McGill University

Subsonic Aerodynamics

MECH 533

Final Project

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1 Introduction

The study of low Reynolds-number airfoils allows us to understand the underlying processes that create performance differences. The ideal airfoil shape will vary depending on its size, the speed at which it is travelling and the medium it is travelling in. The scaling effect is defined by the Reynolds-number $Re = Vc/\nu$, where V is the flight speed, c is the chord, and ν is the kinematic viscosity. It is a ratio of the inertial effects to the viscous effects.

The performance of an airfoil is quantified by the lift and drag coefficients C_L and C_D. Its effectiveness can therefore be defined by the ratio C_L/C_D. At the critical Reynolds-number of 70,000 for a smooth airfoil, we can see a dramatic improvement of effectiveness. In the following sections, it will be shown that as the Reynolds-number increases, the lift to drag ratio improves.

2 Fundamentals of Fluid Mechanics

As the fluid flows around the airfoil, there will be sections where the pressure is lower than than the far-field static pressure. This decreased pressure then has to increase back up to the far-field static pressure when it reaches the trailing edge also known as recovery. Therefore, there is the presence of an adverse pressure gradient along the surface. The adverse pressure gradient is the cause of flow separation, which greatly impairs the lifting properties of the airfoil.

In the lowest Reynolds-number range (below 30,000), the boundary layer is mostly laminar. Laminar flow is less resistant to flow separation due to adverse pressure gradients. Once separated, it quickly transitions into turbulent flow, which can then reattach itself as a turbulent boundary layer. This behavior creates a laminar separation bubble.

However, a Reynolds-number of 50,000 based on the separation bubble length is required for the flow to reattach. Therefore, airfoils with a chord resulting in a Reynolds-number less than 50,000 are too short for reattachment. This number supports the fact that there is a significant increase in performance at the critical Reynolds-number of 70,000.

At Reynolds-number of 100,000, the bubble can extend 20-30% of the airfoil, changing the effective shape of the airfoil. For higher Reynolds-number , the bubble will shrink down to a few percent of the chord. However, increasing the angle of attack will create greater adverse pressure gradients. As a result, the small bubble can burst and form a longer bubble. This loss of efficiency cannot be immediately recovered by lowering the angle of attack, creating a hysteresis behavior.

When the Reynolds-number reaches 200,000, the laminar bubble can usually be avoided by letting the pressure recovery occur when the flow has become turbulent. Nonetheless, efficiency can further be improved by increasing the turbulent boundary layer's resistance to separation. For Reynolds-number above 1,000,000, laminar separation is rarely an issue. Efficiency is now gained by decreasing skin friction drag due to viscous effects in the boundary layer. An ideal airfoil would therefore have just enough separation resistance without the cost of adding too much skin friction drag.

It is important to note that the separation behavior depends on the local boundary layer Reynolds-number . Therefore, it is still possible for laminar separation to occur for very high Reynolds-number e.g. thin airfoils with small nose at high angle of attack.

Since turbulent boundary layers are more resistant to separation than laminar ones, it is sometimes desirable to artificially accelerate transition. This can be done mechanically through surface roughness or even vibrations.

3 Experimental Testing of Airfoils

Multiple issues arise when it comes to experimental testing of airfoils. Correlating lift and drag is difficult due to the different in orders of magnitude of around 100. Furthermore, stall and separation are usually the regions of interest, but they are also the regions where small changes lead to big differences.

Windtunnel results often suffer from the wall effects. The walls lead to an internal flow problem as opposed external. Also, the boundary layer from the walls may affect the flow around the airfoil. Free-flight testing allows to eliminate wall effects. However, it becomes hard to determine the performance of the airfoil only since three-dimensional effects and non-airfoil parts both affect the performance.

Therefore, experimental results often show inconsistencies from one test to another, which makes it hard for designers to rely upon them.

4 Theoretical Design of Airfoils

Although low Reynolds-number airfoils may operate at high Mach numbers where compressibility effects are significant and may be used in applications where three-dimensional effects are not negligible, we only consider two-dimensional incompressible flows since they very well understood.

Using complex analysis and conformal transformations, it is possible to derive exact analytical solutions of the flow field around the airfoil. Furthermore, the solution can be computed very quickly with computers. As long as the boundary layer stays attached, the solution gives a decent approximation of the airfoil performance.

For high Reynolds-number (above 1,000,000), lift and drag can be calculated with high precision as long as there is no separation. Since transition usually occurs near the minimum pressure point, it is possible to avoid the early separation by carefully designing the airfoil in that section to reduce the adverse pressure gradient.

Design procedures can be direct or inverse. The direct procedure finds the flow field solution of a given airfoil, whereas the inverse procedure finds the airfoil shape given a pressure field. These methods are valid for attached flow with a Reynolds-number under 300,000. For lower Reynolds-number , where laminar separation and bubble occur, there are no generally accepted methods to calculated those peculiar phenomena.

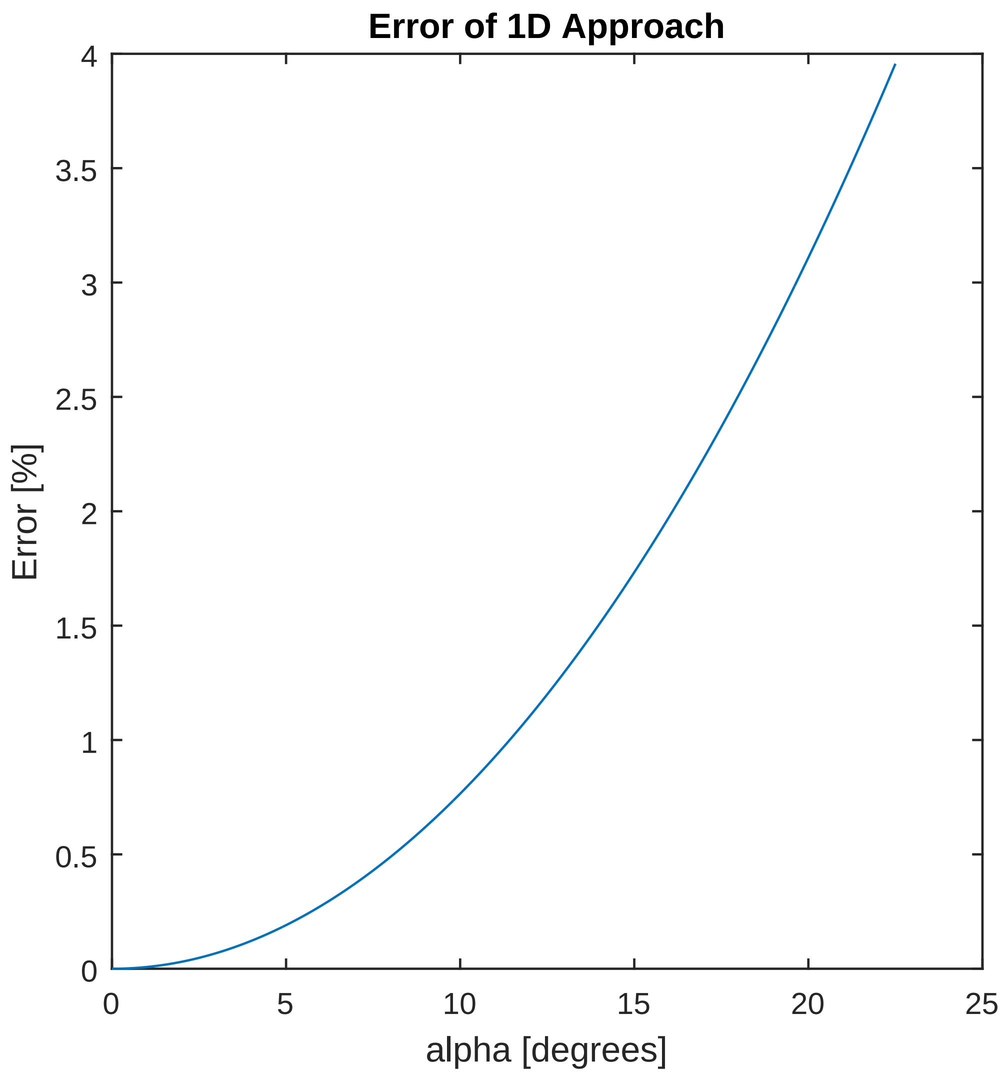
5 Special-Purpose Airfoils

Depending on the design requirements, the airfoil shape may take very different forms. For example given an upper surface geometry and a desired lift, the pressure distribution can be defined. Inverting the pressure field allows to find the full airfoil shape, as it was the case for the BoAR 80. Another example is the Lissaman-Hibbs 8025 that required a flat upper surface for the solar cells it carried. Knowing desirable features of the pressure field and how the shape affects it allows the designers to create a nose section and undersurface that will meet the required lift and drag coefficients.

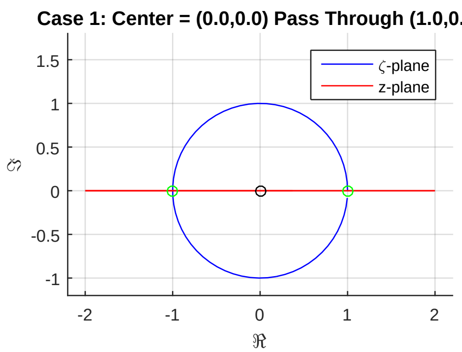
6 Conclusion

The study of low Reynolds-number airfoils can qualitatively explain the difference in performance as a result of transition, separation and reattachment.

Question 1 Error Plot



Question 7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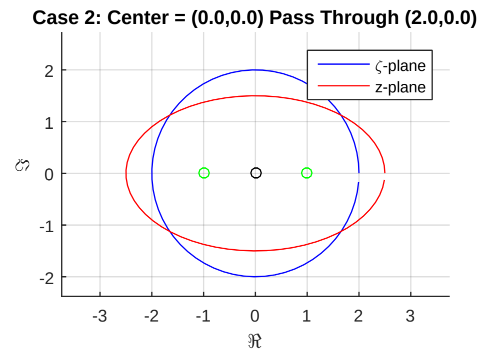
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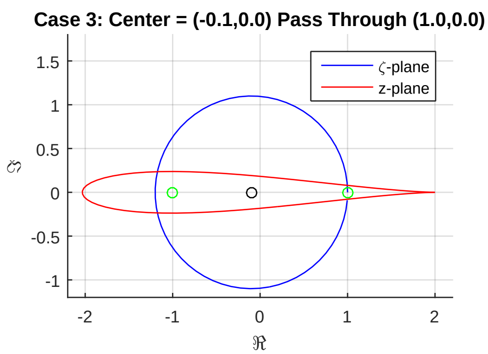
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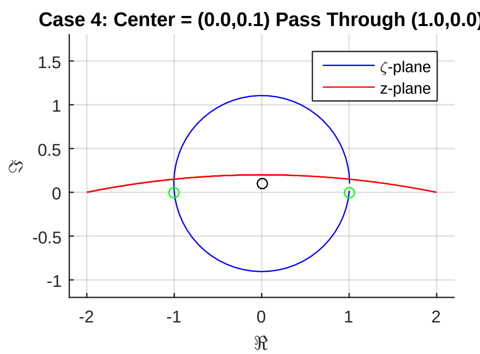
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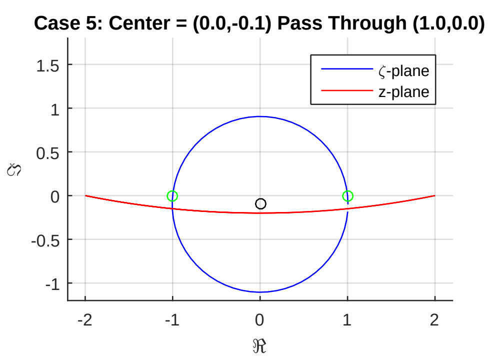
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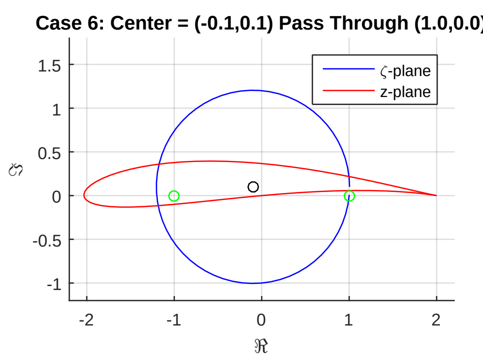
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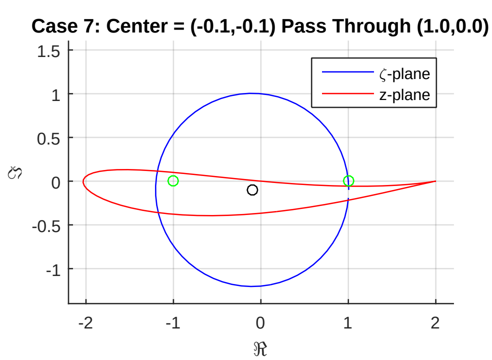
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