Lesson 25

Viscous Aerodynamics

Aircraft Systems AEM 691 SP: Spring 2016

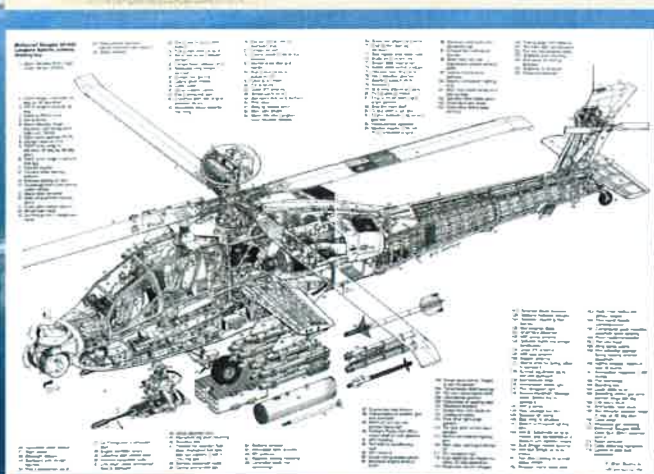
Section 001 (local) with CRN: 15875
Section 996 (distance) with CRN: 16846

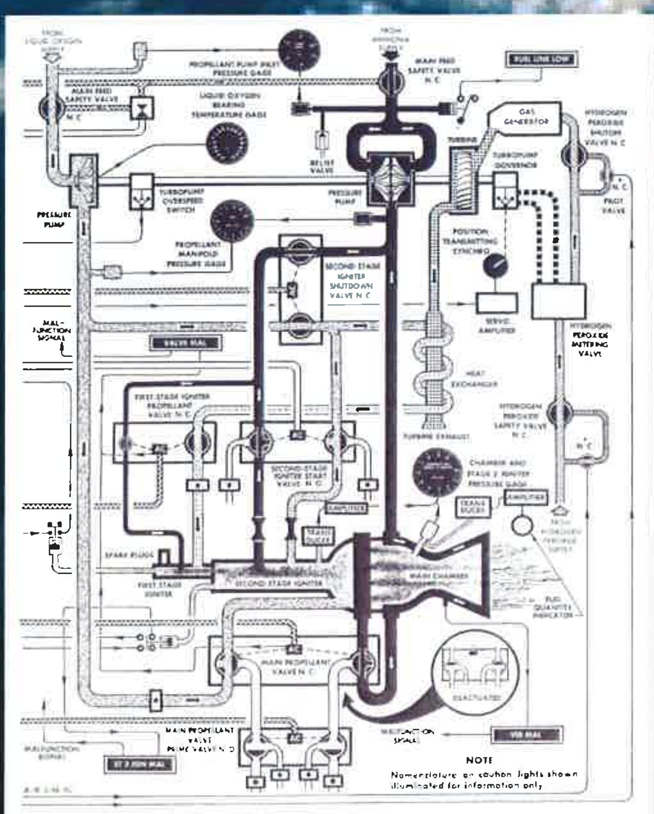
Enroll now for Spring 2016. This class is on a 4 year rotation; next offered in 2020!

Instructor: Charles O'Neill

Texts: *Aircraft Systems, Mechanical, Electrical, and Avionics*, Moir, AIAA
The YC-14 STOL Prototype: Design, Development, Newberry, AIAA

Prerequisites: Consent of instructor or Undergraduate Engineering





Topics include:

- Flight Control Systems
- Engine Control Systems
- Fuel Systems
- Hydraulic Systems
- Electrical Systems
- Environmental Control (ECS)
- Avionics
- Mission Systems

- Certification & Regulatory Issues
- Failure Mode and Effects Analysis

- Boeing 727 Design Case Study
- Boeing YC-14 STOL Case Study
- Lightweight Fighter (LWF)

- Southern Air Museum (Birmingham, AL)

Viscous Flows in Aerodynamics

Airfoil and Wing behavior and characteristics are <u>strongly</u> affected by viscous terms.

Viscous effects manifest as:

- Stall (ie $C_{L_{max}}$)

- Separation

- Drag

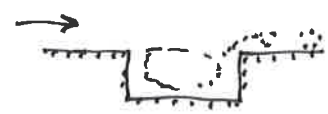
- Lift (Kutta Condition ≈ sharp TE)

- Wakes

- Hard to diagnose wind tunnel results

- Unsteady flow

- And much MUCH more...



Bad news:

There is no general solution to the Navier-Stokes equation(s).

Worse news:

"Before I die, I hope someone will clarify quantum physics for me.
After I die, I hope God will explain turbulence to me."

— Albert Einstein

Good news:

Job security and demand for analysis.

Review of Navier-Stokes equations of fluid flow

Mass:

$$\frac{\partial \rho}{\partial t} + \underbrace{\nabla\cdot(\rho\vec{V})}_{\text{divergence of momentum.}} = 0$$

No viscous terms here...

Momentum

$$\underbrace{\frac{\partial(\rho\vec{V})}{\partial t}}_{\text{time derivative of momentum}} + \underbrace{\nabla\cdot\left(\rho\vec{V}\vec{V}^T\right)}_{\text{divergence of Momentum flux}} = \underbrace{\rho f}_{\text{body force}} - \underbrace{\nabla p}_{\text{pressure gradient}} + \boxed{\underbrace{\nabla\cdot\bar{\bar{\tau}}}_{\text{Viscous term}}}$$

Energy

$$\underbrace{\frac{\partial(\rho h_0 - p)}{\partial t}}_{\text{time rate of change of energy}} + \underbrace{\nabla\cdot\left(\rho\bar{V}h_0\right)}_{\text{energy flux}} = \underbrace{\dot{q}_v}_{\text{energy source}} + \underbrace{\rho f\cdot\bar{V}}_{\text{body forces}} + \boxed{\underbrace{\nabla\cdot\left(\bar{\bar{\tau}}\cdot\bar{V}\right)}_{\text{Viscous term}}} - \underbrace{\nabla\cdot\dot{q}}_{\text{heat transfer}}$$

Non-dimensionalization of simplified N-S. (see Lesson 4)

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho V) = 0$$

$$\frac{\partial(\rho V)}{\partial t} + \nabla\cdot(\rho V V^T) = -\nabla p + \boxed{\frac{1}{Re}\nabla\cdot\bar{\bar{\tau}}}$$

$$\frac{\partial(\rho h_0)}{\partial t} + \nabla\cdot(\rho V h_0) = M^2\frac{\partial p}{\partial t} + \boxed{\frac{M^2}{Re}\nabla\cdot(\bar{\bar{\tau}}\cdot V)} - \frac{1}{Re\,Pr}\nabla\cdot\dot{q}$$

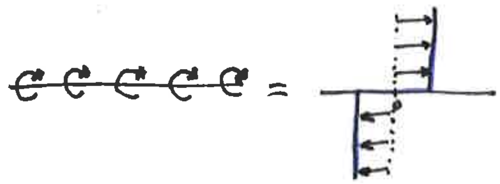
- Viscous terms are scaled by $\frac{1}{Re} = \frac{\mu}{\rho V L}$

- The Re # reflects a relative ratio of inertial to viscous forces for identical fluxes, not an absolute ratio.

- $Re \to \infty$ indicates that the flow behaves in an inviscid manner. Except that the no-slip condition $V=0$ implies a thinner BL and possibly larger τ shear stress.

Simple Inviscid Model

place sources and vortex sheets on surface, a velocity jump results

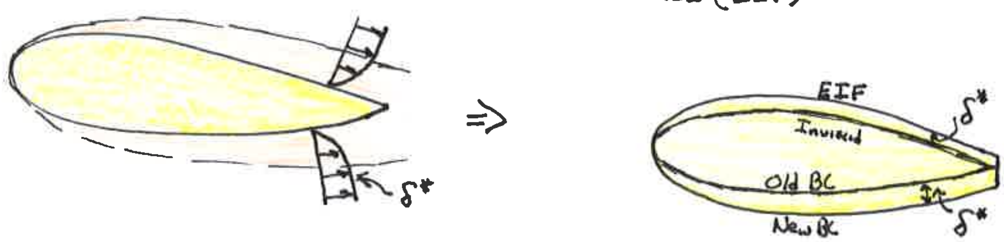


This captures the inviscid behavior but certainly <u>not</u> the viscous boundary conditions.

We justified this approximation by claiming that the viscous portion of the flow field was near the surface.

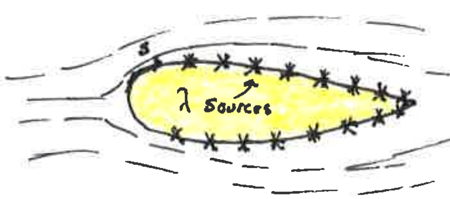
Displacement Body Model

Given that a BL creates a fictitious displacement thickness, offset a displaced new boundary condition for the inviscid solver. "Equivalent Inviscid Flow (EIF)"



Wall Transpiration Model

Given a BL creates a displacement velocity $\left(\frac{d}{dz}(\rho w) > 0\right)$, add a source sheet on the inviscid boundary.



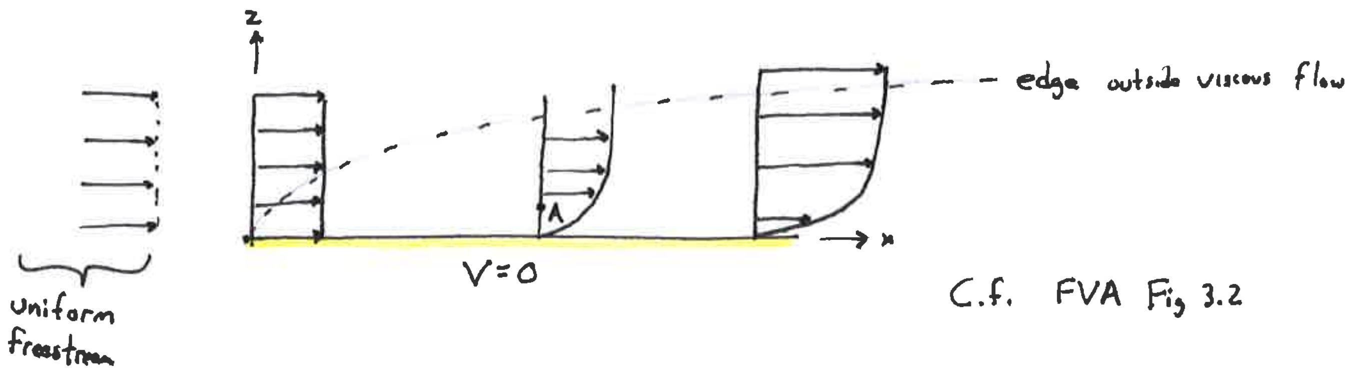
$$\lambda(s) = \frac{1}{\rho}\frac{dm}{ds}$$ where $m \equiv$ mass defect

Remember we previously found that (corollary of Kutta-Joukowski $L' = \rho V \Gamma$)

$$D' = \rho V_\infty \Lambda$$ where $\Lambda \equiv$ total source magnitude.

$\boxed{\text{We now have drag!}}$

A boundary layer acts as a displacement on the fluid



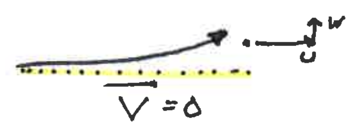
C.f. FVA Fig 3.2

For a steady state process, the divergence of $V = 0$ from mass continuity.

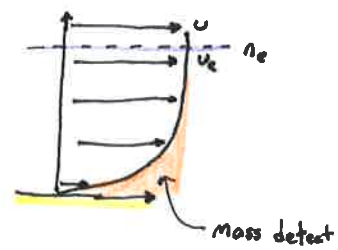
$$\cancelto{0}{\frac{\partial \rho}{\partial t}} + \nabla \cdot (\rho V) = 0 \quad \Rightarrow \quad \frac{d}{dx}(\rho u) + \cancelto{v=0}{\frac{d}{dy}(\rho v)} + \frac{d}{dz}(\rho w) = 0$$

At a point in the BL (say A), the BL thickens downstream such that $\frac{du}{dx} < 0$

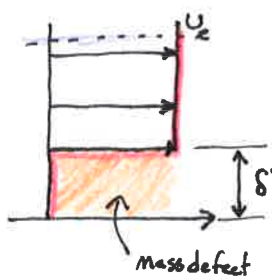
Thus, $\frac{d}{dz}(\rho w) > 0$, a vertical velocity occurs.



Displacement thickness. (Integrate over BL)



$$\text{Mass defect} \equiv \underbrace{\int_0^{n_e} (\underbrace{\rho_e u_e}_{\text{edge}} - \underbrace{\rho u}_{\text{cross section velocity}})\, dn}_{\text{Positive when } \rho u < \rho_e u_e} = \rho_e u_e \delta^*$$



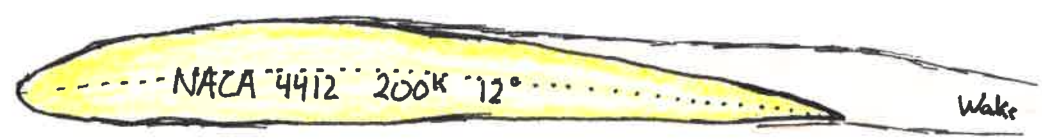
$$\delta^* \equiv \text{displacement thickness} = \int_0^{n_e} \left(1 - \frac{\rho u}{\rho_e u_e}\right) dn$$

If the flow were uniformly at velocity u_e and density ρ_e, what height δ^* is necessary to give the mass defect seen in the BL.

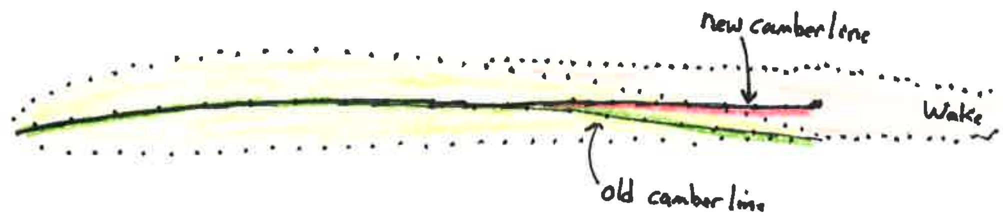
Viscous Decambering

For reasons involving pressure gradients and accelerated flow, the boundary layer height δ^* on the upper (suction) side of an airfoil tends to grow faster than the lower.

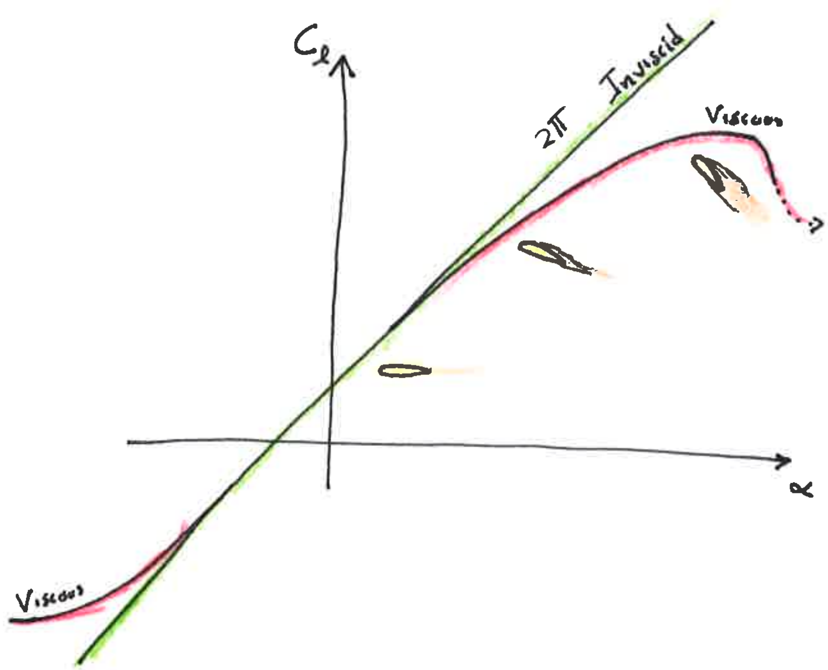
The result is a boundary layer profile similar to:



If the boundary layer height defines a new shape for the boundary conditions, the airfoil's shape changes. The "mean" camber line now includes the wake thickness.

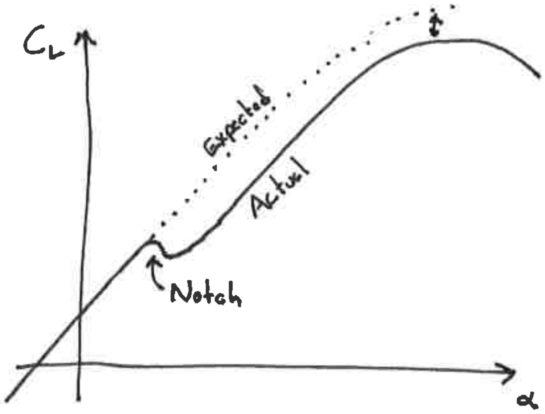


The viscous BL creates an effectively upward flap deflection for the displacement body. We know that TE flaps are particularly effective at C_L generation (or in this case decrease).



Ex: Notches in Wind Tunnel Data

Often in wind tunnel experiments, a "notch" is found in C_L vs α.



Aero engineers don't like notches since they (the notches) reduce $C_{L_{max}}$ by the notch width (approximately). And, the notch can generate non-linear flight behavior. And, notches can annoy or increase pilot workload or stress.

Why? A small area of the surface is stalling or decambering.

Also seen in directional stability (yaw axis) with dorsal fins