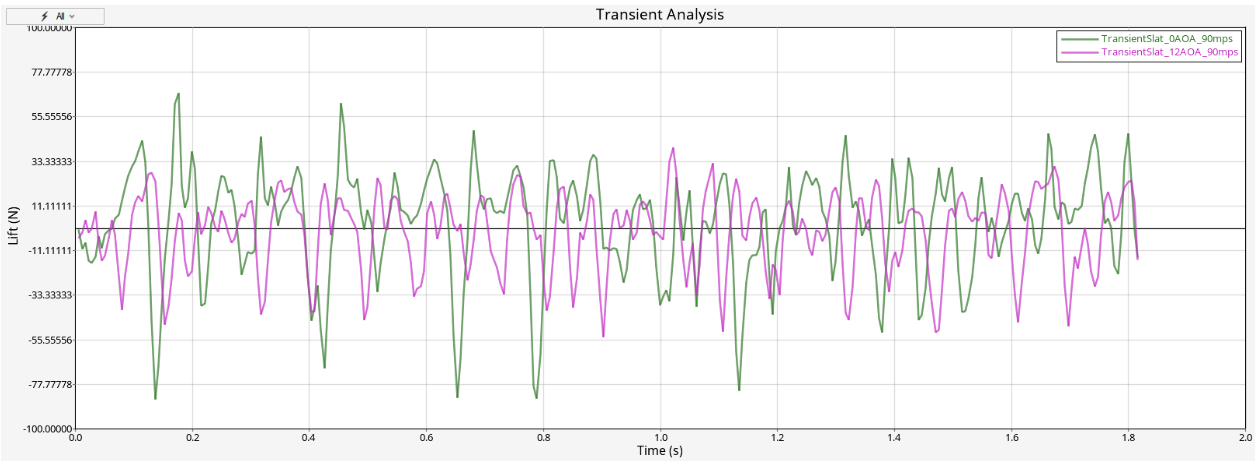


Figure 13: Transient Y-Traction Force (Lift) at 90 m/s for NACA 0015 Airfoil with Slat at 0° and 12° AoA

The transient y-traction force (lift) data at 90 m/s provides deeper insight into the stability implications of the slat design. The lift force plots for 0° and 12° AoA show a huge difference in amplitude. At 0° AoA the lift values show large oscillations with amplitudes ranging from approximately -85.7N to +67.3N. These fluctuations correspond to the vortex shedding observed in the transient analysis where periodic vortices above the airfoil create alternating high and low-pressure regions, leading to unstable lift forces. At 12° AoA, the lift oscillations are much smaller, with amplitudes ranging from -54.5N to +40.1N indicating a more stable flow due to reduced flow separation and vortex formation.

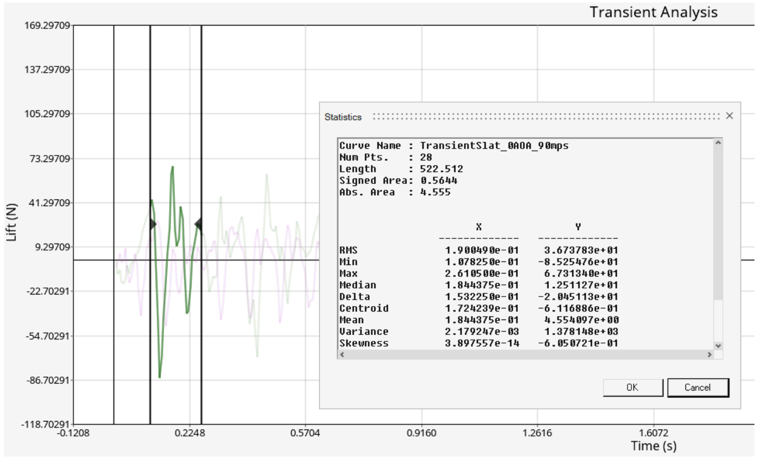


Figure 14: Statistical Analysis for NACA 0015 Airfoil with Slat at 0° AoA and 90 m/s

At 0° AoA, the large fluctuations in lift suggest stability challenges, as the airfoil experiences significant pitching moments or vibrations during level flight. However, at 12° AoA which is typical for takeoff and landing, the smaller oscillations indicate that slats contribute to a more stable aerodynamic performance as the flow remains attached and vortices are less pronounced. This stability is crucial for ensuring safe and predictable aircraft behavior. The transient analysis confirms that slats are most effective at higher angles of attack where their design mitigates stall and maintains flow attachment as intended.

Appendix:

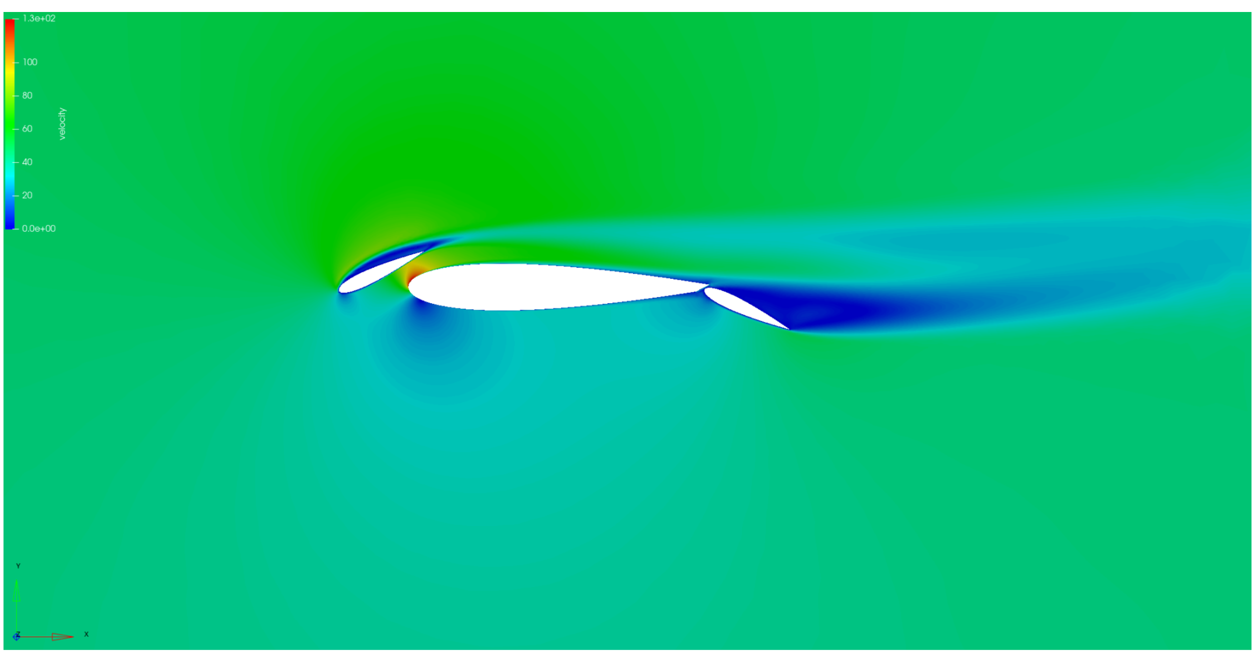


Figure A.1: Slat and flap at 12 deg aoa 45 mps

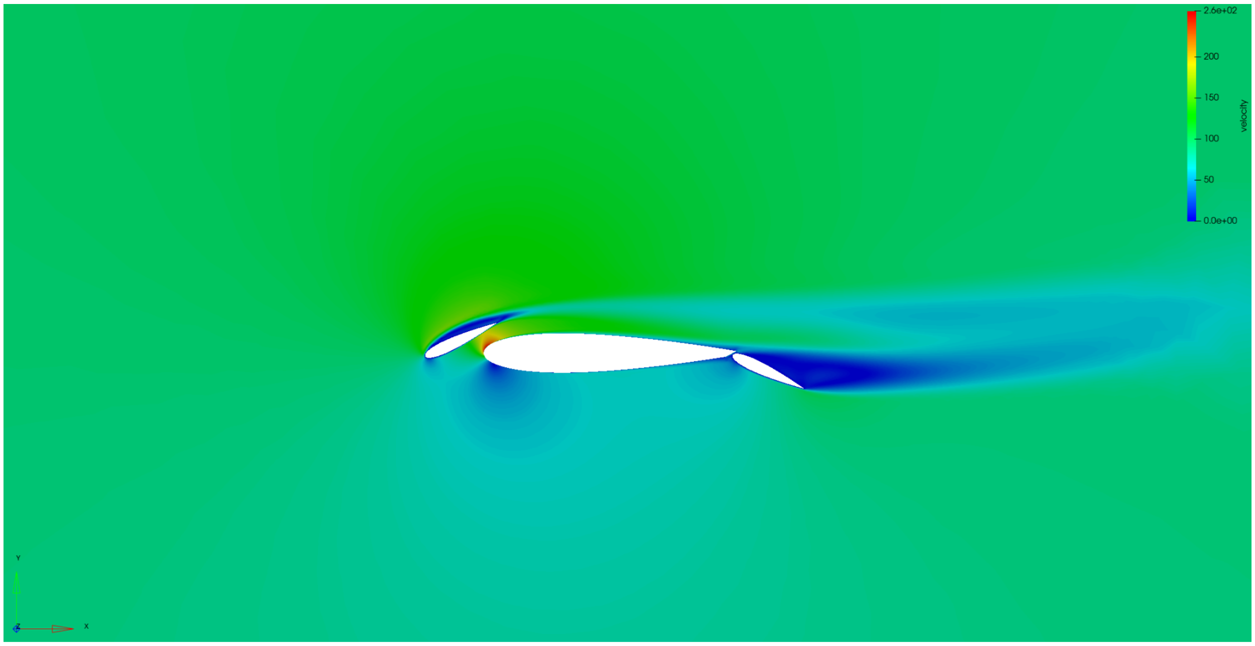


Figure A.2 Slat and flap at 12 deg aoa 90 mps

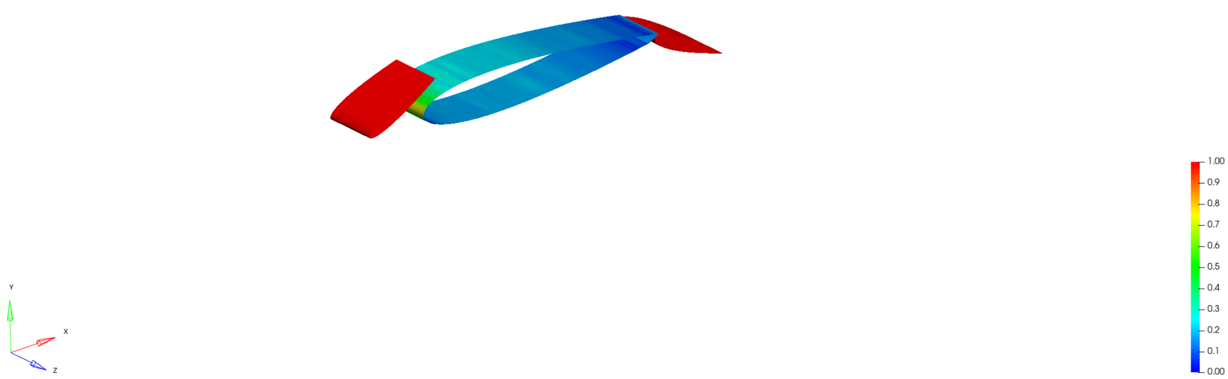


Figure A.3: Surface y plus of slat and flap

Due to mesh issues, a surface y plus did not have the resolution necessary to be accurate for the slat and flap. Because the main airfoil is our point of interest, this shouldn't affect the results greatly.pp