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AERODYNAMIC OPTIMIZATION OF DOUBLE-WEDGE AIRFOILS WITH CURVED RECESSES FOR HIGH SUBSONIC AND SUPERSONIC FLOWS

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Abstract

The aerodynamic performance of airfoils operating at high subsonic and supersonic speeds is often limited by adverse pressure gradients, boundary layer separation and shock wave formation, leading to increase in drag and reduce the efficiency. This study proposes a modified double-wedge airfoil featuring symmetric curved recesses positioned between the mid-chord region to enhance flow characteristics while preserving geometric simplicity. The conventional sharp edges are replaced with 5 mm and 10 mm deep recesses that generate localized low-pressure zones, thereby mitigating shock intensity and promoting improved pressure recovery. Computational Fluid Dynamics (CFD) analyses are conducted at Mach numbers 0.8, 1.5, 2.0, and 2.5 to evaluate aerodynamic behavior with respect to lift and drag across both high subsonic and supersonic regimes. The influence of varying angles of attack is examined to assess drag reduction, shock structure and boundary layer development. The findings indicate delayed flow separation, improved lift-to-drag ratios and reduced wave drag, especially at higher Mach numbers. Comparative assessments between simulation outcomes and preliminary experimental data validate the proposed design approach. Overall, this work presents a practical modification strategy for enhancing aerodynamic efficiency in advanced airfoil configurations.

Keywords: Double-wedge airfoil; Curved recess; Supersonic flow; CFD; Shock control.

1. INTRODUCTION

The aerodynamic performance of an airfoil plays a crucial role in determining the efficiency and stability of high-speed aircraft. Airfoil geometry directly influences lift, drag, and overall aerodynamic behaviour, especially under high subsonic and supersonic flow conditions. Conventional double-wedge airfoils are widely used in supersonic applications due to their structural simplicity and ease of fabrication. However, these configurations often encounter high wave drag, adverse pressure gradients, and premature boundary layer separation, which collectively reduce aerodynamic efficiency (1).

Several studies have been conducted to modify airfoil shapes to achieve smoother pressure distributions and delayed shock formation. Researchers have explored leading-edge shaping, contour modifications, and the inclusion of cavities or surface recesses to mitigate drag and improve lift-to-drag ratios [2]. Despite these efforts, achieving significant performance improvement while maintaining geometric simplicity remains a challenge.

To address this, the present study investigates a modified double-wedge airfoil incorporating symmetric curved recesses near the mid-chord to trailing-edge region. These recesses are designed to alter local pressure distribution, delay boundary layer separation, and reduce shock intensity, ultimately enhancing aerodynamic efficiency. Computational Fluid Dynamics (CFD) simulations are carried out at different Mach numbers to compare the flow characteristics of the modified and conventional airfoils. The objective of this research is to develop a practical design improvement that provides better aerodynamic performance and passive flow control without introducing additional structural complexity.

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1.1. Background of the Study

High-speed aerodynamics involves complex interactions between shock waves and boundary layers. In double-wedge airfoils, sharp discontinuities lead to strong shock formation and high wave drag, limiting their efficiency at transonic and supersonic regimes. Previous studies indicate that even minor geometric alterations can significantly affect shock positioning and flow separation patterns[3].This motivates the development of modified profiles that can smooth pressure gradients and reduce energy losses.

1.2. Objective and Scope

The primary objective of this study is to enhance the aerodynamic performance of double-wedge airfoils by integrating symmetric curved recesses near the mid-chord and trailing-edge regions. CFD simulations are conducted at Mach numbers 0.8, 1.5, 2.0, and 2.5 to analyse flow characteristics under both high subsonic and supersonic conditions. The scope includes evaluation of drag reduction, boundary layer behaviour, and shock wave patterns. The study aims to demonstrate that minor geometric recesses can offer noticeable aerodynamic benefits while retaining a simple structural design, making the concept suitable for future supersonic aircraft and UAV applications**.**

2. Methodology

2.1 Overview

This study employs both Computational Fluid Dynamics (CFD) and experimental testing to evaluate the aerodynamic performance of a modified double-wedge airfoil incorporating symmetric curved recesses near the mid-chord region. The primary objective is to investigate how these recesses influence lift, drag, and overall flow characteristics under high subsonic and supersonic flow regimes.

2.2 Geometric Design

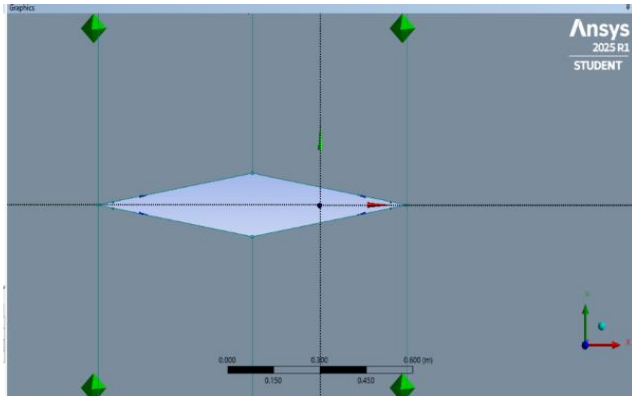

Figure 1: Double wedge airfoil with sharp edge

The baseline double-wedge airfoil was modelled in ANSYS Design Modular, and symmetric curved recesses of depths 10 mm and 5 mm were introduced near the mid-chord region to analyze their aerodynamic influence. These recesses were designed to create localized low-pressure zones, reducing shock strength and delaying boundary-layer separation. The final geometries were imported into ANSYS Fluent for meshing and numerical analysis. The computational domain was defined to minimize

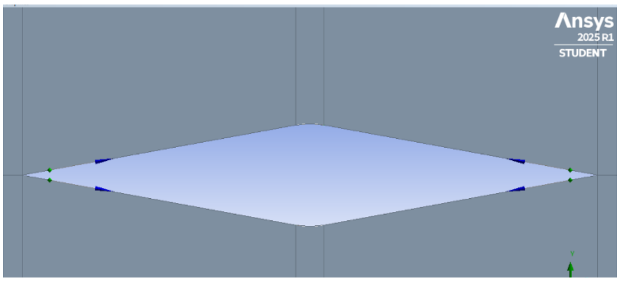

Figure 2: 5 mm Curved Recesses *blockage effects, with boundary conditions applied for high subsonic (Mach 0.8) and supersonic (Mach 1.5–2.5) flow regimes.*

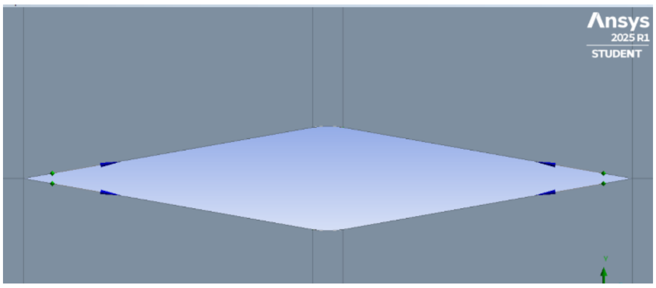

Figure 3: 10 mm Curved Recesses

2.3 Mesh Design

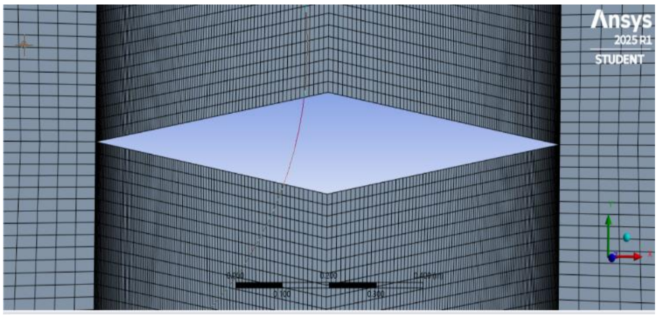

Figure 4: Double wedge airfoil

This image shows the computational mesh of a double-wedge airfoil with a symmetric recess (or cavity) created in ANSYS 2025 R1 Student version. The image illustrates a structured mesh generated around the double-wedge airfoil geometry. The symmetric curved recess at the mid-chord region is clearly visible, with fine mesh refinement along the cavity and surface regions. This ensures accurate capture of shock formation, boundary-layer interactions, and flow separation zones in supersonic flow conditions.

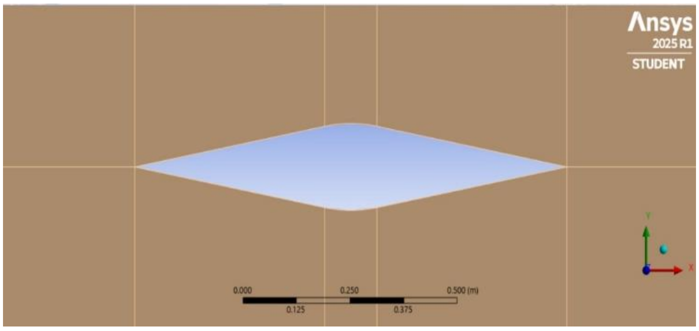

Figure 5: 5 mm Curved Recesses

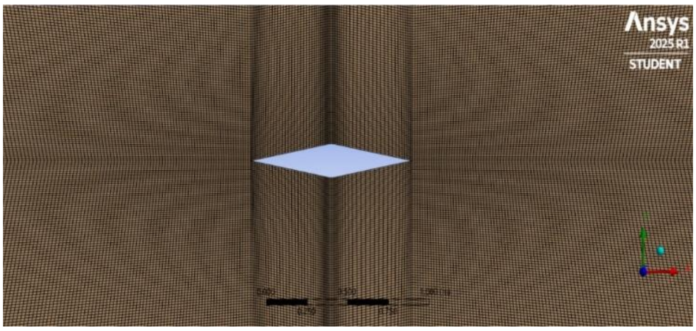

Figure 6: 10 mm Curved Recesses

3. PRESSURE CONTOUR AT MACH 0.8

This image presents pressure contour plots at Mach 1.5 for a modified double-wedge airfoil at three different angles of attack (AOA): 0°, 5°, and 10°, generated using ANSYS 2025 R1 Student version.

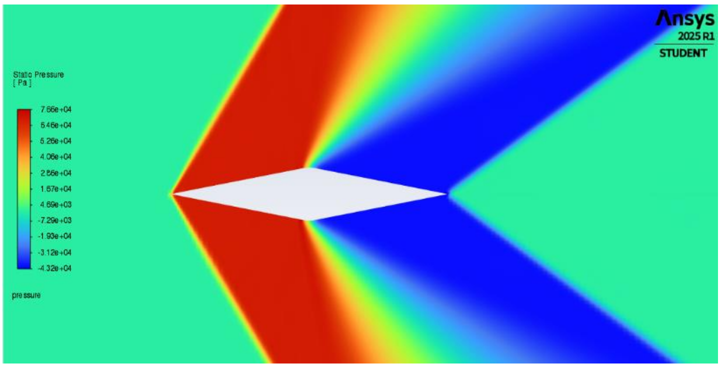

Figure 7: **AOA=0°**

The flow is nearly symmetrical, with a slight pressure difference between the upper and lower surfaces. The shock wave forms symmetrically near the leading edge due to the compressibility effects at Mach 0.8.

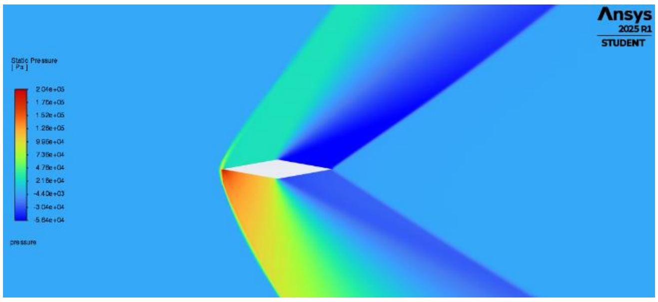

Figure 8: AOA=5°

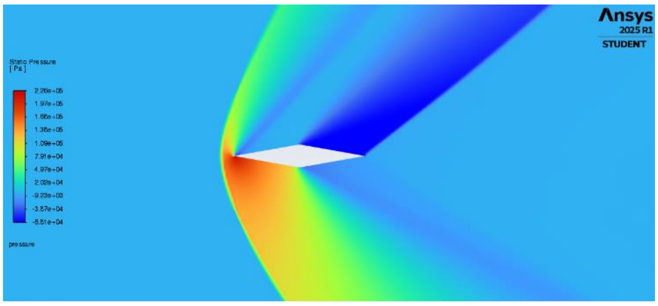

Figure 9: AOA=10°

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The upper surface experiences a significant drop in pressure (shown in blue) while the lower surface shows increased pressure (orange zone). This indicates the generation of lift due to enhanced pressure difference.

The pressure difference becomes more pronounced, and the shock wave shifts downstream on the upper surface, showing stronger flow separation regions. The lift increases further, but drag also starts to rise due to adverse pressure gradients.

3.1 VELOCITY CONTOUR AT MACH 0.8

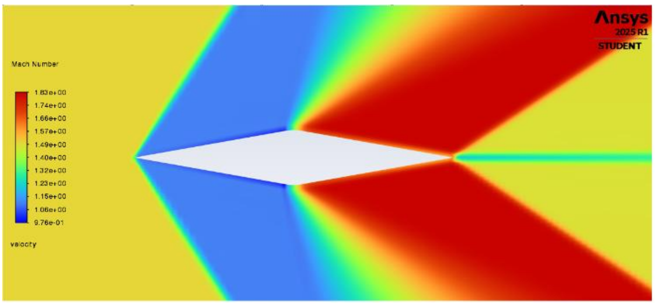

Figure 10: **AOA=0°**

The flow is symmetric, with uniform velocity distribution around the airfoil. Acceleration of flow occurs over both upper and lower surfaces near the leading edge, forming weak shock waves.

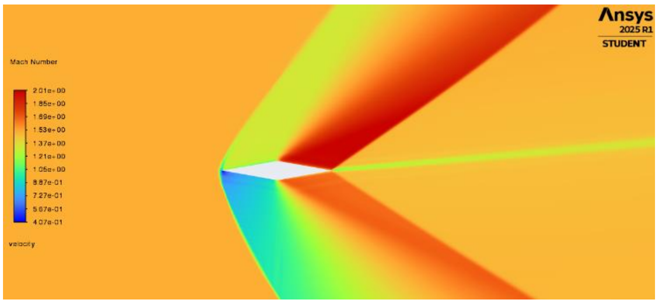

Figure 11: AOA=5°

The upper surface shows higher Mach number regions (blue zones) indicating accelerated flow, while the lower surface has lower velocity (green–yellow zones) due to compression. This asymmetry results in lift generation.

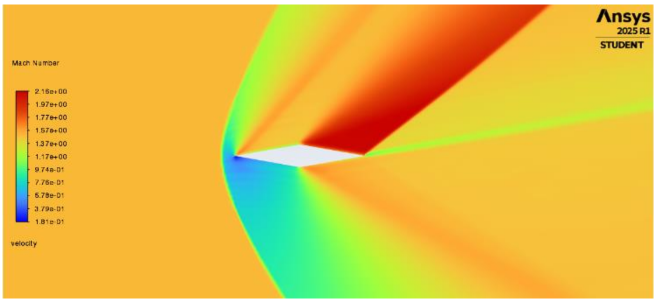

Figure 12: AOA=10°

The high-velocity region on the upper surface expands further downstream, showing stronger shock structures and local flow separation. The lift increases but drag also rises because of enhanced shock strength and boundary layer effects.

CFD ANALYSIS ON MACH NUMBERS 1.5, 2, 2.5.

CFD simulations were conducted at Mach numbers 1.5, 2.0, and 2.5 to study the pressure and velocity distributions around the normal, 5 mm recessed, and 10 mm recessed double-wedge airfoils.

At Mach 1.5, the flow remained relatively stable with distinct oblique shock waves forming at the leading edge. The 5 mm recessed airfoil exhibited smoother pressure distribution and weaker shock formation compared to the normal and 10 mm models, indicating lower drag and improved flow stability. As the Mach number increased to 2.0, shock intensity and compression effects became more prominent, yet the 5 mm recess effectively delayed boundary-layer separation and maintained attached flow, while the 10 mm recess experienced stronger adverse pressure gradients and flow detachment. At Mach 2.5, the effects of shock interaction and pressure variation were significantly amplified, with the normal airfoil showing sharp wave reflections, whereas the 5 mm recessed model maintained better flow control and pressure recovery. Overall, the CFD analysis confirmed that the 5 mm recessed double-wedge airfoil delivered the most efficient aerodynamic performance across all tested Mach numbers, offering a balanced combination of reduced drag, smoother shock behavior, and stable flow characteristics.

Figure 13: Double Wedge Airfoil without curved recesses

This model represents the baseline double-wedge airfoil without any geometric modification. It serves as a reference configuration for comparing aerodynamic behavior. The normal airfoil exhibits moderate lift and drag characteristics, forming clear oblique shocks at supersonic speeds but without additional flow control features.

Figure 14: 5 mm Curved Recesses

The 5 mm symmetric recessed (or cavity) airfoil includes a shallow curved recess on both sides near the mid-chord. This modification enhances flow mixing and pressure recovery, reducing drag while maintaining sufficient lift. During analysis, the 5 mm model showed smoother shock patterns, reduced losses, and an overall higher lift-to-drag ratio compared to the normal airfoil.

Figure 15 :10 mm Curves Recesses

The 10 mm recessed airfoil has a deeper cavity geometry, which increases flow disturbance and shock intensity. While it can generate slightly higher lift at greater angles of attack, it also introduces stronger shock waves and higher drag due to enhanced separation zones. Thus, it performs less efficiently than the 5 mm model.

4.RESULT AND DISCUSSION

EXPERIMENTAL RESULTS DOUBLE WEDGE AIRFOIL WITH 5 MM CURVED RECESSES

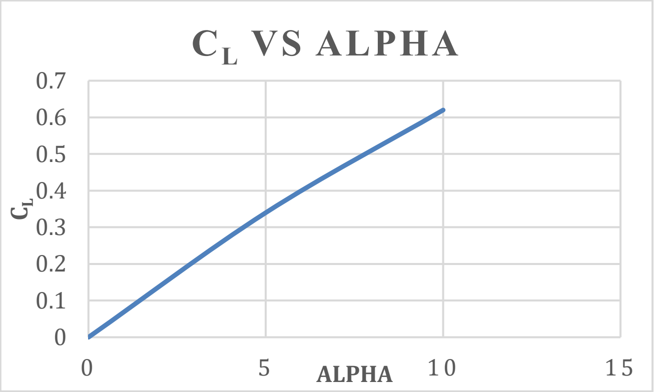

Figure 16: C_L Vs α

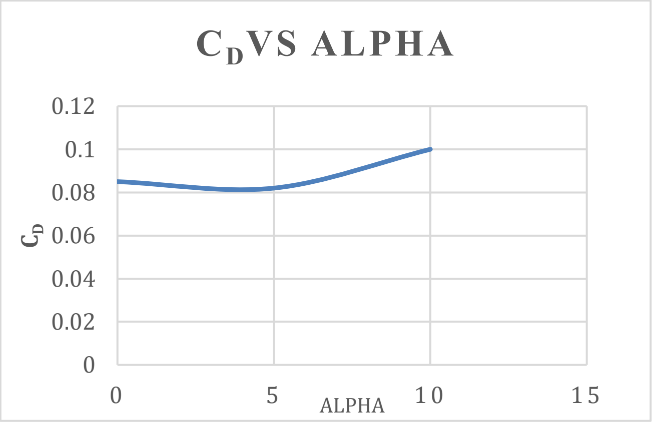

Figure 17: C_D Vs α

Experimental Results Double Wedge Airfoil With 10 mm Curved Recesses

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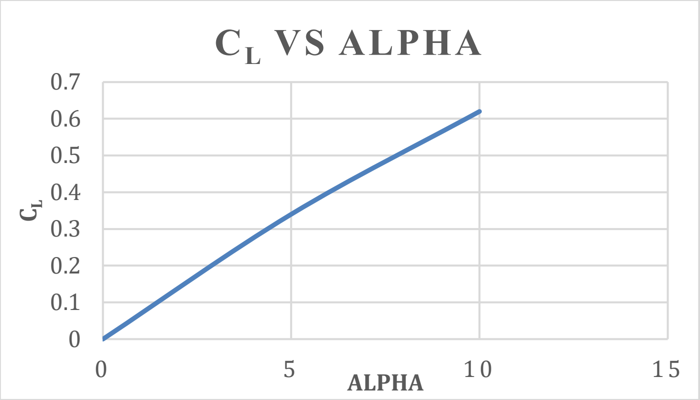

Figure 18: C_L Vs α

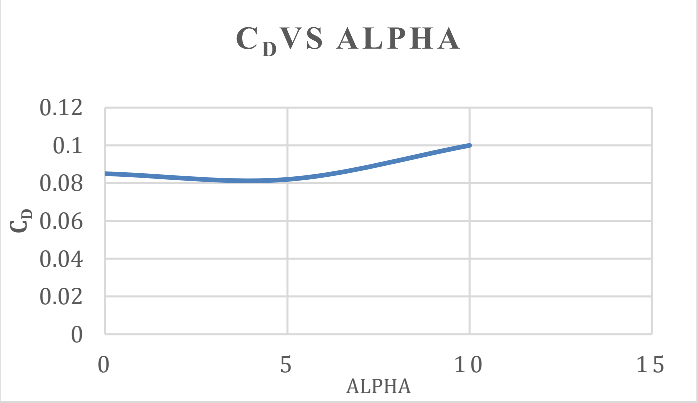

Figure 19: C_D Vs α

The aerodynamic comparison of the sharp wedge and curved recess airfoils at Mach 1.5 clearly highlights the advantage of incorporating curved recess modifications. The 5 mm curved recess produced the highest lift among the modified models, closely approaching the lift of the sharp wedge, while offering a noticeable reduction in drag at all angles of attack. Although the 10 mm curved recess generated slightly lower lift, it achieved better drag performance than both the sharp wedge and the 5 mm recess at 5°, making it more aerodynamically efficient for moderate angles. At 10°, all configurations showed a rise in drag due to strong shock interactions, yet both curved recess models still demonstrated improved C_D compared to the sharp wedge.

5.CONCLUSION:

The 5 mm recess is therefore more suitable for applications requiring higher lift output, whereas the 10 mm recess provides a better lift-to-drag efficiency balance. Overall, introducing curved recesses enhances the supersonic performance of the airfoil, with the 5 mm recess optimized for lift and the 10 mm recess optimized for efficiency. Based on the experimental and computational results, it clearly shows that 5 mm of flat surface in the airfoil will performing better in subsonic and supersonic speeds, because of encounter of shock in supersonic speeds and flow separation with respect to subsonic speeds.

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