Intro to Airfoils

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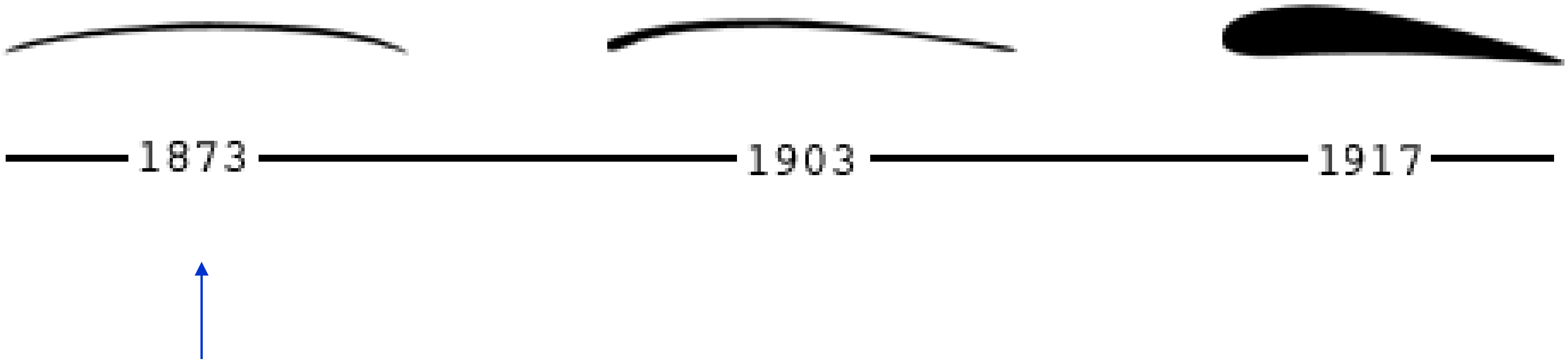
Topics To be Studied

- Airfoil Nomenclature
- Lift and Drag forces
- Lift, Drag and Pressure Coefficients

Uses of Airfoils

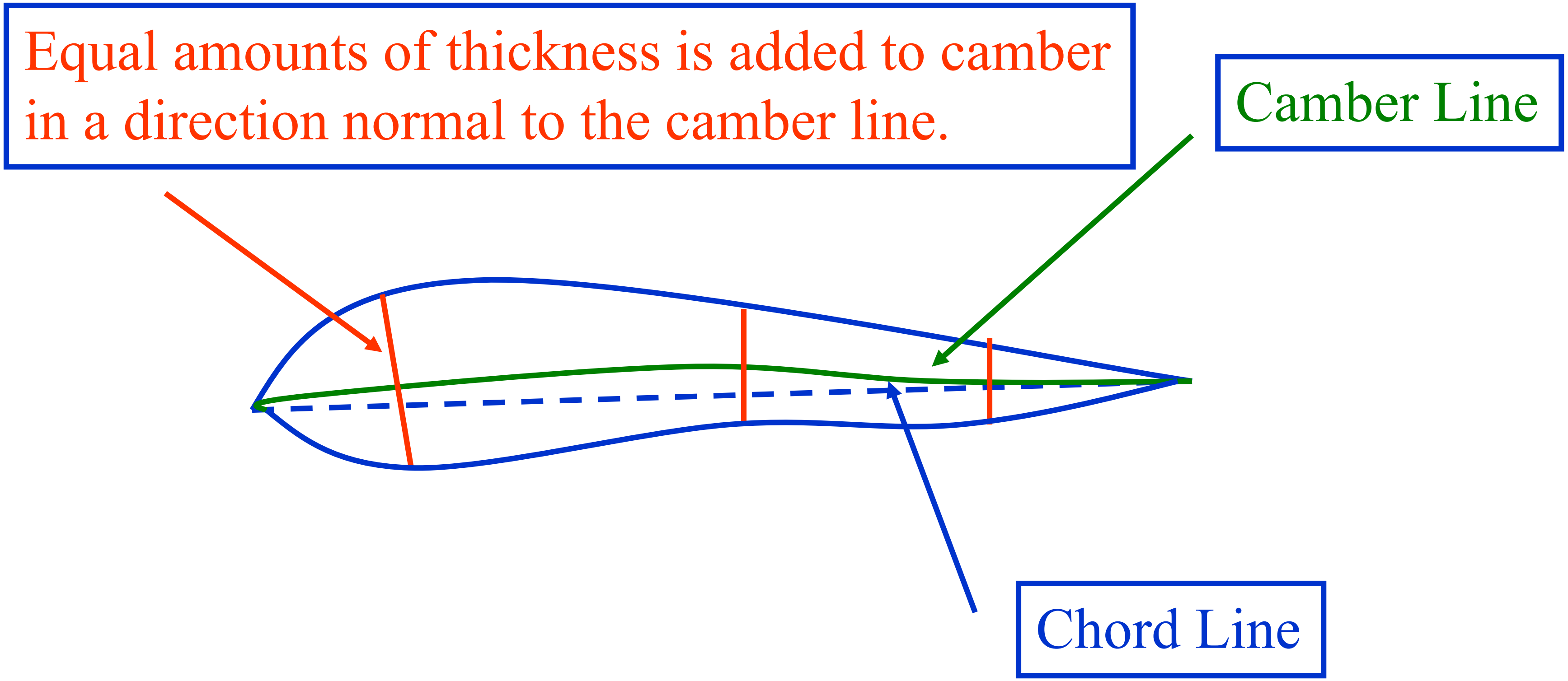
- Wings
- Propellers and Turbofans
- Helicopter Rotors
- Compressors and Turbines
- Hydrofoils (wing-like devices which can lift up a boat above waterline)
- Wind Turbines

Evolution of Airfoils



Early Designs - Designers mistakenly believed that these airfoils with sharp leading edges will have low drag.
In practice, they stalled quickly, and generated considerable drag.

Airfoil



Equal amounts of thickness is added to camber in a direction normal to the camber line.

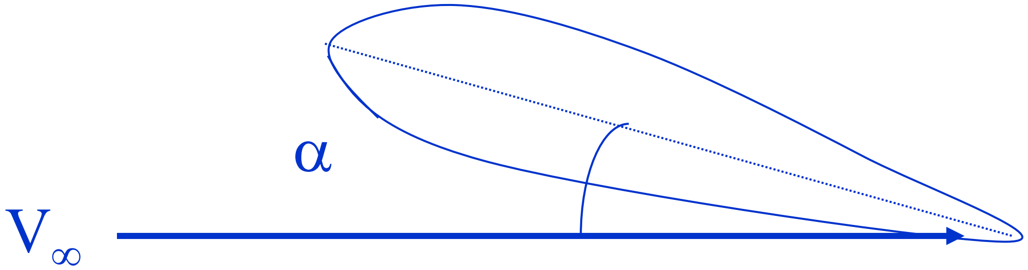
Camber Line

Chord Line

An Airfoil is Defined as a superposition of

- Chord Line
- Camber line drawn with respect to the chord line.
- Thickness Distribution which is added to the camber line, normal to the camber line.
- Symmetric airfoils have no camber.

Angle of Attack



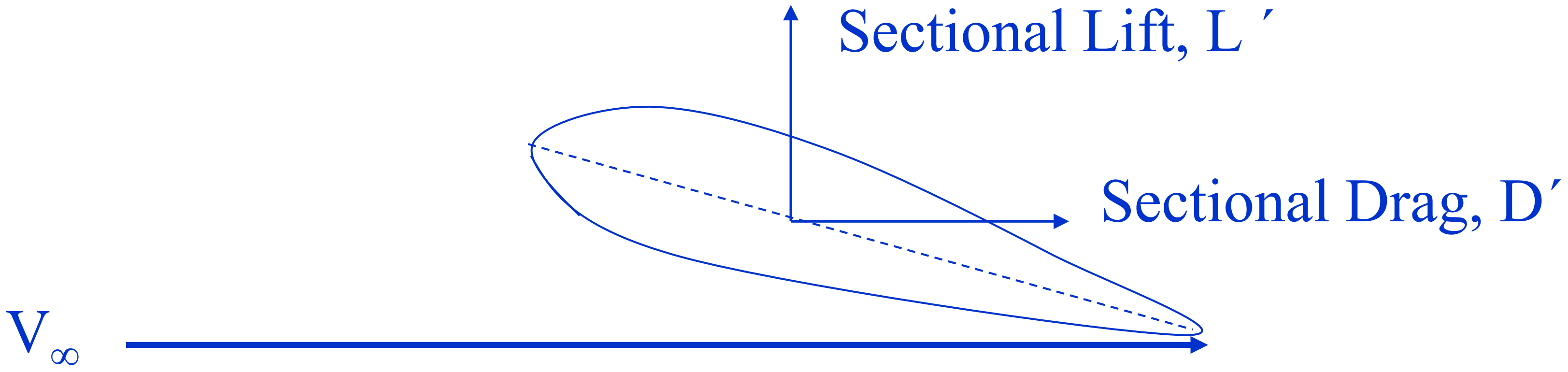
Angle of attack is defined as the angle between the freestream and the chord line. It is given the symbol α.

Because modern wings have a built-in twist distribution, the angle of attack will change from root to tip.

The root will, in general, have a high angle of attack.

The tip will, in general, have a low (or even a negative) α.

Lift and Drag Forces acting on a Wing Section



The component of aerodynamic forces <u>normal</u> to the freestream, per unit length of span (e.g. per foot of wing span), is called the sectional lift force, and is given the symbol L ′.

The component of aerodynamic forces <u>along</u> the freestream, per unit length of span (e.g. per foot of wing span), is called the sectional drag force, and is given the symbol D ′.

Sectional Lift and Drag Coefficients

- The sectional lift coefficient C_l is defined as:

$$C_l = \frac{L'}{\frac{1}{2}\rho V_\infty^2 c}$$

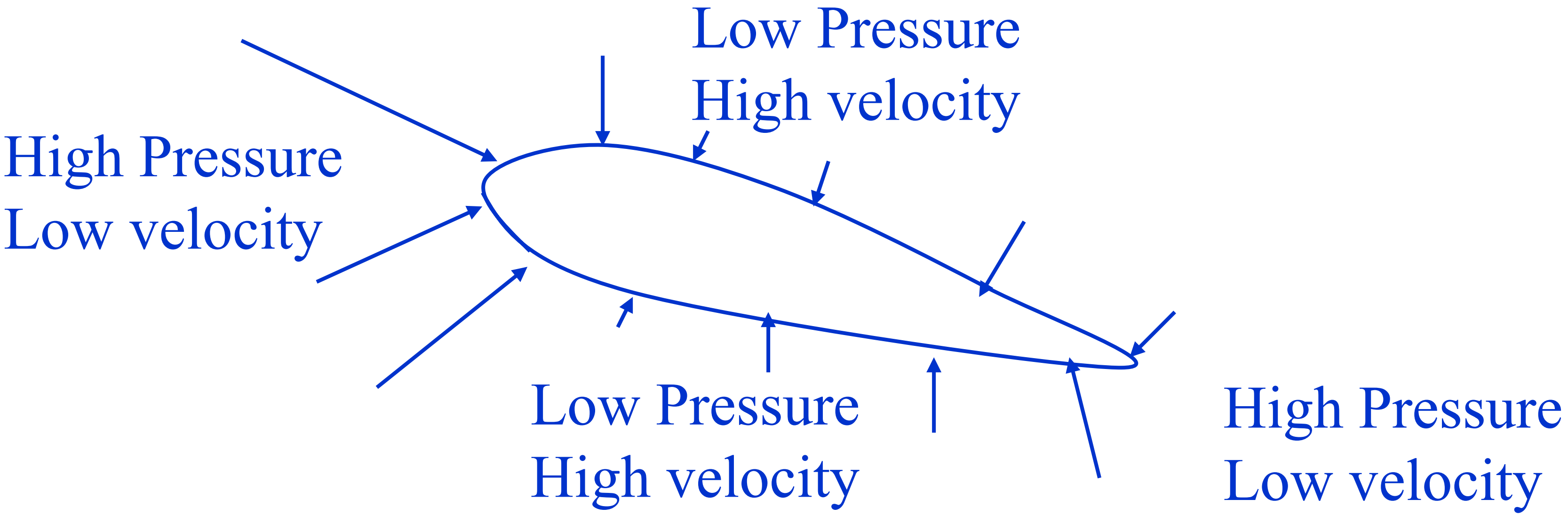
- Here c is the airfoil chord, i.e. distance between the leading edge and trailing edge, measured along the chordline.
- The sectional drag force coefficient C_d is likewise defined as:

$$C_d = \frac{D'}{\frac{1}{2}\rho V_\infty^2 c}$$

Note that...

- When we are taking about an entire wing we use L, D, C_L and C_D to denote the forces and coefficients.
- When we are dealing with just a section of the wing, we call the forces acting on that section (per unit span) L' and D', and the coefficients C_l and C_d

Pressure Forces acting on the Airfoil



Low Pressure
High velocity

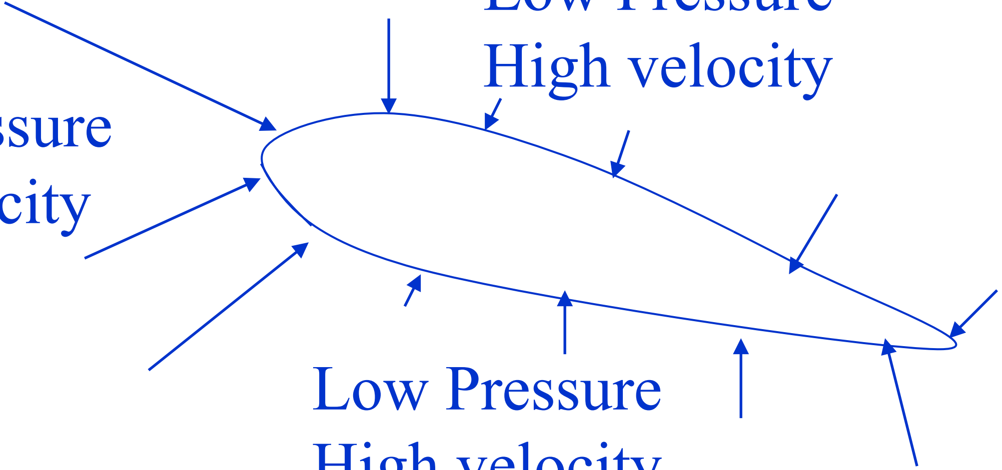
High Pressure
Low velocity

Low Pressure
High velocity

High Pressure
Low velocity

Bernoulli's equation says where pressure is high, velocity will be low and vice versa.

Pressure Forces acting on the Airfoil



Low Pressure
High velocity

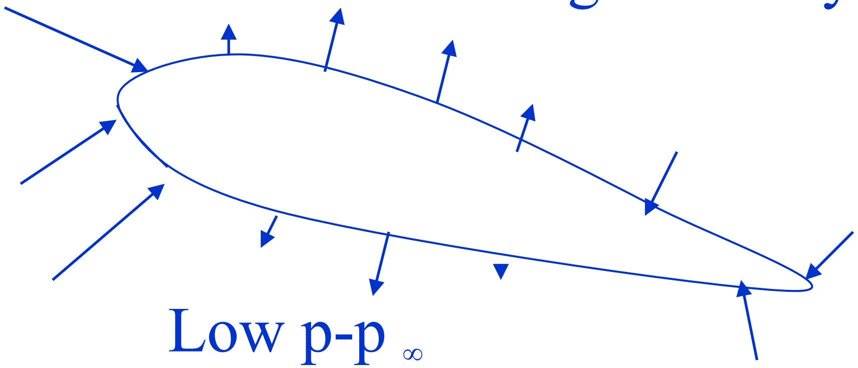
High Pressure
Low velocity

Low Pressure
High velocity

High Pressure
Low velocity

Bernoulli’s equation says where pressure is high, velocity will be low and vice versa.

Subtract off atmospheric Pressure p_∞ everywhere. Resulting Pressure Forces acting on the Airfoil



Low $p-p_\infty$
High velocity

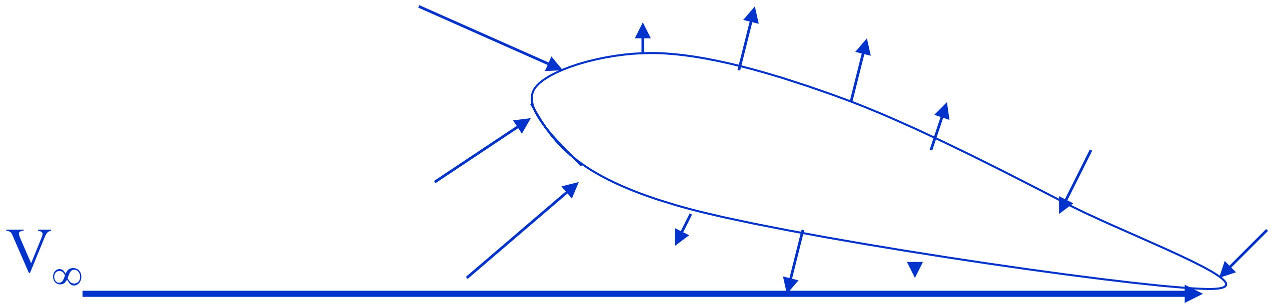
High $p-p_\infty$
Low velocity

Low $p-p_\infty$
High velocity

High $p-p_\infty$
Low velocity

The quantity $p-p_\infty$ is called the gauge pressure. It will be negative over portions of the airfoil, especially the upper surface.
This is because velocity there is high and the pressures can fall below atmospheric pressure.

Relationship between L′ and p



$$L' = \text{Force normal to the wind direction}$$

$$= \text{Forces acting on the lower side - Force on upper side}$$

$$= \int_{\text{Leading Edge}}^{\text{Trailing Edge}} \mathrm{p}_{\text{lower side}}\, dx - \int_{\text{Leading Edge}}^{\text{Trailing Edge}} \mathrm{p}_{\text{upper side}}\, dx$$

$$= \int_{\text{Leading Edge}}^{\text{Trailing Edge}} \left(\mathrm{p}_{\text{lower side}} - \mathrm{p}_{\text{upper side}}\right) dx$$

Relationship between L′ and p (Continued)

$$L' = \int_{\substack{\text{Leading}\\ \text{Edge}}}^{\substack{\text{Trailing}\\ \text{Edge}}} \left(\mathrm{p}_{\text{lower side}} - \mathrm{p}_{\text{upper side}}\right) dx$$

$$= \int_{\substack{\text{Leading}\\ \text{Edge}}}^{\substack{\text{Trailing}\\ \text{Edge}}} \left(\left[\mathrm{p}_{\text{lower side}} - p_\infty\right] - \left[\mathrm{p}_{\text{upper side}} - p_\infty\right]\right) dx$$

Divide left and right sides by $\frac{1}{2}\rho V_\infty^2 c$

We get:

$$\frac{L'}{\frac{1}{2}\rho V_\infty^2 c} = \int_{\substack{Leading\\ Edge}}^{\substack{Trailing\\ Edge}} \left(\frac{p_{lower} - p_\infty}{\frac{1}{2}\rho V_\infty^2} - \frac{p_{upper} - p_\infty}{\frac{1}{2}\rho V_\infty^2}\right) d\frac{x}{c}$$

Pressure Coefficient Cp

From the previous slide,

$$\boxed{\frac{L'}{\frac{1}{2}\rho V_\infty^2 c} = \int_{\substack{Leading\\Edge}}^{\substack{Trailing\\Edge}} \left(\frac{p_{lower} - p_\infty}{\frac{1}{2}\rho V_\infty^2} - \frac{p_{upper} - p_\infty}{\frac{1}{2}\rho V_\infty^2} \right) d\frac{x}{c}}$$

The left side was previously defined as the sectional lift coefficient C_l.

The pressure coefficient is defined as:

$$C_p = \frac{p - p_\infty}{\frac{1}{2}\rho V_\infty^2}$$

Thus,

$$C_l = \int_{\substack{Leading\\edge}}^{\substack{Trailing\\edge}} \left(C_{p,lower} - C_{p,upper} \right) d\frac{x}{c}$$

Why use C_l, C_p etc.?

- Why do we use “abstract” quantities such as C_l and C_p?
- Why not directly use physically meaningful quantities such as Lift force, lift per unit span , pressure etc.?

The Importance of Non-Dimensional Forms

Consider two geometrically similar airfoils.
One is small, used in a wind tunnel.
The other is large, used on an actual wing.
These will operate in different environments - density, velocity.
This is because high altitude conditions are not easily reproduced in wind tunnels.
They will therefore have different Lift forces and pressure fields.
They will have identical C_l , C_d and C_p

- if they are geometrically alike
- operate at identical angle of attack, Mach number and Reynolds number

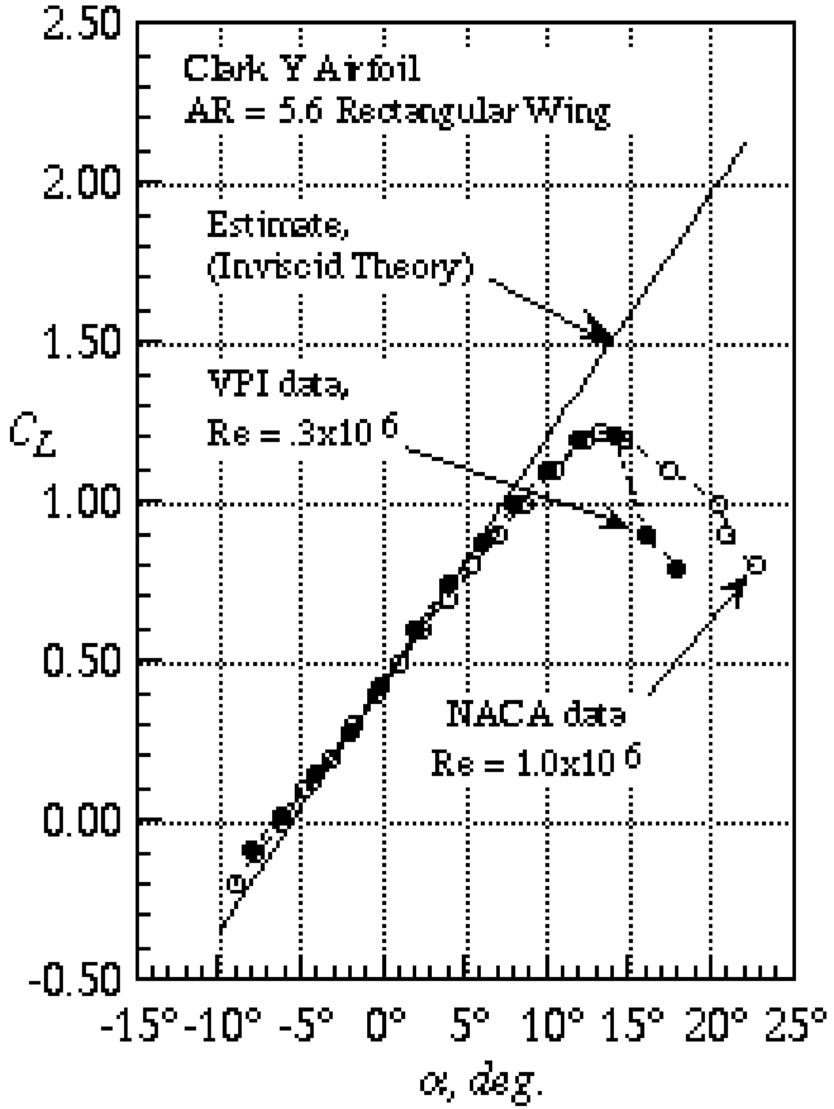
The Importance of Non-Dimensional Forms

In other words,
a small airfoil , tested in a wind tunnel.
And a large airfoil, used on an actual wing
will have identical non-dimensional coefficients C_l , C_d and C_p

- if they are geometrically alike
- operate at identical angle of attack, Mach number and Reynolds number.

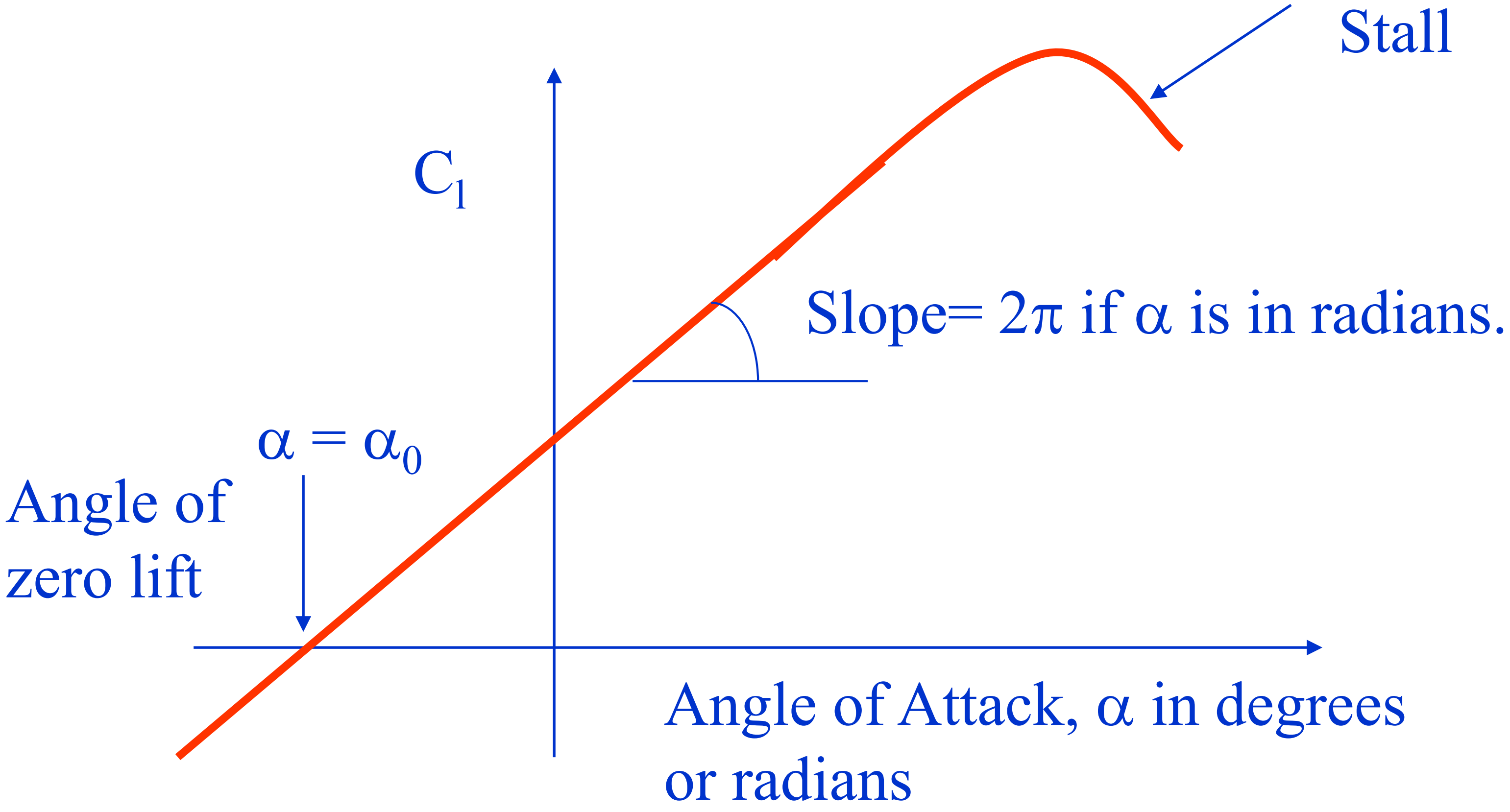
This allows designers (and engineers) to build and test small scale models, and extrapolate qualitative features, but also quantitative information, from a small scale model to a full size configuration.

Once C_l, C_d etc. are found, they can be plotted for use in all applications - model or full size aircraft

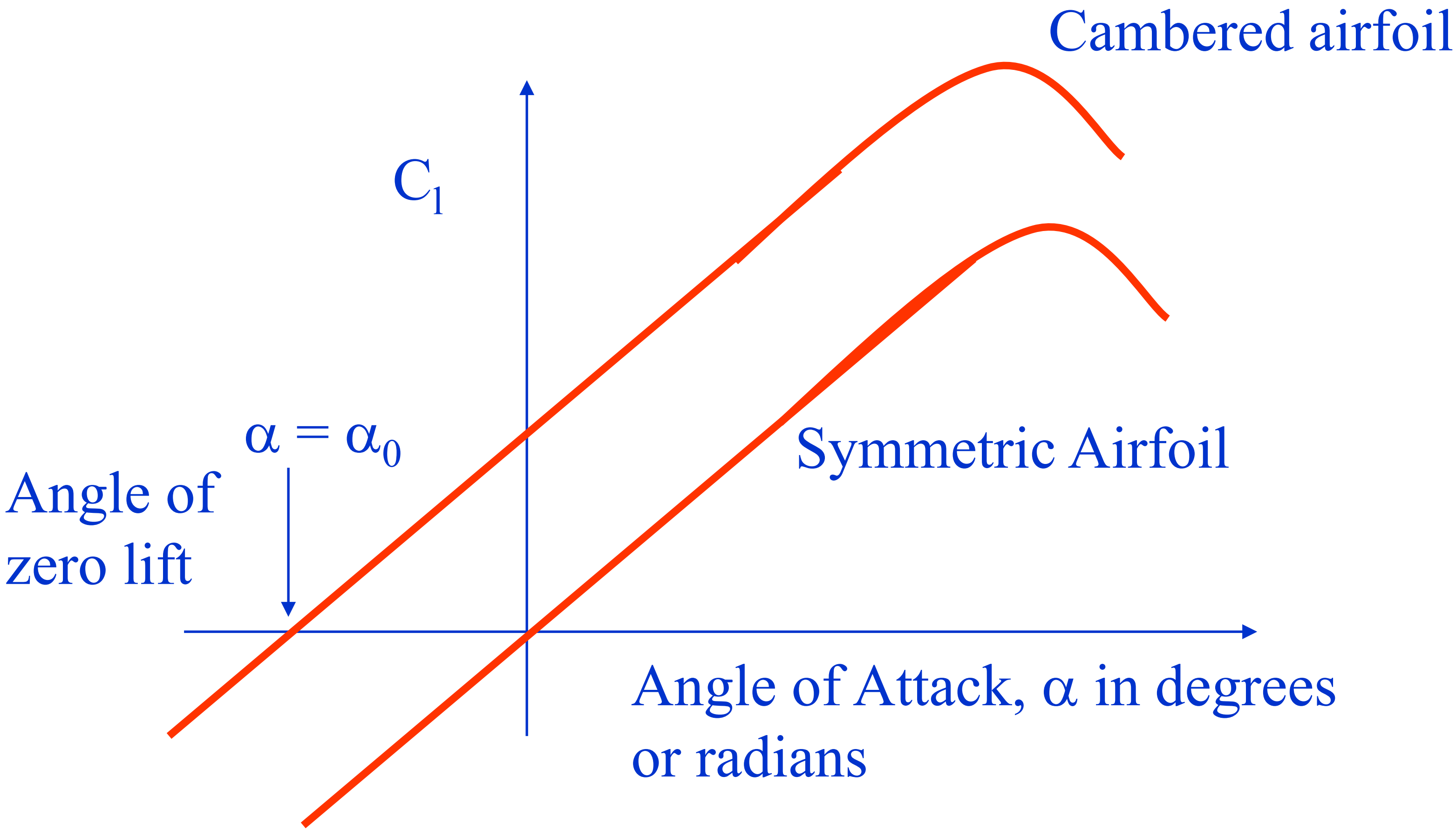


- The geometry must be similar (i.e. scaled) between applications.
- The Reynolds number must be the same for the model and full scale.
- The Mach number must be the same for the model and full scale.
- Then, the behavior of non-dimensional quantities Cp, C_L, C_D, etc will also be the same.

Characteristics of C_l vs. α



The angle of zero lift depends on the camber of the airfoil



Mathematical Model for C_l vs. α at low angles of attack

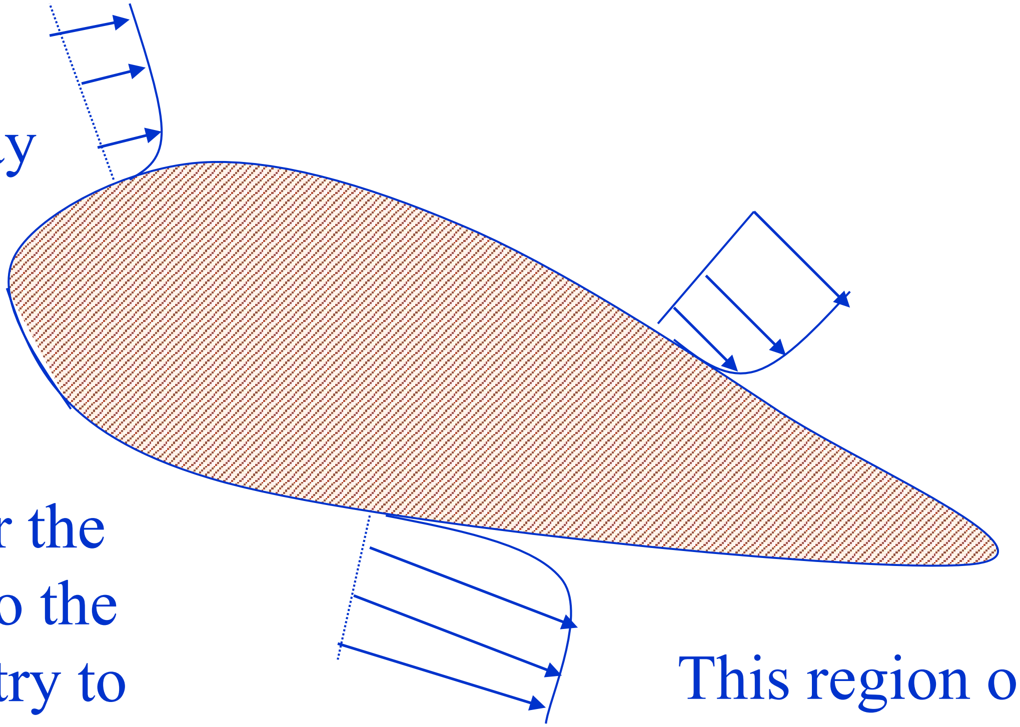
Incompressible Flow: $C_l = 2\pi(\alpha - \alpha_0)$

α is in radians

Drag is caused by

- Skin Friction - the air molecules try to drag the airfoil with them. This effect is due to viscosity.
- Pressure Drag - The flow separates near the trailing edge, due to the shape of the body. This causes low pressures near the trailing edge compared to the leading edge. The pressure forces push the airfoil back.
- Wave Drag: Shock waves form over the airfoil, converting momentum of the flow into heat. The resulting rate of change of momentum causes drag.

Skin Friction



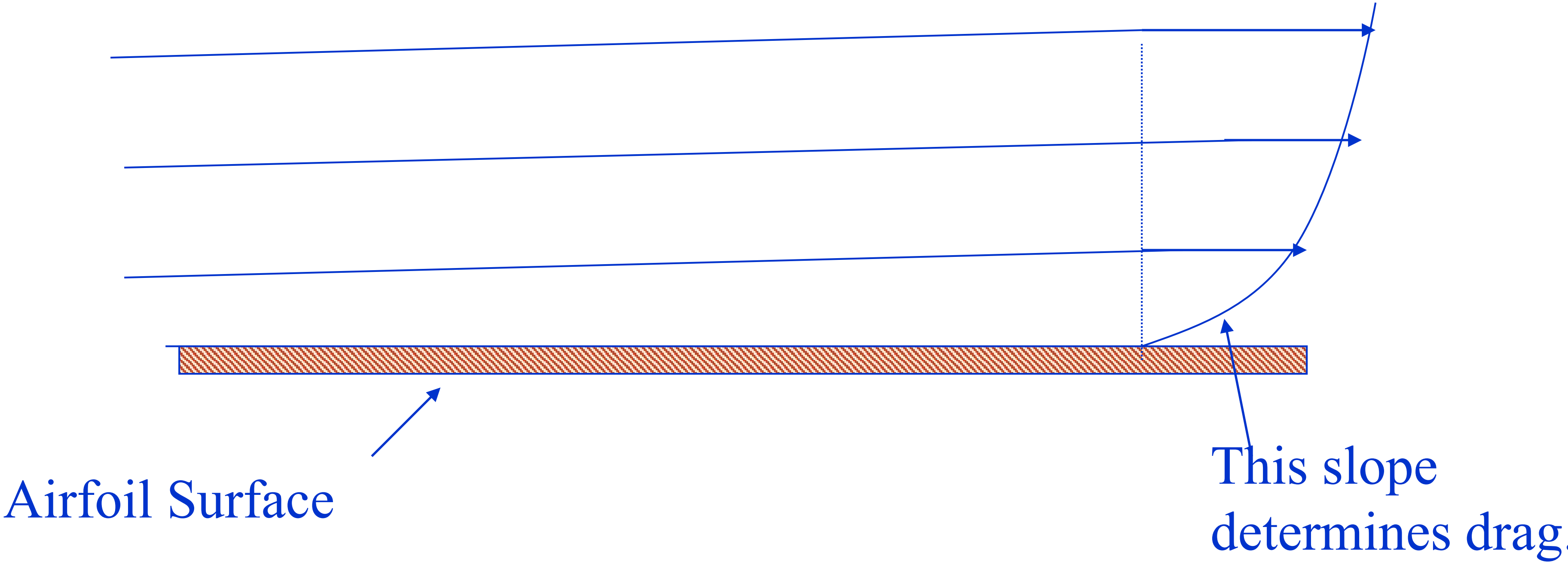
Particles away from the airfoil move unhindered.

Particles near the airfoil stick to the surface, and try to slow down the nearby particles.

This region of low speed flow is called the boundary layer.

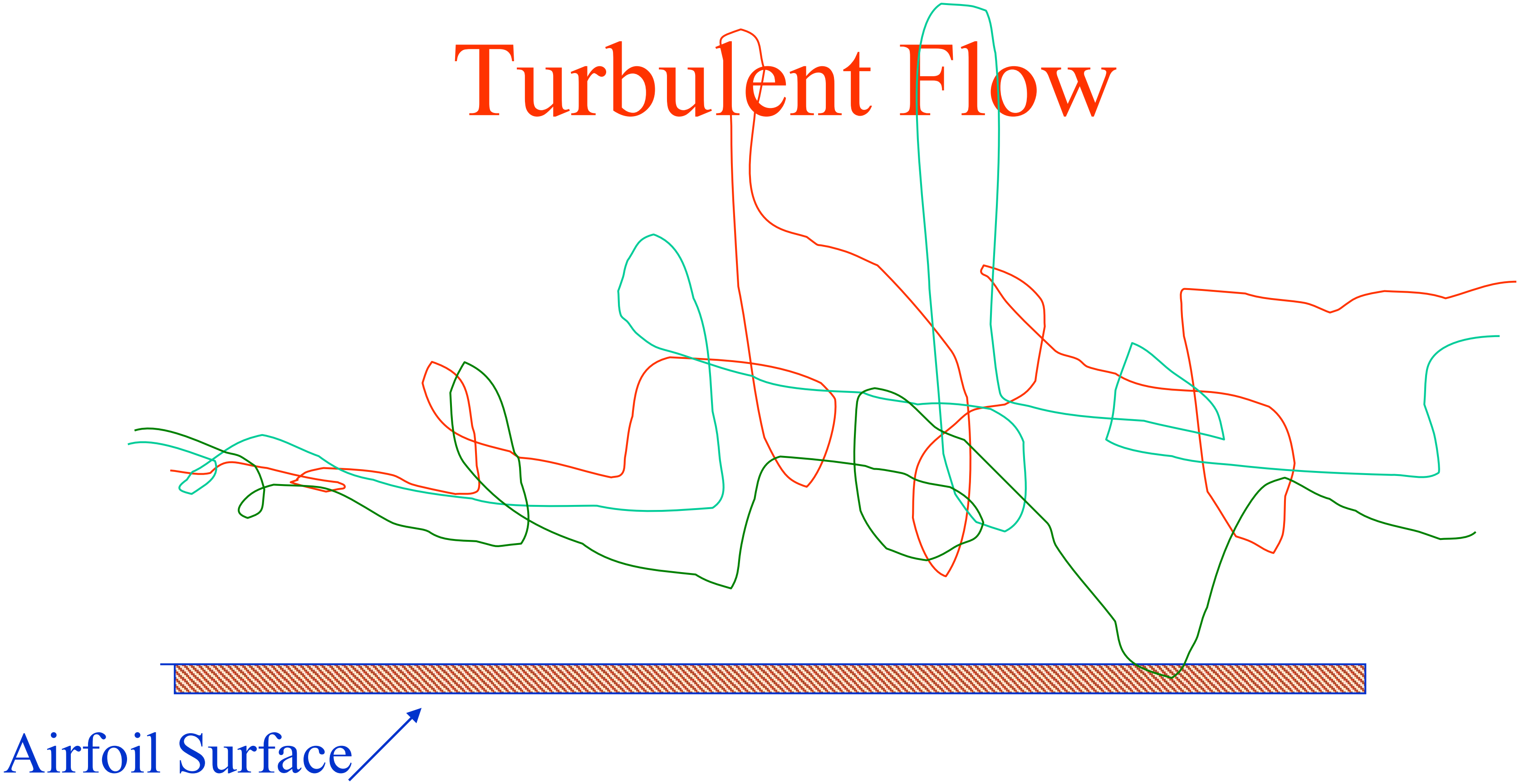
A tug of war results - airfoil is dragged back with the flow.

Laminar Flow



Streamlines move in an orderly fashion - layer by layer.
The mixing between layers is due to molecular motion.
Laminar mixing takes place very slowly.
Drag per unit area is proportional to the slope of the velocity profile at the wall.
In laminar flow, drag is small.

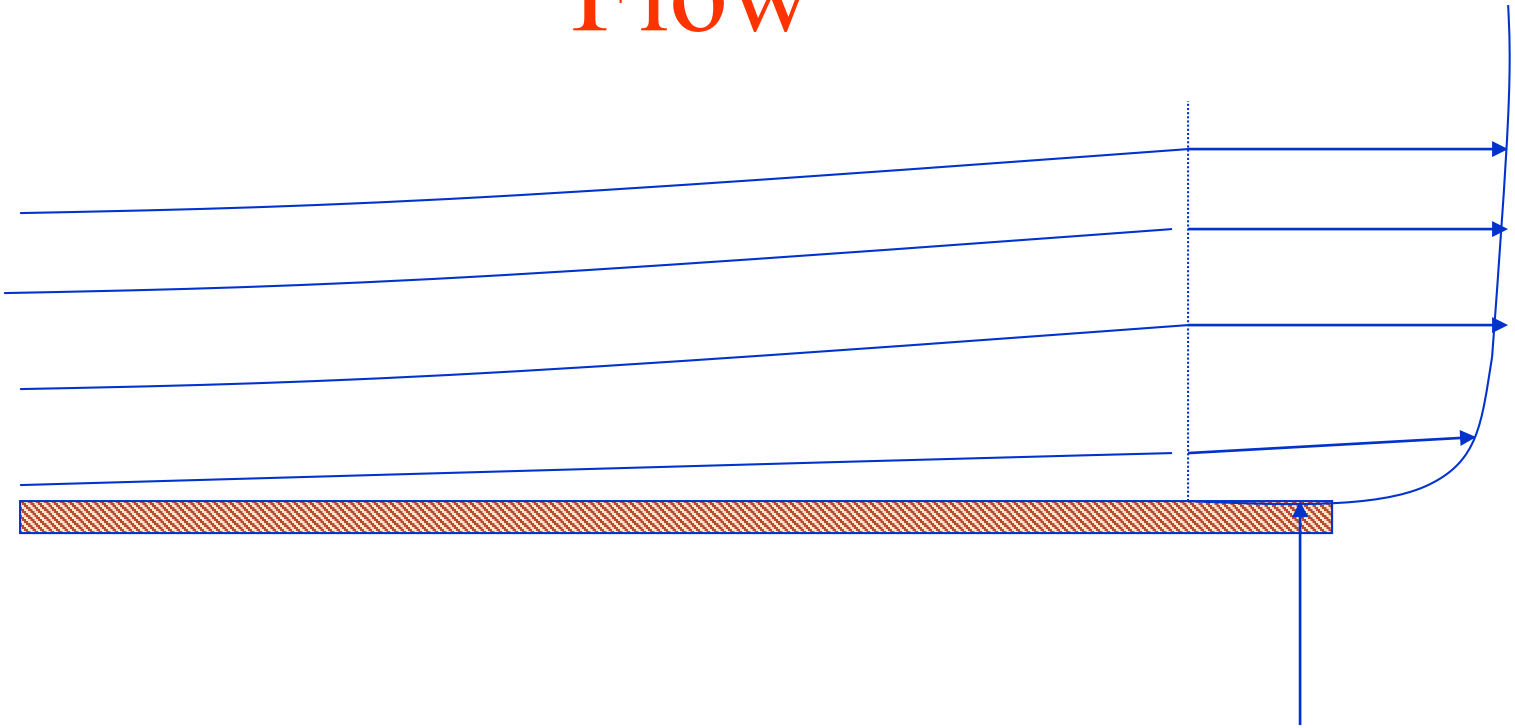
Turbulent Flow



Turbulent flow is highly unsteady, three-dimensional, and chaotic. It can still be viewed in a time-averaged manner.

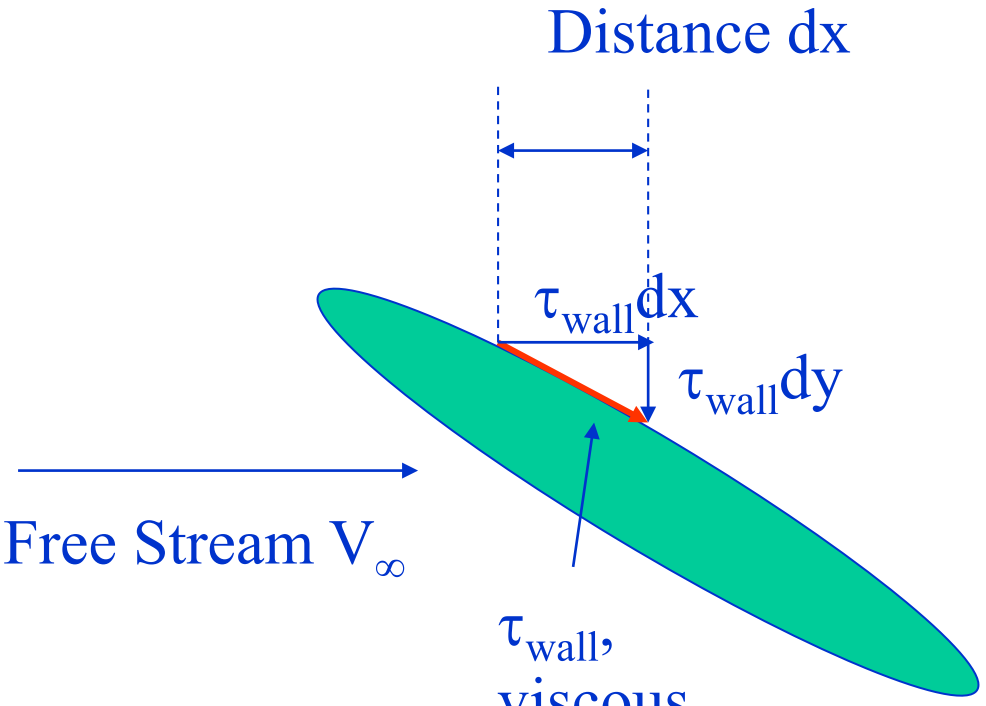
For example, at each point in the flow, we can measure velocities once every millisecond to collect 1000 samples and and average it.

“Time-Averaged” Turbulent Flow



Velocity varies rapidly near the wall due to increased mixing.
The slope is higher. Drag is higher.

Viscous Drag Force per unit Span, $D`_{viscous}$



Distance dx

$\tau_{wall}dx$

$\tau_{wall}dy$

Free Stream V_∞

τ_{wall},
viscous
stress, force
per unit
area

Viscous Drag Force per unit Span, D`$_{\text{viscous}}$

$$D'_{viscous} = \int_{\substack{\text{Lower}\\\text{Surface}}} \tau_{\text{wall}} dx + \int_{\substack{\text{Upper}\\\text{Surface}}} \tau_{\text{wall}} dx$$

If we define the skin friction coefficient $\mathrm{C_f}$ as

$$\mathrm{C_f} = \frac{\tau_{\text{wall}}}{{}^1\!/\!{}_2\,\rho V_\infty^2} \text{ and } \mathrm{C_{d,viscous}} = \frac{D'_{viscous}}{{}^1\!/\!{}_2\,\rho V_\infty^2 c}$$

where c is the chord, and V_∞ is the freestream velocity,

$$\mathrm{C_{d,viscous}} = \int_{upper} \mathrm{C_f} d\left(\frac{x}{c}\right) + \int_{lower} \mathrm{C_f} d\left(\frac{x}{c}\right)$$

Skin Friction Coefficient

- Skin friction coefficient is often analytically or empirically known for simple shapes such as flat plates.
- In our next lecture, we will present analytical/empirical expressions for skin friction coefficient, and show you how to integrate to compute the drag of flat plate like shapes.
- In the computer projects, you will learn how to use software such as XFOIL to compute the drag coefficient.
- During the early stages of airplane design, the airfoil shapes are not yet known. Thus, it is customary to use drag based on flat plate shapes as a first estimate.

In summary...

- Laminar flows have a low drag.
- Turbulent flows have a high drag.
- The region where the flow changes from laminar to turbulent flow is called transition zone or transition region.
- If we can postpone the transition as far back on the airfoil as we can, we will get the lowest drag.
- Ideally, the entire flow should be kept laminar.