Lecture # 08: Boundary Layer Flows and Drag

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AerE343L #4: Hot wire measurements in the wake of an airfoil

Pressure rake with 41 total pressure probes (the distance between the probes d=2mm)

Test conditions:
- Velocity: \( V = 15 \text{ m/s} \)
- Angle of attack: \( \text{AOA}=0, \text{ and } 12 \text{ deg.} \)
- Date sampling rate: \( f = 1000\text{Hz} \)
- Number of samples: 10,000 (10s in time)
- No. of points: 20~25 points
- Gap between points: \( \sim 0.2 \text{ inches} \)
AerE343L #4: Hot wire measurements in the wake of an airfoil

Lab#4

**Hotwire probe**

**FFT**

**Figure 7.7** Velocity components in a turbulent pipe flow: (a) $x$-component velocity; (b) $y$-component velocity; (c) $z$-component velocity.

**Time sequence with data sampling rate of 1000 Hz**

**Force -Z component (N)**

**Frequency (Hz)**

**Y/C $\times 100$**

**X/C $\times 100$**

GA(W)-1 airfoil

25 m/s shadow region

-40 -20 0 20 40 60 80 100 120 140

-60

-40

-20

0

20

40

60

-4.5 -3.5 -2.5 -1.5 -0.5 0.5 1.5 2.5 3.5 4.5

vort:
AerE343L #4: Hot wire measurements in the wake of an airfoil

Required data for the lab report:

1. Wake velocity profiles at AOA = 0 and 12 deg
2. Wake turbulence intensity profiles at AOA = 0 and 12 deg.
3. Estimated drag coefficients at AOA = 0, and 12 deg.
4. FFT transformation to find vortex shedding frequency in the wake of the airfoil
5. Discussions based on the measurement results
Boundary Layer Flows

Which one will induce more drag?
Laminar boundary layer?
Turbulent boundary layer?

\[ \tau_w = \mu \frac{\partial U}{\partial y} \bigg|_{wall} \]
CONVENTIONAL AIRFOILS and LAMINAR FLOW AIRFOILS

- Laminar flow airfoils are usually thinner than the conventional airfoil.
- The leading edge is more pointed and its upper and lower surfaces are nearly symmetrical.
- The major and most important difference between the two types of airfoil is this, the thickest part of a laminar wing occurs at 50% chord while in the conventional design the thickest part is at 25% chord.
- Drag is considerably reduced since the laminar airfoil takes less energy to slide through the air.
- Extensive laminar flow is usually only experienced over a very small range of angles-of-attack, on the order of 4 to 6 degrees.
- Once you break out of that optimal angle range, the drag increases by as much as 40% depending on the airfoil.

FIGURE 2: Extent of laminar flow on some famous airfoils.
Flow Separation

Shoulder of airfoil - maximum speed outside of the boundary layer

Laminar boundary layer

Boundary layer region (shaded)

Transition (laminar becomes turbulent)

Stagnation point region

Pressure = Total pressure $p_t$

Separation point (Stalled flow)

Flow outside boundary layer is inviscid flow

Turbulent boundary layer

Increasing distance downstream

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Aerodynamic Performance of An Airfoil

\[ C_i = \frac{L}{\frac{1}{2} \rho V_w^2 c} \]

\[ C_d = \frac{D}{\frac{1}{2} \rho V_w^2 c} \]

Before stall

After stall

Airfoil stall

Experimental data

25 m/s

shadow region

GA(W)-1 airfoil

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Flow Separation and Transition on Low-Reynolds-number Airfoils

- Low-Reynolds-number airfoil (with $\text{Re}<500,000$) aerodynamics is important for both military and civilian applications, such as propellers, sailplanes, ultra-light man-carrying/man-powered aircraft, high-altitude vehicles, wind turbines, unmanned aerial vehicles (UAVs) and Micro-Air-Vehicles (MAVs).

- Since laminar boundary layers are unable to withstand any significant adverse pressure gradient, laminar flow separation is usually found on low-Reynolds-number airfoils. Post-separation behavior of the laminar boundary layers would affect the aerodynamic performances of the low-Reynolds-number airfoils significantly.

- Separation bubbles are usually found to form on the upper surfaces of low-Reynolds-number airfoils. Separation bubble would burst suddenly to cause airfoil stall at high AOA when the adverse pressure gradient becoming too big.
Surface Pressure Coefficient distributions (Re=68,000)

Typical surface pressure distribution when a laminar separation bubble is formed (Russell, 1979)

GA (W)-1 airfoil
(also labeled as NASA LS(1)-0417)
Laminar Separation Bubble on a Low-Reynolds-number Airfoil

PIV measurement results at AOA = 10 deg, Re=68,000

(Hu et al., ASME Journal of Fluid Engineering, 2008)
Stall Hysteresis Phenomena

- **Stall hysteresis**, a phenomenon where stall inception and stall recovery do not occur at the same angle of attack, has been found to be relatively common in low-Reynolds-number airfoils.

- When stall hysteresis occurs, the coefficients of lift, drag, and moment of the airfoil are found to be multiple-valued rather than single-valued functions of the angle of attack.

- **Stall hysteresis** is of practical importance because it produces widely different values of lift coefficient and lift-to-drag ratio for a given airfoil at a given angle of attack. It could also affect the recovery from stall and/or spin flight conditions.
The hysteresis loop was found to be clockwise in the lift coefficient profiles, and counter-clockwise in the drag coefficient profiles.

The aerodynamic hysteresis resulted in significant variations of lift coefficient, $C_l$, and lift-to-drag ratio, $l/d$, for the airfoil at a given angle of attack.

The lift coefficient and lift-to-drag ratio at $AOA = 14.0$ degrees were found to be $C_l = 1.33$ and $l/d = 23.5$ when the angle is at the increasing angle branch of the hysteresis loop.

The values were found to become $C_l = 0.8$ and $l/d = 3.66$ for the same $AOA=14.0$ degrees when the angle is at the deceasing angle branch of the hysteresis loop.
PIV Measurement results

(Hu, Yang, Igarashi, Journal of Aircraft, Vol. 44, No. 6, 2007)
Refined PIV Measurement Results

(Hu, Yang, Igarashi, Journal of Aircraft, Vol. 44. No. 6 , 2007)
Aerodynamics of Golf Ball

\[ C_D = \frac{F_d}{\frac{1}{2} \rho V^2 D} \]

- \( C_D \): Drag coefficient
- \( F_d \): Drag force
- \( \rho \): Density of air
- \( V \): Velocity
- \( D \): Diameter of the object

\( \frac{e}{D} \): Relative roughness

- \( e = 0 \) (smooth)
- \( e = 1.5 \times 10^{-3} \)
- \( e = 5 \times 10^{-3} \)
- \( e = 1.25 \times 10^{-2} \)

Re = \( \frac{UD}{v} \)

- Reynolds number

Separation
Laminar boundary layer
Turbulent boundary layer
Transition
Thin wake
Thick wake
Laminar Flows and Turbulence Flows

Re = 100,000

Smooth ball
Rough ball
Golf ball

Centerline Velocity (U/U∞)
Distance (X/D)

-2.0 -1.5 -1.0 -0.5 0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0
-0.4 -0.2 0 0.2 0.4 0.6 0.8 1.0

-2.0 -1.5 -1.0 -0.5 0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0
-0.4 -0.2 0 0.2 0.4 0.6 0.8 1.0

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