

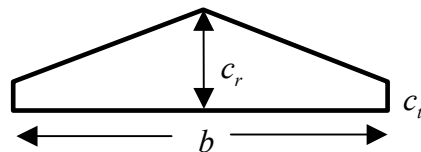
16.100 Homework Assignment # 9
Due: Monday November 21, 9am

Reading Assignment

Anderson, 3rd edition: Chapter 19 (everything)

Problem 1

In this problem, you will develop an estimate for the friction drag on the trapezoidal wing of an F-16C at approach conditions. We will assume the approach speed is 200 mph and take the air conditions as sea-level, standard day. We will also consider a wind tunnel test of a 1/10 scale model of the F-16C at 100 mph (assume the tunnel air conditions are also sea-level, standard day). The trapezoidal wing is the wing extended to the centerline (i.e. the fuselage and the strake are not included). The planform and dimensions of the trapezoidal wing for the full-scale F-16C are shown below:



where $b = 31$ ft, $c_r = 16.2$ ft, and $c_t = 3.2$ ft. In the following estimates, we will modify the usual approach for estimating skin friction drag based on a single mean value of c_f to include a laminar and a turbulent boundary layer section each with its own value of c_f . We will assume that the boundary layer transitions at a Reynolds number based on x of 10^6 .

- a) For the actual F-16C at approach, estimate the skin friction drag coefficient accounting for both the laminar and turbulent boundary layer effects. Include a drawing that indicates the specific region on the wing for which the flow is laminar.
- b) For the wind tunnel test, estimate the skin friction drag coefficient again accounting for the laminar and turbulent boundary layer regions. Also include a drawing indicating where these different regions occur on the wind tunnel wing.
- c) Based on your estimates, will the wind tunnel friction drag be an accurate estimate of the actual friction drag at approach?

Problem 2

In this problem, we will use Xfoil to simulate the flow of over two airfoils, the NACA 0004 and the NACA 0012, at range of Reynolds numbers from $Re = 1 \times 10^3$ to $Re = 1 \times 10^9$ at zero angle of attack. The drag versus Reynolds number behavior is different for these two airfoils. The purpose of this problem is to explain what is causing the behaviors observed. You **must** base your explanations on the behavior of the boundary layers which can be examined by plotting:

- The skin friction distribution on the airfoil, c_f versus x/c
- The amplification factor distribution on the airfoil, N versus x/c
- The displacement thickness distribution on the airfoil, δ^* versus x/c

Xfoil also provides a breakdown of the drag into skin friction and pressure drag. This may also be useful to help confirm your understanding. Directions for running Xfoil are available on the 16.100 webpage, listed under the Materials.

We will discuss the amplification factor in lecture, but here's what you need to know for this problem set. The amplification factor measures the amplification that would occur to a small disturbance in the boundary layer. Specifically, the amplification is given by e^N . Thus, for $N=0$ (i.e. $e^0 = 1$), no amplification of the disturbance would occur and it would simply convect and diffuse but not grow in magnitude. As a boundary layer begins to transition from laminar to turbulent, disturbances are amplified, thus $N>0$. Experimentally, it has been found that for airfoils with reasonably smooth surfaces, the flow in a boundary layer becomes turbulent when the amplification factor reaches $N=9$. Xfoil uses this approach to model transition and thus you can plot the distribution of N along the airfoil surface.

- a) To begin, calculate the drag coefficient versus Reynolds number for both airfoils over the range of Reynolds numbers. Perform enough solutions to represent the behavior of the drag with respect to Reynolds number accurately. For the NACA 0004, the behavior of the drag changes most from $Re = 1 \times 10^6$ to $Re = 1 \times 10^7$. For the NACA 0012, the behavior of the drag changes most from $Re = 1 \times 10^5$ to $Re = 1 \times 10^6$. In these two regimes, it is recommended that additional Reynolds numbers are solved so that the behavior is accurately depicted. On the same graph, in a log-log scale, plot the drag coefficients for both airfoils.
- b) For the NACA 0012 below $Re = 1 \times 10^5$, the slope of the drag coefficient versus Reynolds number is not $-\frac{1}{2}$ as predicted from flat plate, laminar boundary layer theory. Explain why this is happening by inspecting the boundary layer behavior for $Re \leq 1 \times 10^5$.
- c) For $Re > 1 \times 10^5$, the drag coefficient on the NACA 0012 drops vary rapidly. Again, explain why this is happening based on the behavior of the boundary layer in this Reynolds number regime.
- d) For the NACA 0004, the drag coefficient changes rapidly around $Re = 1 \times 10^6$. Explain why this is happening based on the behavior of the boundary layer in the Reynolds number regime.
- e) For both airfoils, the drag coefficient does not change much for higher Reynolds numbers (i.e. $Re \geq 1 \times 10^7$). Explain why this is happening based on the behavior of the boundary layers in this Reynolds regime.