AE301 Aerodynamics I
UNIT D: Applied Aerodynamics

ROAD MAP . . .

- **D-1**: Aerodynamics of 3-D Wings
- **D-2**: Boundary Layer and Viscous Effects
- **D-3**: XFLR (Aerodynamics Analysis Tool)

Unit D-2: List of Subjects

- What is Boundary Layer?
- Laminar v.s. Turbulent Flow
- Flat Plate Laminar Boundary Layer
- Boundary Layer Transition to Turbulent Flow
- Ideal v.s. Real Flow
- Flow Separation
- Attached v.s. Separated Flow
- Flow Separation and Stall
- Viscous Effects on Drag
What is Boundary Layer?

Boundary layer is a thin layer formed on the surface of a solid body in a flow field. Due to the viscosity, the velocity within the boundary layer changes with respect to the vertical distance from the surface (usually non-linearly).

The boundary layer “grows” as the flow moves over the body (the boundary layer thickness is defined as: $\delta$)

Within the boundary layer, the velocity varies from zero (surface) to the free stream (edge of the layer): this is called, the “boundary layer velocity profile”

At the surface (wall) of the body, wall shear stress can be given as: $\tau_w = \mu \left( \frac{dV}{dy} \right)_{y=0}$

This wall shear stress is one of the major contributor to the vehicle drag, called the “skin friction drag”
LAMINAR V.S. TURBULENT FLOWS

**Laminar flow:** where the streamlines are smooth and regular, and a fluid element moves smoothly along a streamline.

**Turbulent flow:** where the streamlines break up and a fluid element moves in a random, irregular, and chaotic fashion (means streamlines cannot be defined as it is unsteady in nature).

**Transition** from laminar to turbulent occurs as Reynolds number of the flow increases (usually the boundary layer “transition point” is defined, based on the **transition Reynolds number**: $Re_{tr}$).
The solution known as **“Blasius” solution** of flat plate laminar boundary layer (flat plate means: zero pressure gradient)

\[ C_f = \frac{1.328}{\sqrt{Re_L}} \text{ laminar} \]

\[ \delta = \frac{5.2}{\sqrt{Re_x}} \text{ laminar} \]

\[ \tau_w = \frac{0.664}{\sqrt{Re_x}} \]

\[ c_{f,x} \equiv \frac{\tau_w}{0.5 \rho_{\infty} V_{\infty}^2} = \frac{\tau_w}{q_{\infty}} \]

(laminar flat plate boundary layer)

(Lower case \( c_{f,x} \) represents the skin friction drag coefficient per unit length at a location of \( x \))

The skin friction coefficient (due to the wall shear stress) will cause the total skin friction drag for the flat plate of length \( L \):

\[ D_f = \int_0^L \tau_w \, dx = 0.664 q_{\infty} \int_0^L \frac{dx}{\sqrt{Re_x}} = \frac{0.664 q_{\infty}}{\sqrt{\rho_{\infty} V_{\infty}/\mu_{\infty}}} \int_0^L \frac{dx}{\sqrt{\rho_{\infty} V_{\infty}/\mu_{\infty}}} = 1.328 q_{\infty} \sqrt{L} \]

Total skin friction drag coefficient of the flat plate of length \( L \) can be defined as:

\[ C_f \equiv \frac{D_f}{q_{\infty} S} = \frac{D_f}{q_{\infty} L(1)} = \frac{1.328 q_{\infty} \sqrt{L}}{q_{\infty} L \sqrt{\rho_{\infty} V_{\infty}/\mu_{\infty}}} \frac{1.328}{\sqrt{\rho_{\infty} V_{\infty}/\mu_{\infty}}} = \frac{1.328}{\sqrt{Re_L}} \]

(Upper case \( C_f \) represents the total skin friction drag coefficient of the given flat plate of length \( L \))
Class Example Problem D-2-1

Consider a flow of air over a flat plate (5 cm long in the flow direction, and 1 m wide). The freestream conditions correspond to standard sea-level, and the flow velocity is 120 m/s. Assuming the laminar flow, determine the followings:

(a) The boundary layer thickness at the trailing edge of the plate
(b) The drag force (due to skin friction) developed on the plate
TURBULENT BOUNDARY LAYER

Turbulent boundary layer is thicker than the laminar boundary layer, under the same condition of flow.

Turbulent boundary layer is often very difficult to analyze: heavily dependent on experimental results.

TRANSITION FROM LAMINAR TO TURBULENT BOUNDARY LAYER

The adverse pressure gradient, rough surface (skin), and many other factors determine boundary layer transition.

The physical mechanism of boundary layer transition, even for a simple flat plate, is still not completely understood. The boundary layer transition mechanism is still the area of intensive research in aerodynamics today.
Consider a flow of air over a flat plate (5 cm long in the flow direction, and 1 m wide). The freestream conditions correspond to standard sea-level, and the flow velocity is 120 m/s. If the flow is turbulent, determine the followings:
(a) The boundary layer thickness at the trailing edge of the plate
(b) The drag force (due to skin friction) developed on the plate
Homework D-2-1/D-2-2

Consider a flow of air over a flat plate (10 cm long in the flow direction, and 1 m wide). The freestream conditions correspond to standard sea-level, and the flow velocity is 200 m/s. Determine the boundary layer thickness at the trailing edge of the plate and the drag force due to skin friction developed at the plate for the case of (a) laminar and (b) turbulent flow.
The general solution procedure:

1. Calculate $D_f$ for the combined area $A + B$, assuming that the flow is completely turbulent

2. Obtain the turbulent $D_f$ for the area $B$ only, by calculating the turbulent $D_f$ for area $A$ and subtracting this from the result of part (1)

3. Calculate the laminar $D_f$ for the area $A$

4. Add results from parts (2) & (3) to obtain total drag on the complete surface area $A + B$

5. Note that the Wright Flyer I is a biplane and has total 4 surfaces (top & bottom and 2 wings), so the total skin friction drag on the complete biplane wing configuration will be the $\times 4$ of the skin friction drag on a single surface, calculated from part (4)
Homework D-2-2a

The wing span of Wright Flyer I (biplane) is 40 feet 4 inches, and the planform area of each wing is 255 ft$^2$. Assume that the wing is rectangular shape. If the airplane is in flight with 30 mph (under the standard sea-level flight condition), estimate the skin friction drag on the wings. Assume that the transition Reynolds number is $6.5 \times 10^5$.

(step 1) Calculate drag force for the combined area ($A + B$), assuming that the flow is completely turbulent.
(step 2) Obtain the turbulent drag force for the area $B$ only, by subtracting drag force for the area $A$ (for turbulent flow) from the result of (step 1). Note: you must, first, determine the transition point from laminar to turbulent flow.
Homework D-2-2b (continued from D-2-2a)

The wing span of Wright Flyer I (biplane) is 40 feet 4 inches, and the planform area of each wing is 255 ft$^2$. Assume that the wing is rectangular shape. If the airplane is in flight with 30 mph (under the standard sea-level flight condition), estimate the skin friction drag on the wings. Assume that the transition Reynolds number is $6.5 \times 10^5$.

(step 3) Calculate drag force for the area $A$ for laminar flow.
(step 4) Add results from (step 2) and (step 3) to obtain total drag on the combined surface area ($A + B$).
(step 5) For biplane, you need to add up drag force of total 4 surfaces to have total skin friction drag.
RECALL: [IDEAL V.S. REAL FLOW: CIRCULAR CYLINDER] (UNIT B-3)

As we learned in Unit B-3, the pressure distribution around circular cylinder (ideal flow) is symmetric, thus no lift and no drag will be produced. This is known as d’Alembert’s paradox.

Flow separation, due to the adverse pressure gradient, and resulting complex wake region induces the non-symmetric pressure distribution, thus “pressure drag due to separation” is the main drag contributor of real flows around circular cylinder

IDEAL V.S. REAL FLOW: AERODYNAMICS OF AIRFOILS AND WINGS

A very similar analogy (that we employed for the analysis of flow over a circular cylinder) can also be applied for the aerodynamics of airfoils and wings. The formation of boundary layer and its behavior (transition from laminar to turbulent flows, as well as the flow separation, due to the pressure gradient) plays very important roles in generations of aerodynamic lift and drag of airfoils and wings.
**RECALL: [PRESSURE GRADIENT] (UNIT B-1)**

$p$ (pressure) is a function of spatial coordinates: $p = p(x, y)$

The mathematical representation: **pressure gradient**, $\nabla p$, is a vector such that:

- Magnitude = **maximum rate of change** of $p$ per unit length of the coordinate space at the given point
- Direction = direction of the **maximum rate of change** of $p$ at the given point

Using pressure gradient, directional pressure change can be given: $\frac{dp}{ds} = \nabla p \cdot \hat{n}$

(This is “how much change of pressure takes place in the direction specified by the line vector $\hat{n}$”: more commonly called physical “**pressure gradient**”)

**FLOW SEPARATION**

Pressure gradient: $dp/ds$ (along the surface of an airfoil) may be favorable (negative) or adverse (positive), and adverse pressure gradient causes flow to **separate** from the surface.
FLOW SEPARATION ON A AIRFOIL

Flow separation on an airfoil causes:

- A drastic loss of lift (stall)
- A major increase in drag, caused by pressure drag due to separation

FLOW SEPARATION AND STALL

At extremely high angles of attack, the flow separates from the top surface of an airfoil, leading it to stall. Desired “post-stall” characteristics (smooth and gradual stall or sudden violent stall) and ease of recovery are important design factors of airfoil
Flow Separation and Stall

RECALL: [LEADING EDGE STALL] (UNIT C-4)

Example: NACA 4412

- Characteristics of relatively thin airfoils with thickness ratios between 10 and 16 percent of the chord length.
- Post-stall: rapid loss of the lift (not desirable)

RECALL: [EFFECTS OF AIRFOIL THICKNESS ON STALL] (UNIT C-4)

Thin airfoil: thin airfoil is desired for high-speed applications (from high transonic to supersonic), in order to minimize profile and wave drags.

Thick airfoil (example: NACA 4421): thick airfoil is usually desired, especially for low-speed applications (low subsonic), due to the favorable stall characteristics (Trailing Edge Stall).
The presence of viscosity in a flow produces two sources of drag:

- **Skin friction drag** (due to shear stress on the surface of the body, called the wall shear stress) => this is often called “Parasite Drag”
- **Pressure drag** (due to flow separation) => this is often called “Drag due to Separation”

Trade-off between these two drag components may be possible by carefully engineered design: for example,

- Natural Laminar Flow (NLF) airfoil (NACA 6-series)
- Golf ball dimples

**RECALL: [THE DRAG POLAR] (UNIT D-1)**

The induced drag \( (C_{D_i}) \) is the drag due to lift (3-D effect)

The profile drag \( (c_d) \) is a drag on a 2-D airfoil, from which includes: (i) **drag due to skin friction** (or parasite) drag and (ii) **drag due to pressure** (or separation) drag:

\[
c_d = c_{d,f} + c_{d,p}
\]

The total drag on an airplane is:

\[
C_D = \text{"Profile" Drag + "Induced" Drag} = c_d + \frac{C_L^2}{\pi e \ AR}
\]
Homework D-2-3

Answer the followings (explain in your own words).
(a) What is the “boundary layer”?  
(b) Explain “how” flow separates on the surface of the airfoil.
(c) Explain “how” aircraft stalls. What are the important design factors of airfoil, in terms of flow separation and stall?
(d) Explain the reasons of choosing “thin” and “thick” airfoils: explain “pros” and “cons” of choosing these two types of airfoils.
(e) The presence of viscosity in a flow produces two sources of drag: explain these two different types of viscous drags.