Aerodynamics: Physics and Myths

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Posted at: https://charles-oneill.com

How this discussion is structured:

1) Start with an interesting question or observation.
2) Dig into the physics, TTPs, and details.
3) Zoom out and give actionable knowledge.

- Refer to a CFI/CFII, FARs, and your POH/AFM.
- This discussion may contain simplifications or errors that are not appropriate or safe for your aircraft.
- This talk discusses the physics, mathematics, and engineering and is not a substitute for a CFI.

Q: Why do airplanes fly?

This is **not** a trivial question!

- Wings generate lift. *But why?*
- Lift results from lower/higher pressure. *But why?*
- Bernoulli? Momentum? Vortex?
- **Macro**: "Bound vorticity" is lift. *What? Why?*
- **Micro**: Molecular dynamics. *How to track!?*

My intent is to give you a unique approach to aerodynamics answering this question with some physics and only a hint of math.

Fluid Flow causes Lift & Drag

Three fundamentals for fluid flow:

1. Conservation of Mass.

   Mass is neither created nor destroyed.

2. Conservation of Momentum.

   Newton's law.

3. Conservation of Energy.

   Energy is neither created nor destroyed.

"Chemical kinetics firmly restrains time's arrow in the taut bow of thermodynamics for milliseconds to millennia." — F. L. Lambert

Bernoulli Lift Myths

For low Mach # flows (and technical entropy limits)

$$P + \frac{1}{2}\rho V^2 = Constant$$

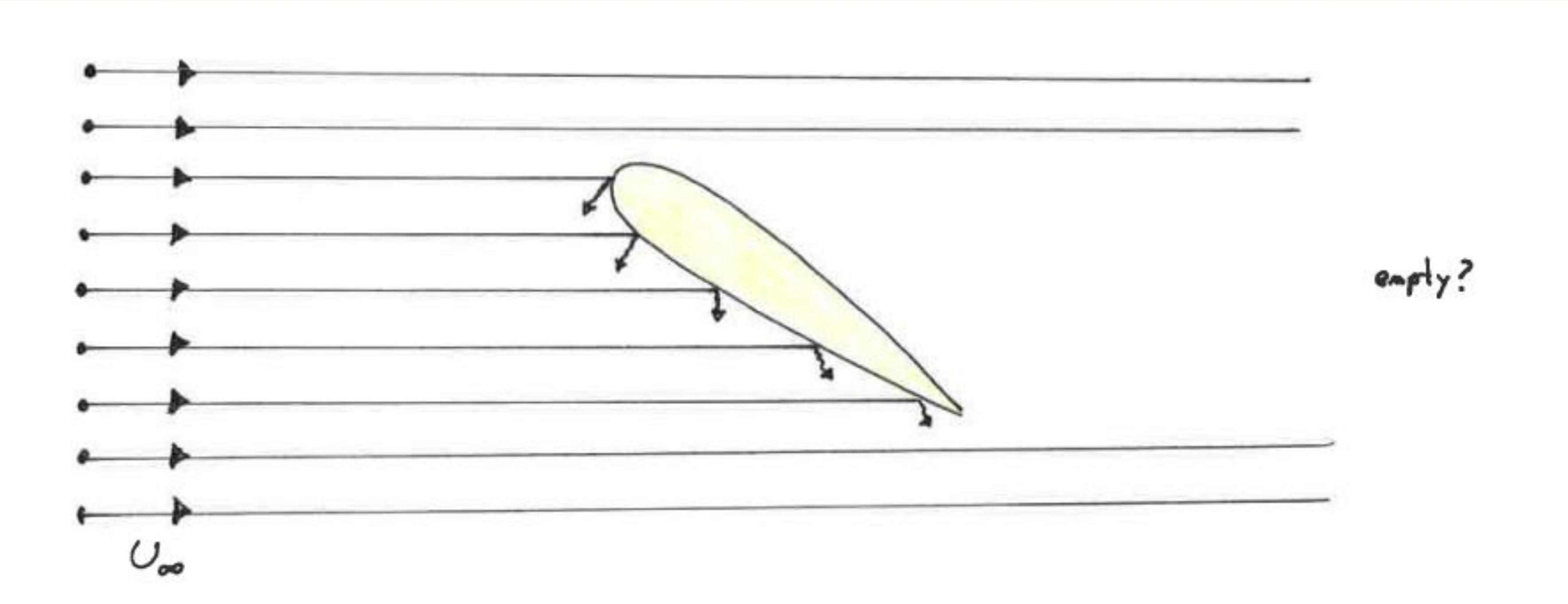
This concept does NOT provide guidance on how the pressure or velocity is changing in a flow given a specific geometry. Bernoulli has a more complicated form that is valid for more complex cases, but the same problem still exists.

The reason Bernoulli arguments are so hard to follow is that they don’t actually solve the flow field. It can’t answer:

“Why?”

Momentum Myths

- Does the deflection of air create lift? Extreme case below!



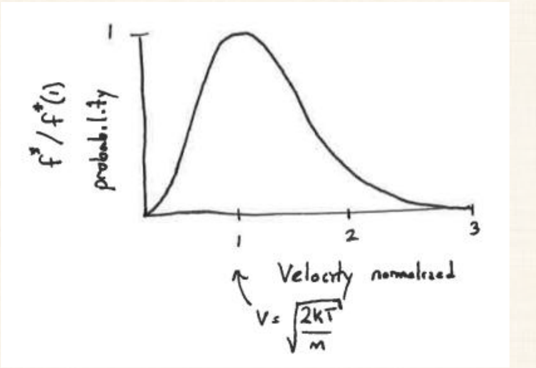
- The surprising answer is that this extreme momentum approximation IS VALID in the very upper parts of the atmosphere, but not where we operate.

Q: How many air molecules in a cubic inch?

- At STP, a mole of a gas is about 22 liters (5.8 gallons)
- Each mole has about 6.023×10^{23} items.
- Conversion gives the number of atoms per cu-in.

  450,000,000,000,000,000,000
- This is about 8 million molecules on each edge.

- Molecular collisions define the behavior of air flow!
- Ping-pong ball approximation of fluid dynamics. The balls collide and transfer/distribute energy.
- Average flow velocity = macro flow velocity
- Collision velocity = temperature
- Collision # and velocity = pressure



Flow Field Solutions

Example: Navier Stokes Equations of Fluid Flow

1. Conservation of Mass: $\frac{d\rho}{dt} + \nabla \cdot (\rho V) = 0$
2. Conservation of Momentum: $\rho \frac{dV}{dt} + \rho \mathrm{V} \cdot \nabla V = \rho f - \nabla p + \nabla \cdot \tau$
3. Conservation of Energy:

$$\rho \frac{dh}{dt} + \rho \mathrm{V} \cdot \nabla h = \frac{dp}{dt} + \dot{q} + \rho f \cdot V + \nabla \cdot (\tau \cdot V) - \nabla \cdot \dot{q}$$

A. Boundary Conditions: Geometry

B. Equations of State: Example $P = \rho RT$

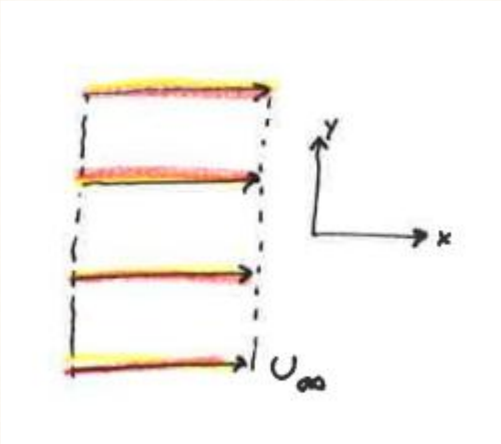
C. Closed form Viscosity & Turbulence Equations

This is how Computational Fluid Dynamics works!

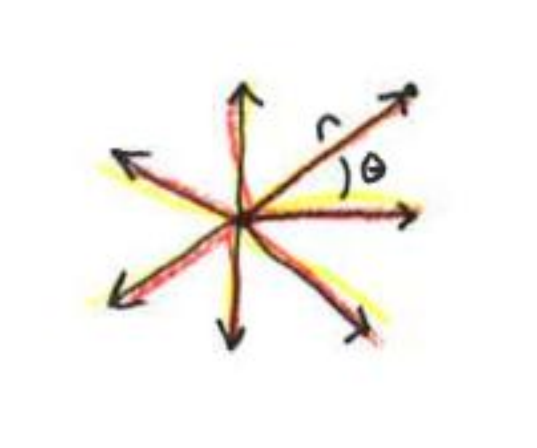
Simple Flow Field Solutions

Is there simpler approximations? Yes!

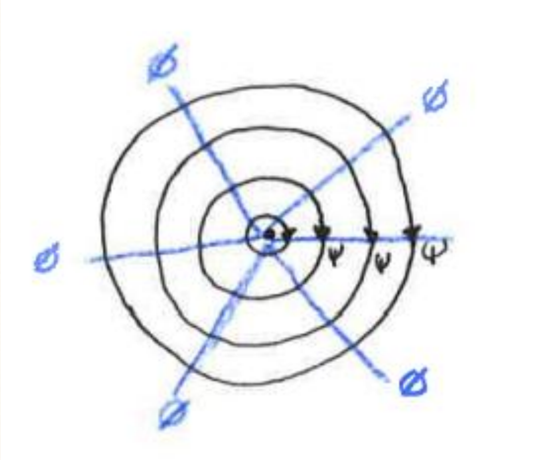
Uniform Flow



Sinks & Sources

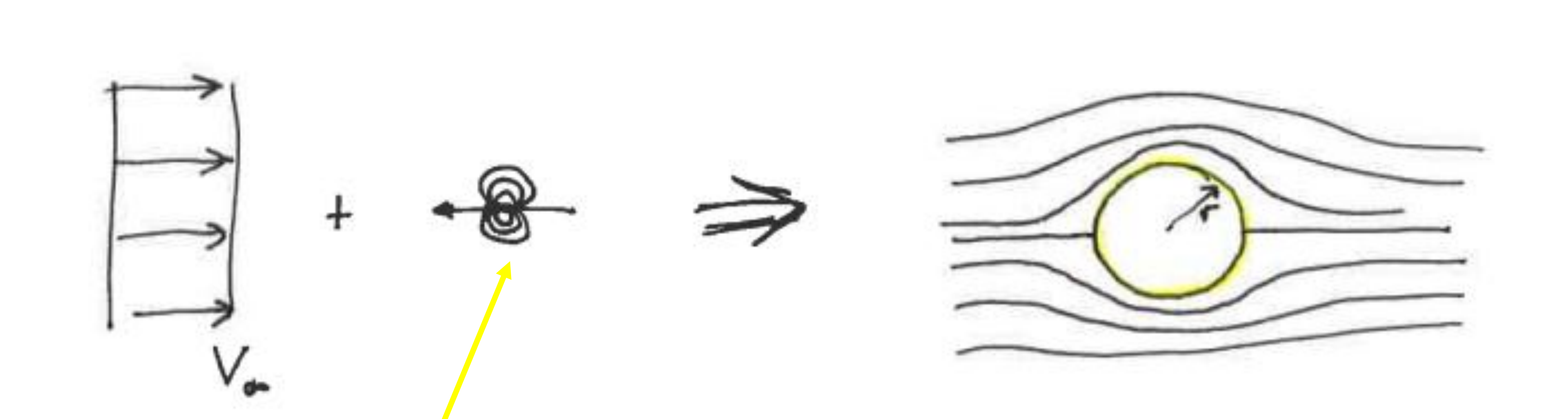


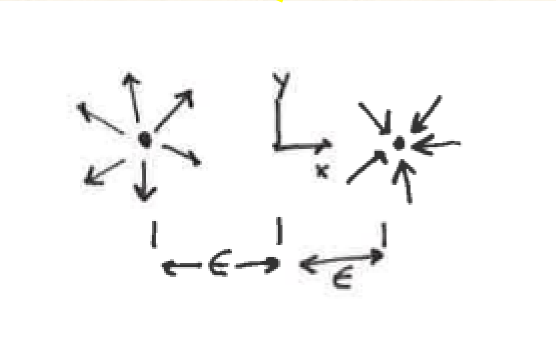
Vortex



We can combine these to approximate almost any flow!

Simple Flow Field Solutions

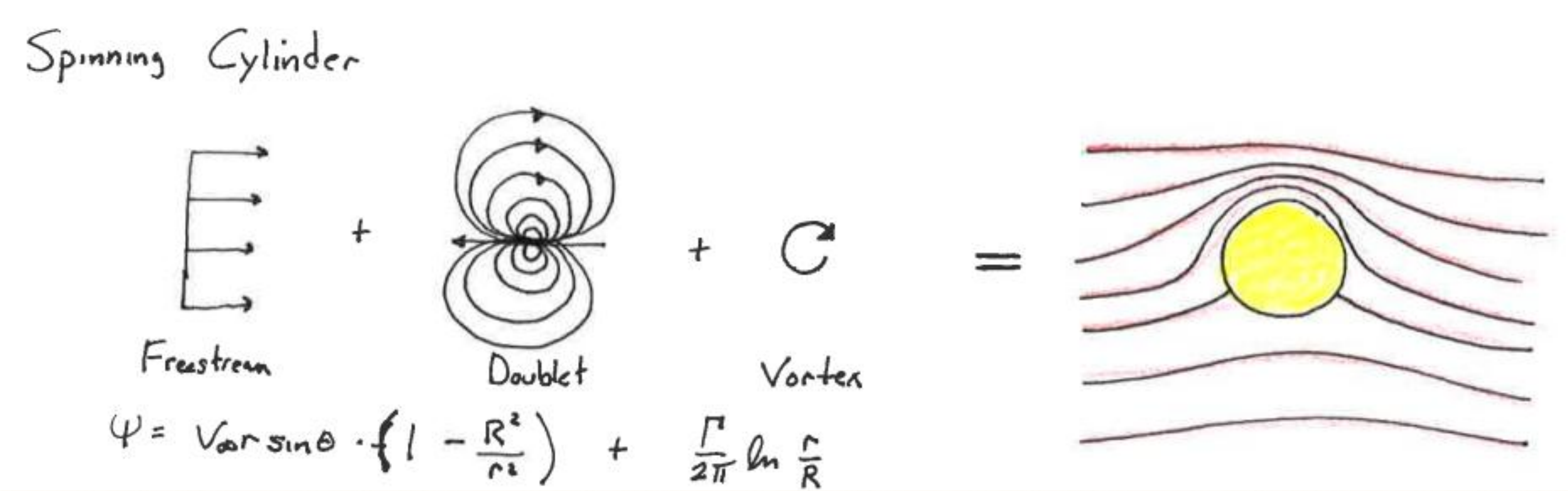




Sink + Source

A uniform flow
+ a source
+ a sink
=
Flow around a cylinder

Simple Flow Field Solutions



Uniform flow +Source +Sink

+ Vortex

=

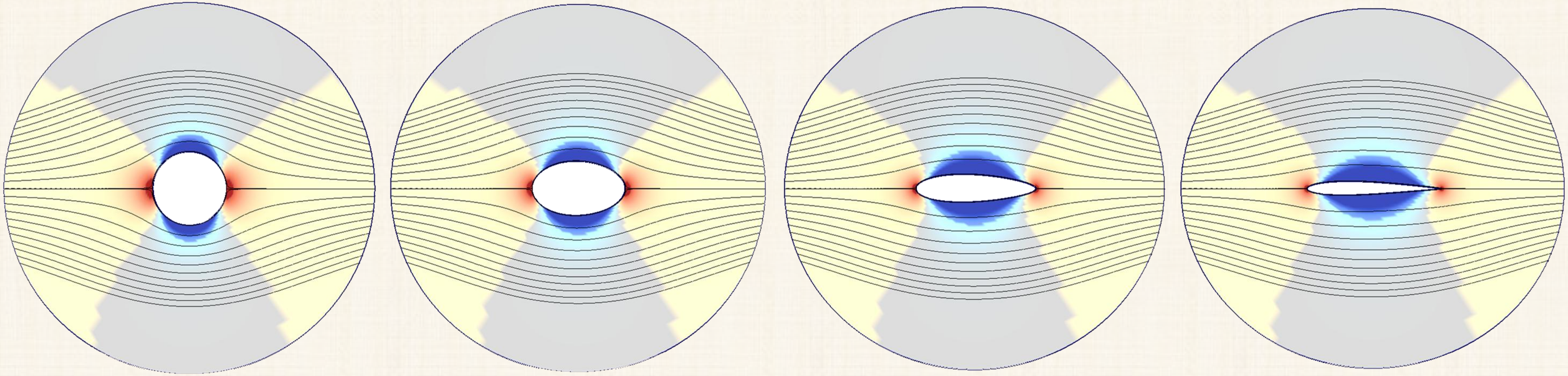
Lift around a cylinder

$$Lift = \rho V \Gamma$$

"Curveball"
"Bending"
"English"
or
"Spin"

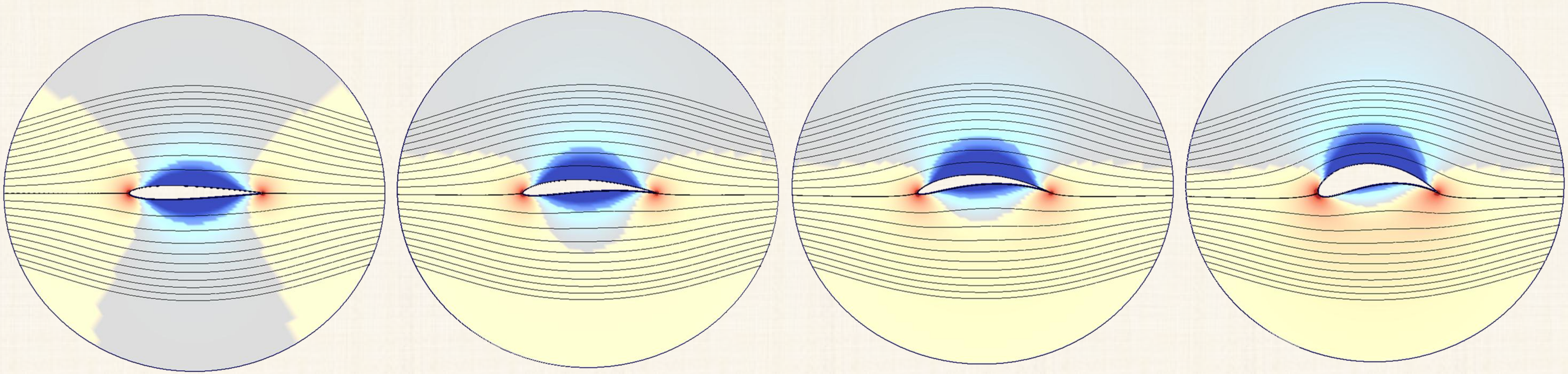
Magic! Airfoil Transformation

A circle is really a thick airfoil in disguise.

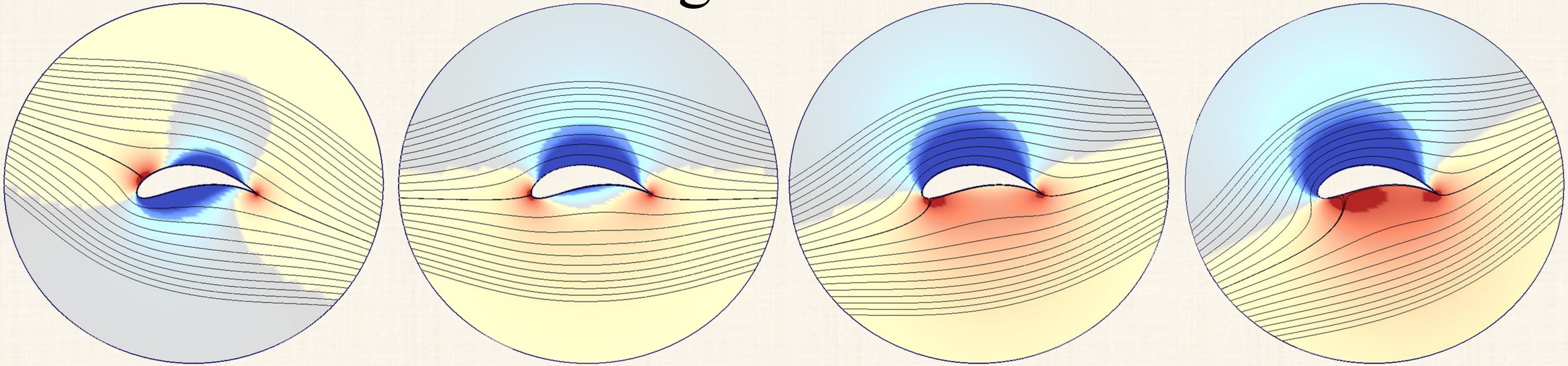


The Circle is mathematically transformed with a Joukowski complex function to a fairly generic airfoil shape including thickness and camber.

Camber and Thickness

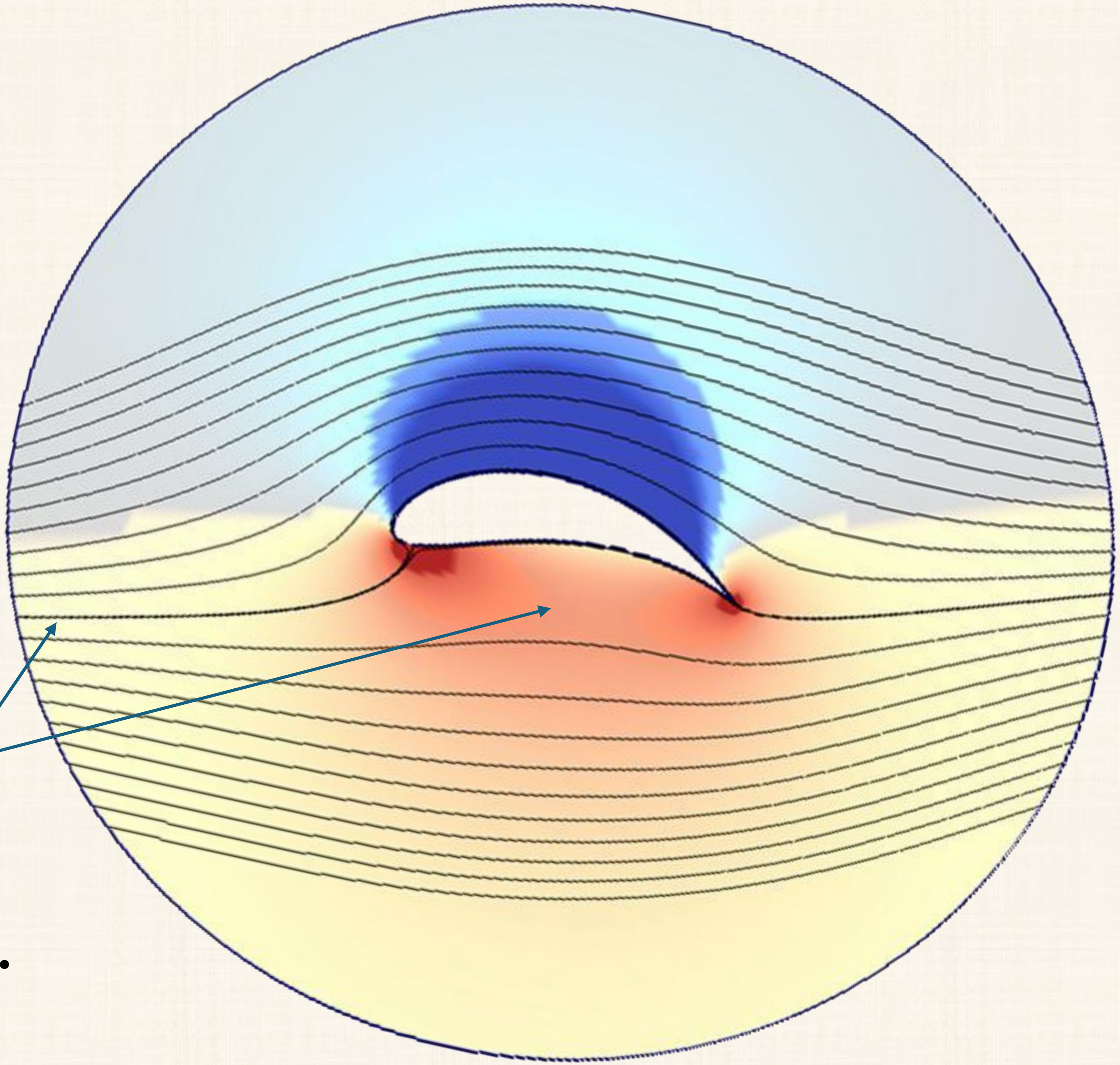


Angle of Attack.



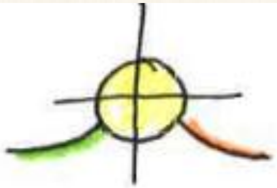
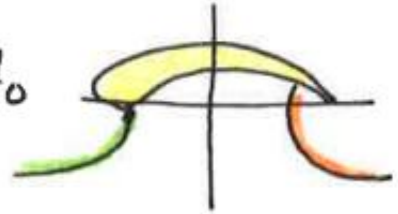
Notice that this captures:

- A vortex speeds the upper flow and slows the lower flow. Lift!
- Stream-tube width vs velocity. (low = wide)



Why? Conservation of mass. Between any two lines, a constant amount of flow rate is conserved.

Q: How much vorticity? Kutta Condition

We have  but J(z) transforms to 

To satisfy the Kutta Joukowski condition, the aft stagnation streamline must align to the trailing edge.

Why?

Real fluids have viscosity. If the TE is <u>not</u> a stagnation point, then the sharp TE generates infinite velocity/acceleration.

$$\frac{V^2}{R} = \frac{V}{1/\infty} \quad \text{undefined.}$$

A real fluid would have a separation point instantly, thus bringing the streamline back to the TE, since ω convects downstream.

Plus, K-J is what we observe in the wind-tunnel. Almost....

Kutta!

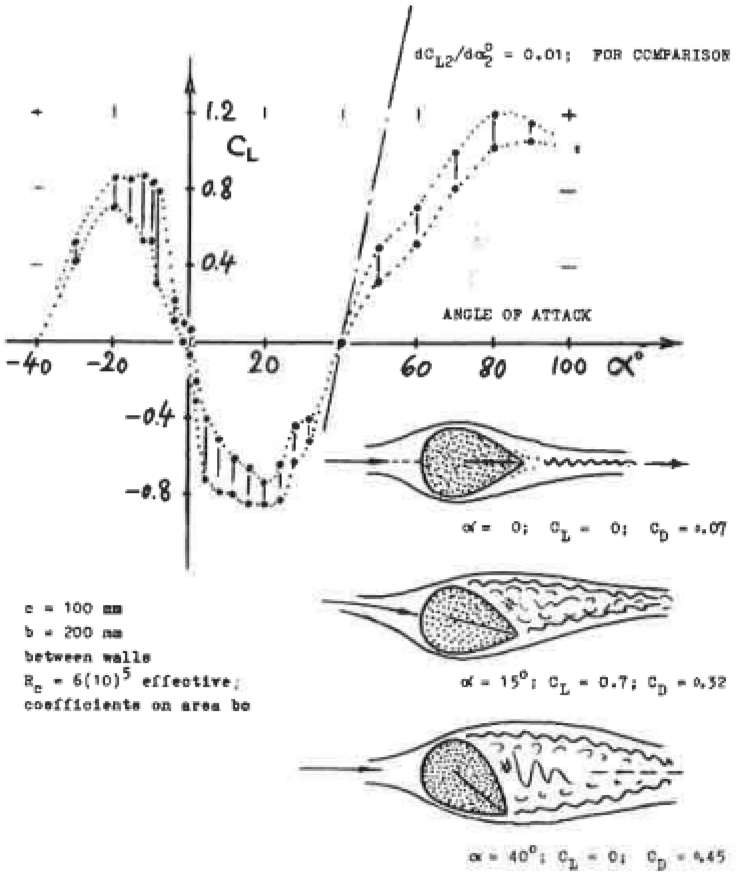
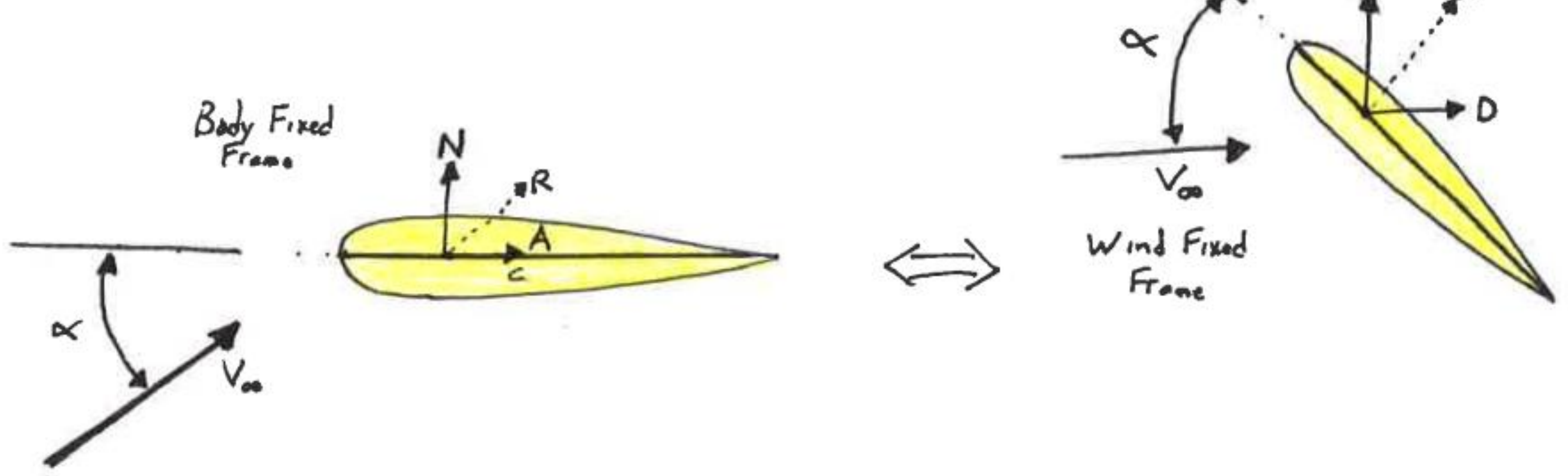


Figure 16. Lift of the extremely thick foil or strut section 0070, tested (18) to an angle of 90%. The lower and upper points plotted, correspond to the time-dependent fluctuations of the separated flow pattern. R'number above critical.

STRUT SECTION. "Streamline" sections, suitable to be applied in struts or in propeller blades near the hub, have usually higher thickness ratios than conventional foil sections. As an extreme example, the lift coefficient of an 0070 section (18) is presented in figure 16. The lift-curve slope at small angles of attack is strongly negative (!) up to $\alpha \approx 20^0$. The flow pattern proves that negative lift is the result of flow separation from the upper side of the section. As a consequence of the well-attached flow along the negatively cambered lower side of the section, suction develops there, thus producing negative lift. As the angle of attack is increased, the lower side eventually produces predominantly positive pressures and a correspondingly positive lift. Also note that the maximum lift coefficient at $\alpha = 90^0$, fluctuating between 1.0 and 1.2, corresponds to suction forces developing around the section's nose. - It is shown in (22,b) how the lift function of an airfoil with $t/c = 68\%$,

C_{l_α} is negative for $|\alpha| < 20°$!!

Aerodynamic Forces and Moments



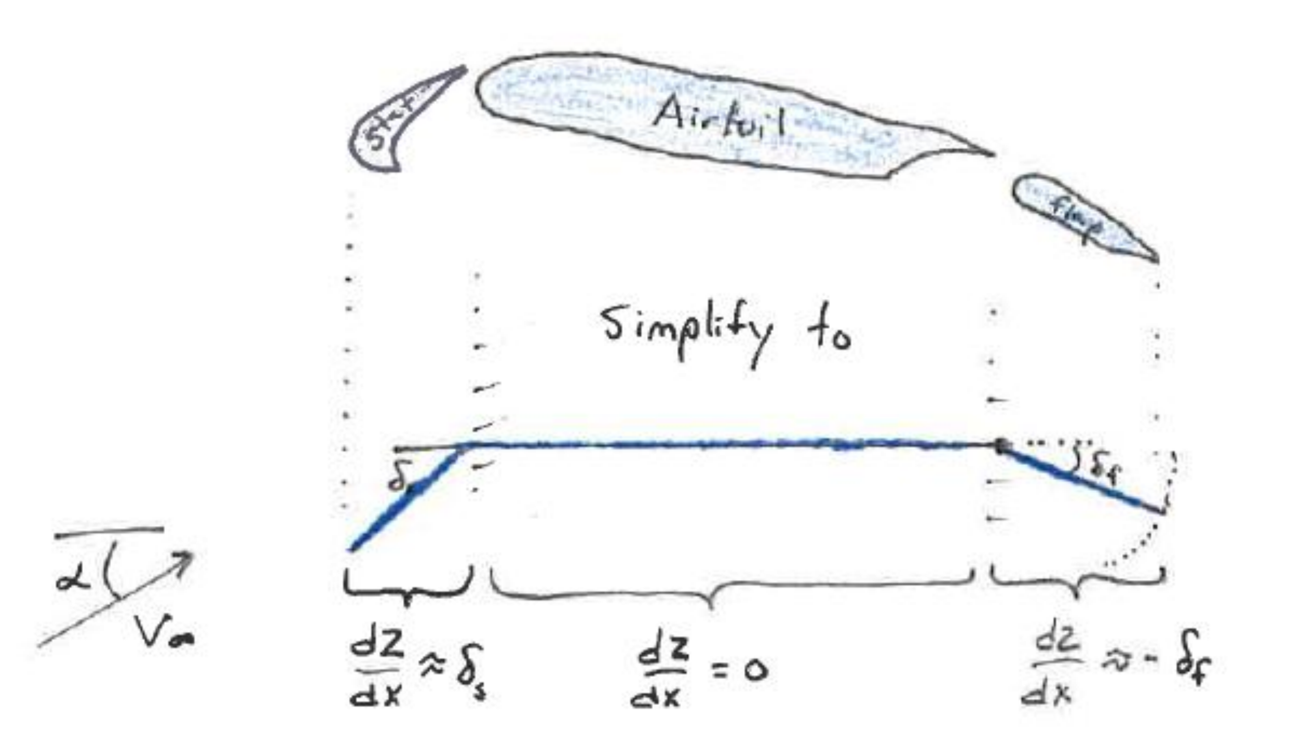
$\alpha \equiv$ angle of attack $\equiv$ "alpha"

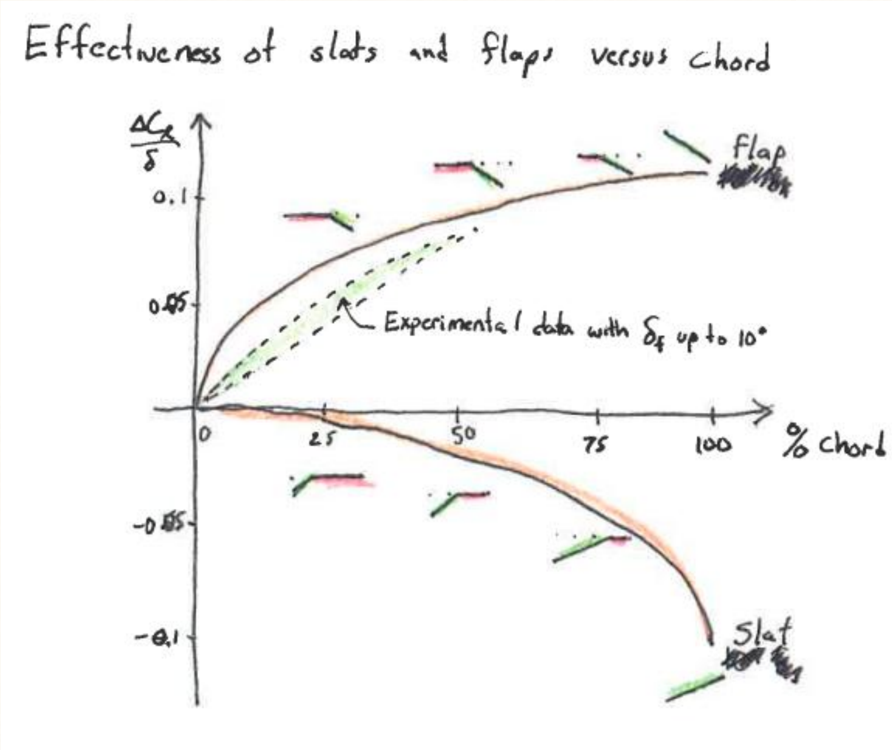
$V_\infty \equiv$ Freestream Velocity $\equiv$ "Vee Infinity"

N $\equiv$ Normal force in body fixed frame perpendicular to c
A $\equiv$ Axial force in body fixed frame parallel to c
} Body frame

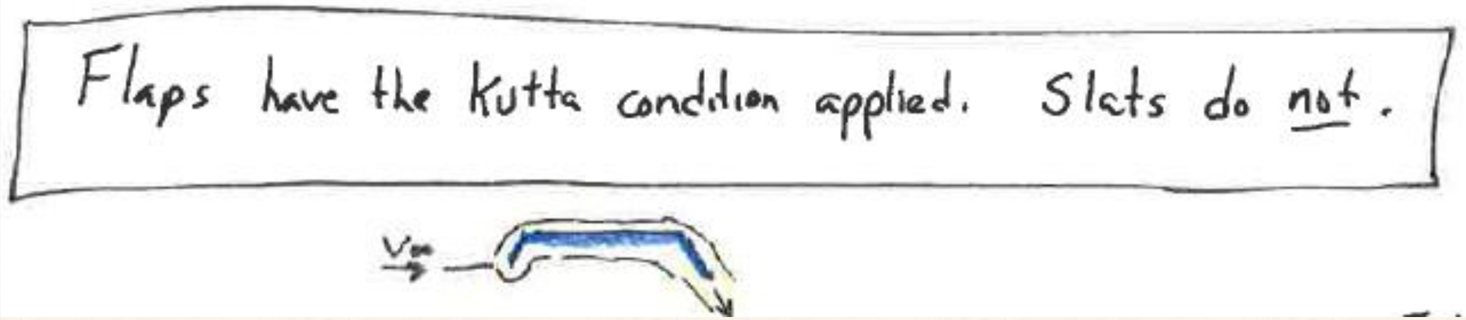
L $\equiv$ Lift force perpendicular to V_∞
D $\equiv$ Drag force ~~perpendicular~~ parallel to V_∞
} Wind frame

Airfoil with Slats and Flaps

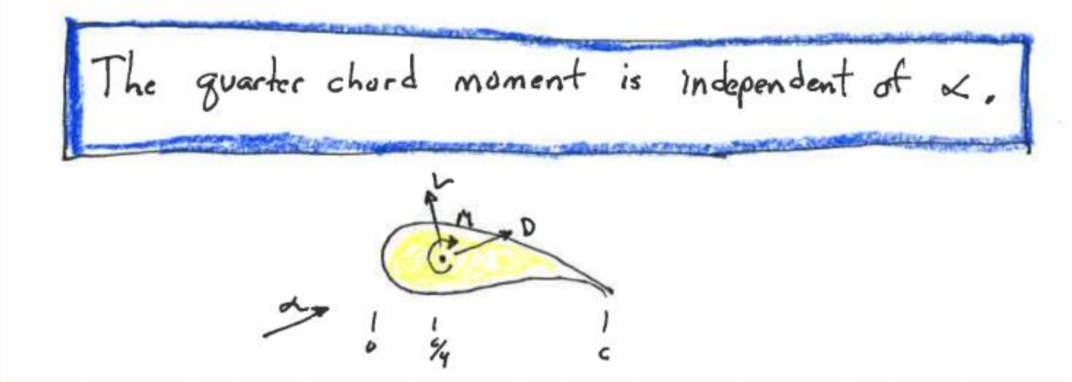


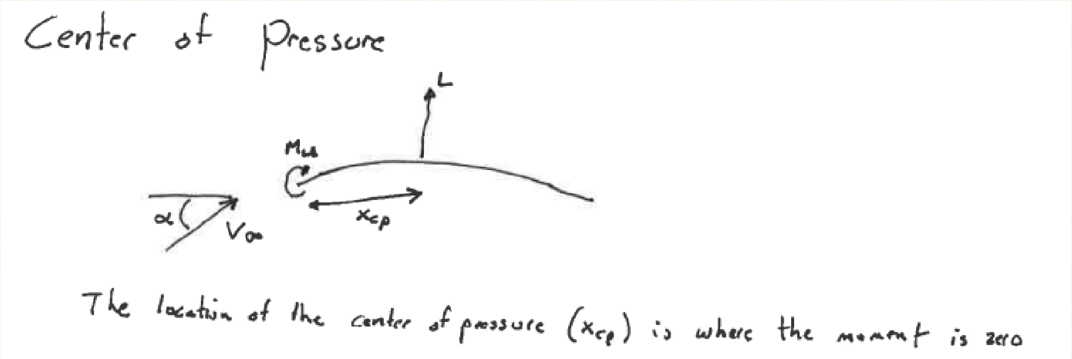


Flaps are far more effective at directly generating lift than slats.

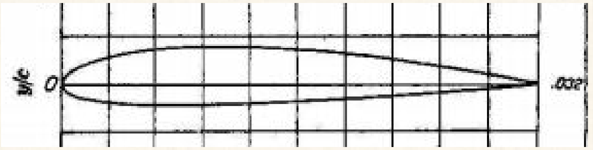


Aerodynamic Center vs Center of Pressure

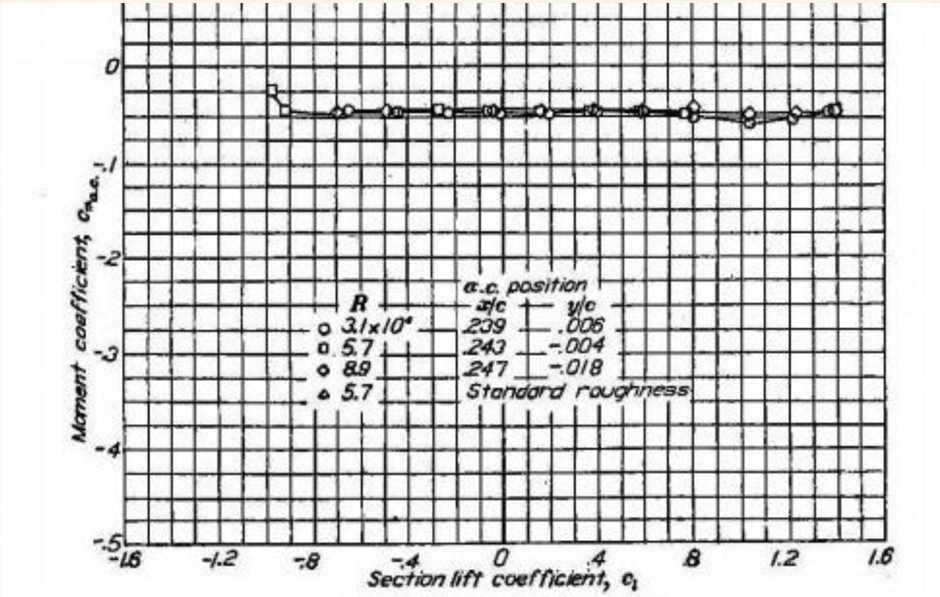




NACA 2412



$$X_{cp} = \frac{c}{4}\left(1 - \frac{4 C_{m_{c/4}}}{2\pi\alpha + C_{l_0}}\right)$$

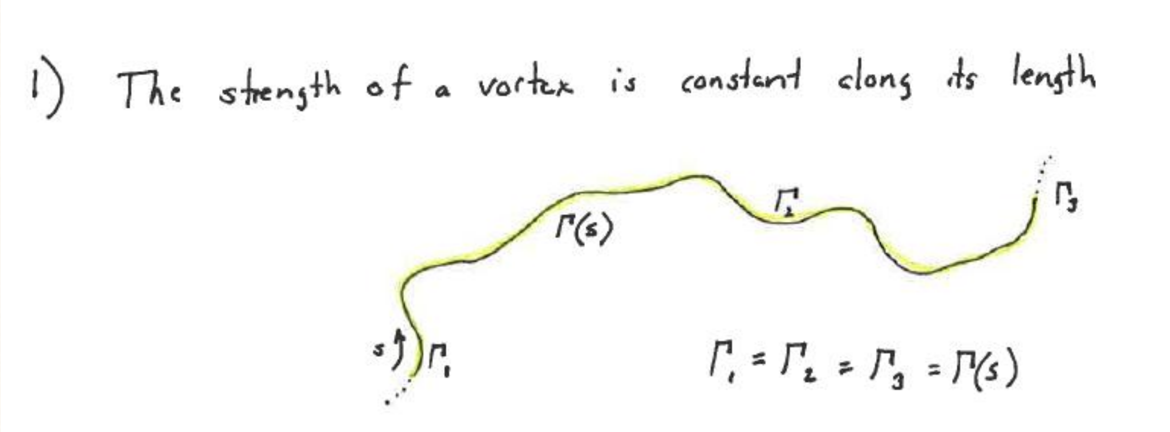


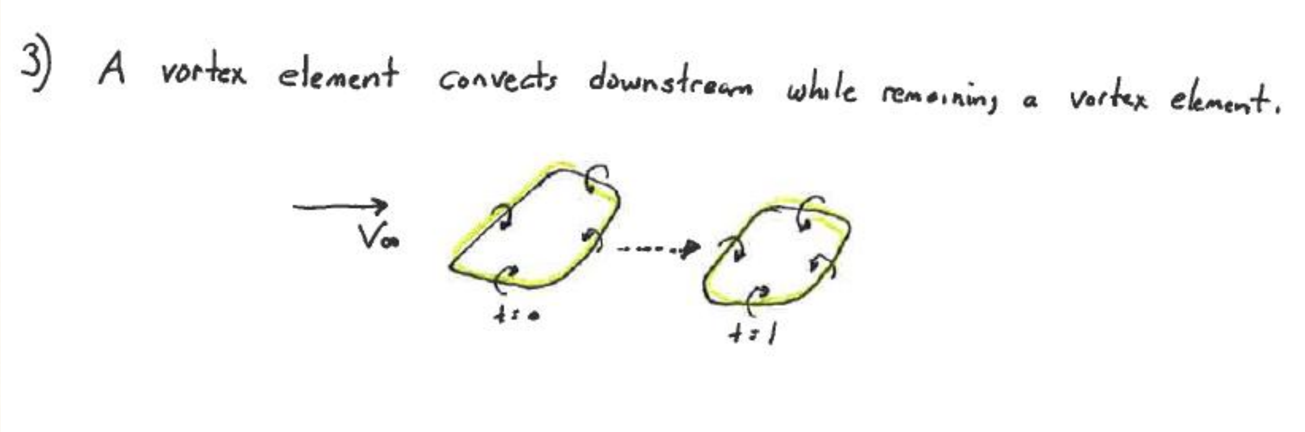
NACA 2412 Wing Section (Continued)

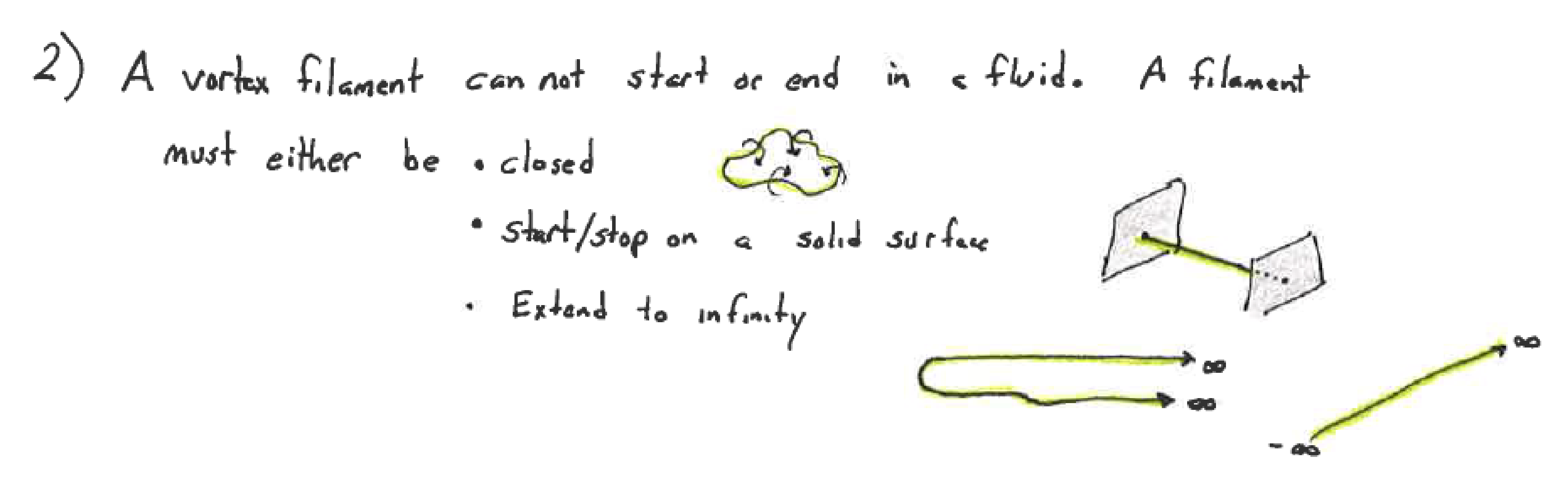
The center of pressure moves as AOA and camber change. At zero lift, the $x_{cp} = \frac{c}{4}\left(1 - \frac{4 C_{m_{c/4}}}{0}\right) \rightarrow \infty$ Not even on the airfoil!!

The FAA loves Center of Pressure, but Aerodynamic Center is much easier to see, calculate, and understand!

Vortex Dynamics: Helmholtz Rules



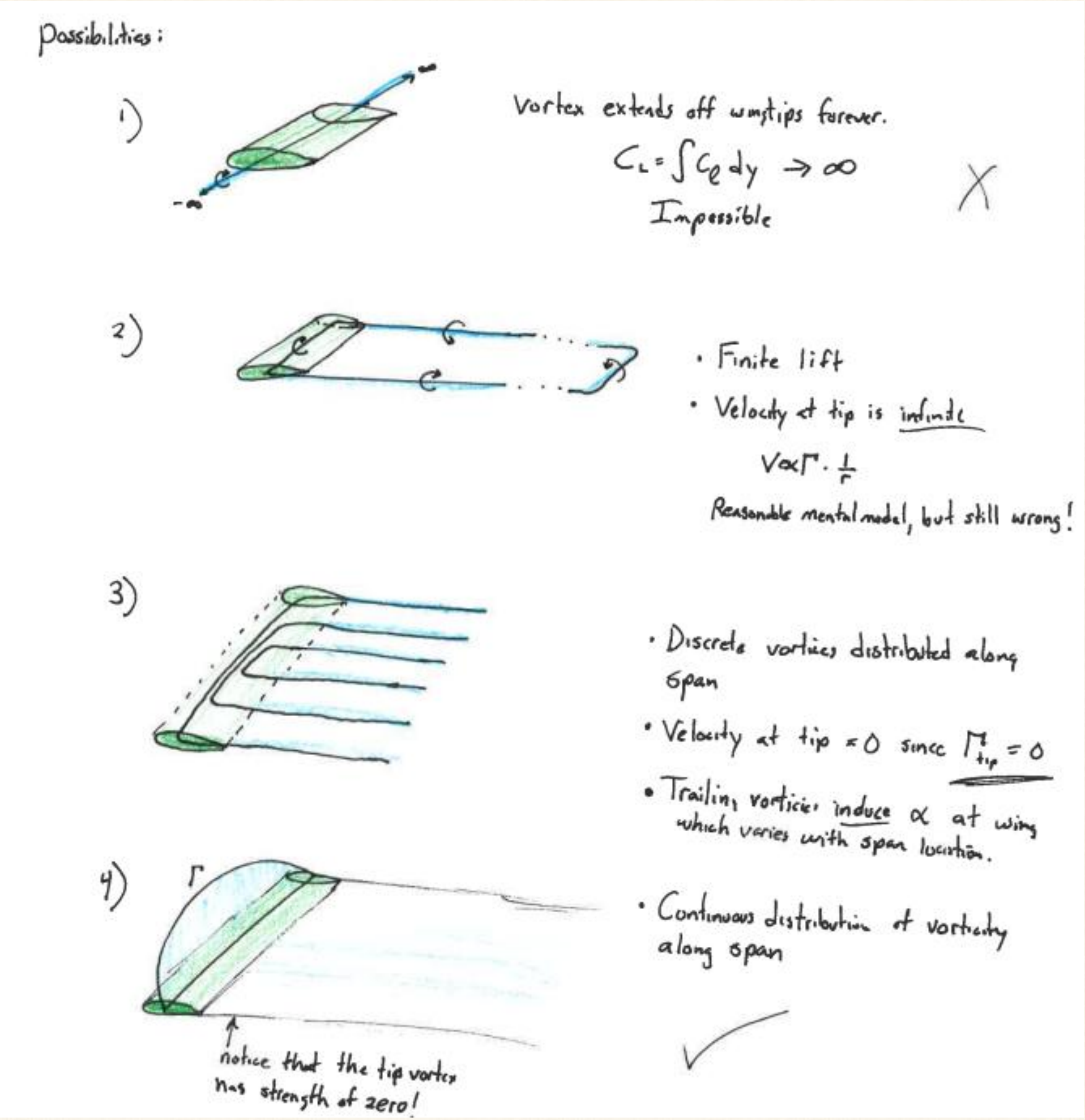


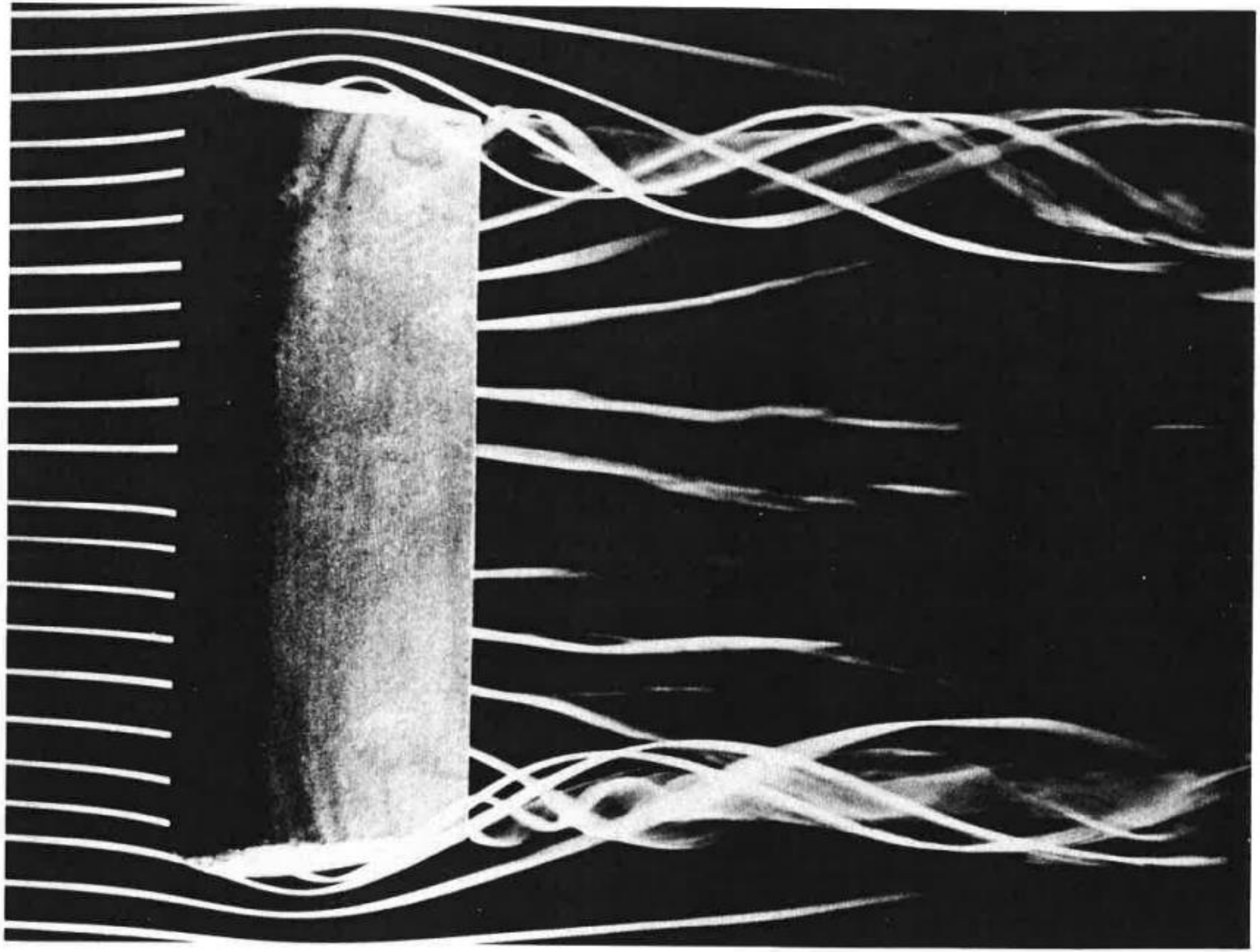


Wing Aerodynamics

The correct concept is #4.

- Bound vortex along wing
- Largest bound vorticity at wing root.
- Zero vorticity at tips
- Trailing vorticity sheet behind the wing.
- Vorticity "rolls up" into two counter-rotating vortices trailing the wing.





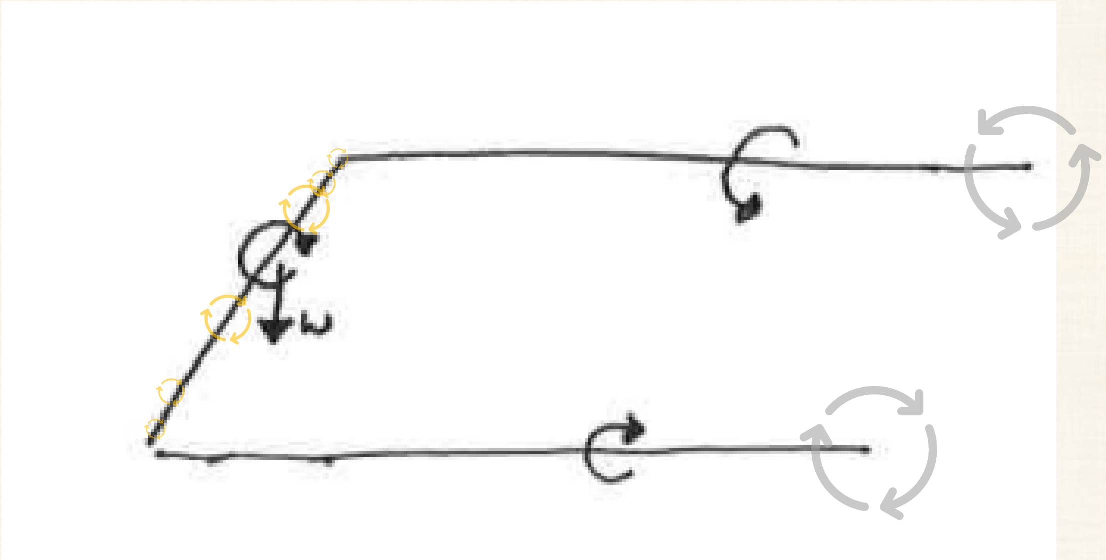
86. Trailing vortices from a rectangular wing. Suction is applied so that at 24° angle of attack the flow remains attached over the entire wing surface, in contrast to the preceding photograph. The centers of the vortex cores therefore spring from the trailing edge at the tips. The model is made of perforated metal covered with blotting paper, and tested in a smoke tunnel at Reynolds number 100,000. *Head 1982*

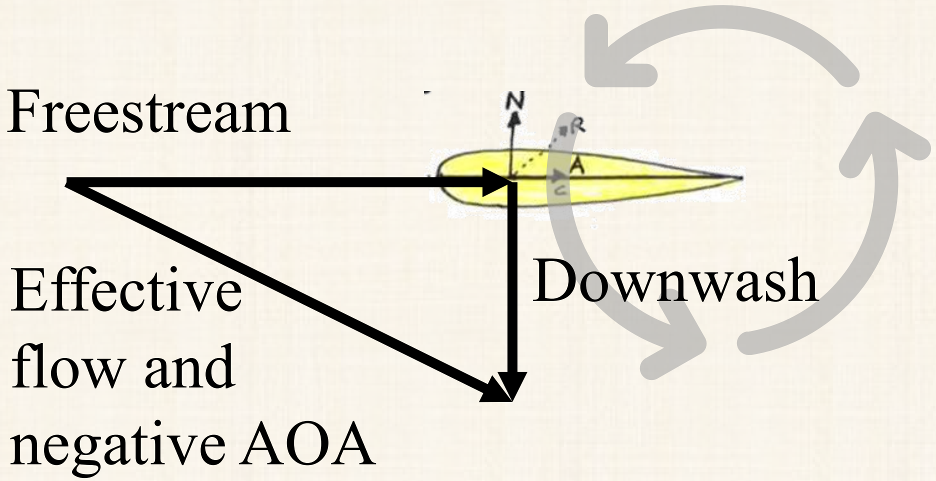
Source: An album of Fluid Motion Van Dyke

Q: What is Induced Drag?

Drag due to the creation of Lift.

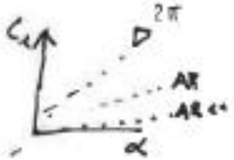
Remember that Lift requires Vorticity. This vorticity travels downstream and "induces" a downward flow.





Yes, the wing flies in a constant downdraft. That's induced drag!

The elliptical lift distribution is optimal for minimizing induced drag.



$$C_{L_\alpha} = \frac{C_{\ell_\alpha}}{1 + \frac{C_{\ell_\alpha}}{\pi AR}}$$

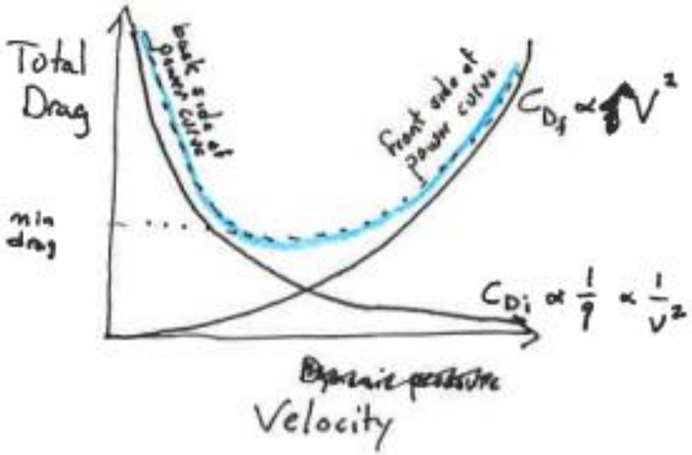
Reducing AR reduces lift slope to away from 2D value.

$$C_{D_i} = \frac{C_L^2}{\pi AR e}$$

where e=1 for elliptic only

Induced drag depends on lift squared and the inverse of AR.

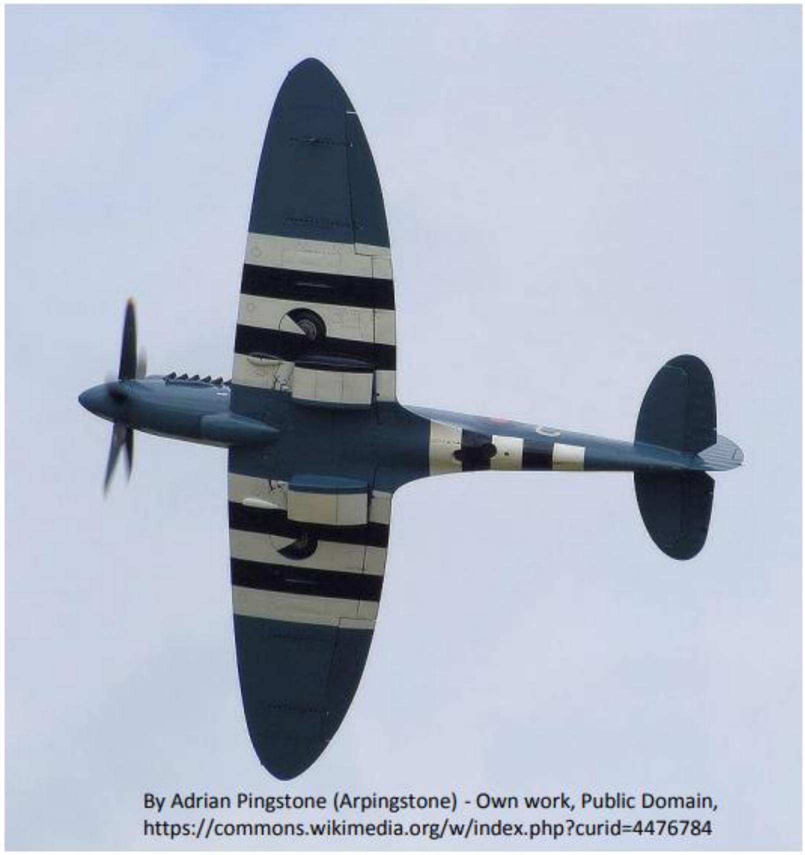
$$= \frac{\left(\frac{L}{b}\right)^2}{q^2 \pi e} = C \frac{(\text{Span loading})^2}{(\text{dynamic pressure})^2}$$



Non-Elliptical distributions have an "e" value are essentially a ratio of actual to elliptical performance

$$e_{\text{non-elliptical}} < e_{\text{elliptical}} = 1$$

Supermarine Spitfire



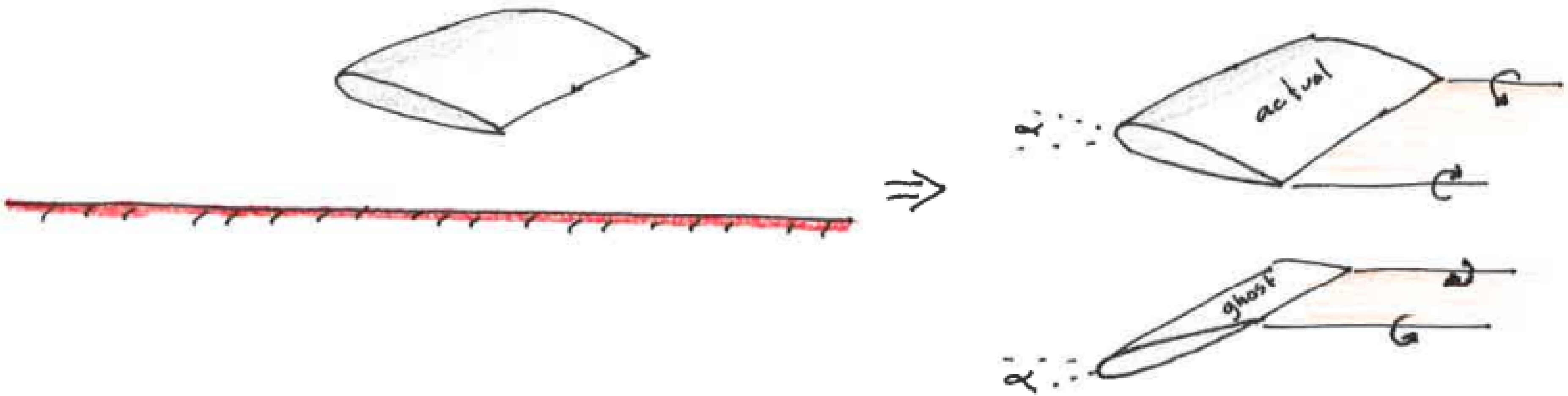
By Adrian Pingstone (Arpingstone) - Own work, Public Domain, https://commons.wikimedia.org/w/index.php?curid=4476784

Ground Effect:

Near the ground, a wing becomes more efficient.

$$C_D = K_{eff} C_L^2 \quad \text{with} \quad \frac{K_{eff}}{K} = \frac{33\left(\frac{h}{b}\right)^{1.5}}{1 + 33\left(\frac{h}{b}\right)^{1.5}}$$

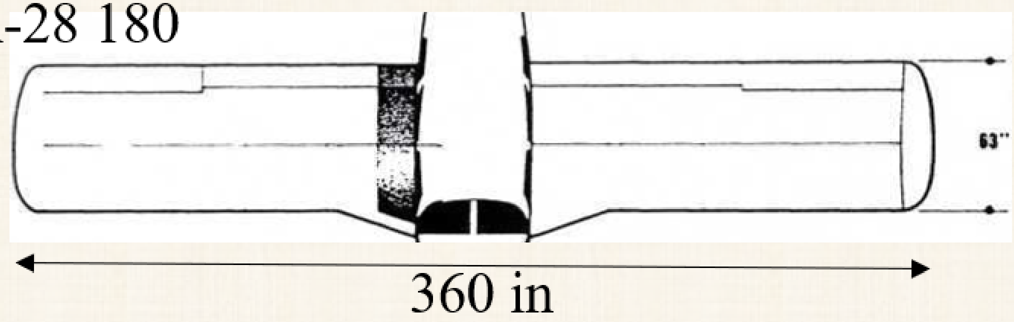
We can model this with a ghost image of a wing below the surface



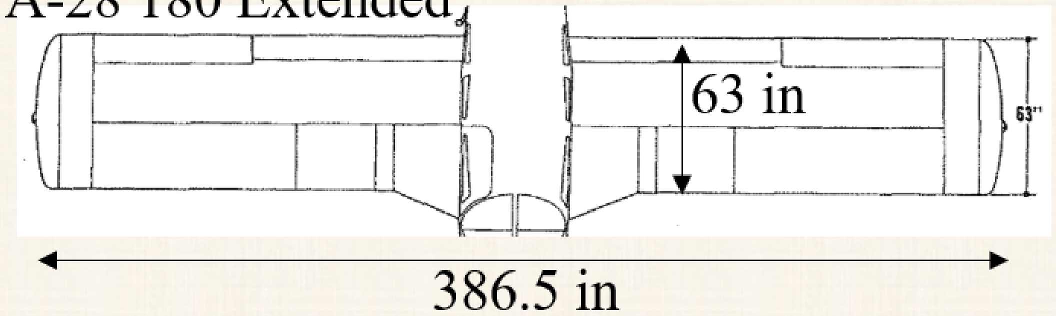
- In effect (pun intended), the downwash is prevented from passing through the ground

A comparison of Piper PA-28 models

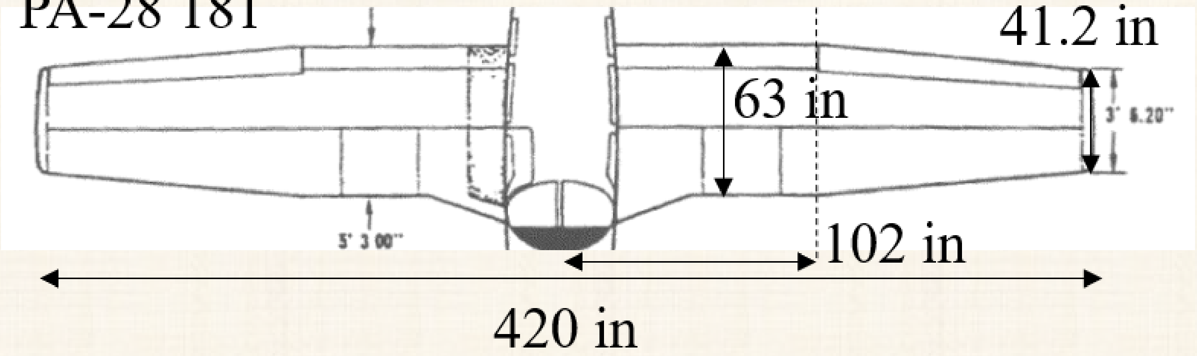
PA-28 180



PA-28 180 Extended



PA-28 181



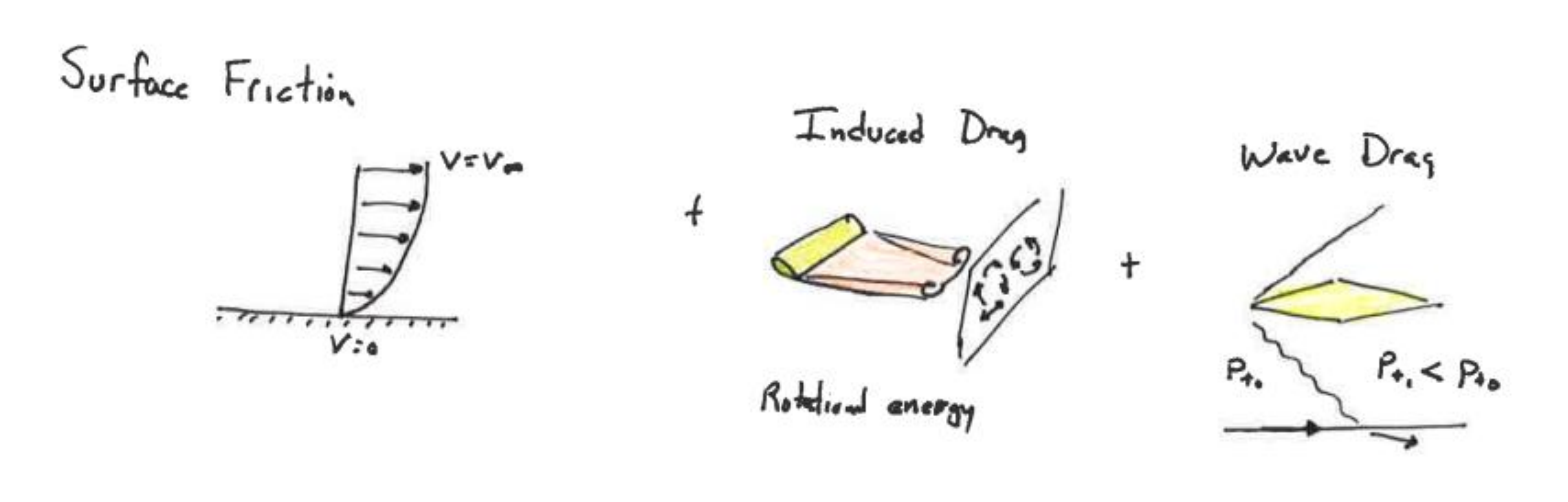
Gathering these results, the extended wing PA-28 has about 75% of the drag of the short wing PA-28 at touchdown.

The tapered wing has about 60% of the drag of the short wing PA-28 at touchdown.

Additionally, the overall induced drag for all variants of the Cherokee is reduced more than 50% when in ground effect.

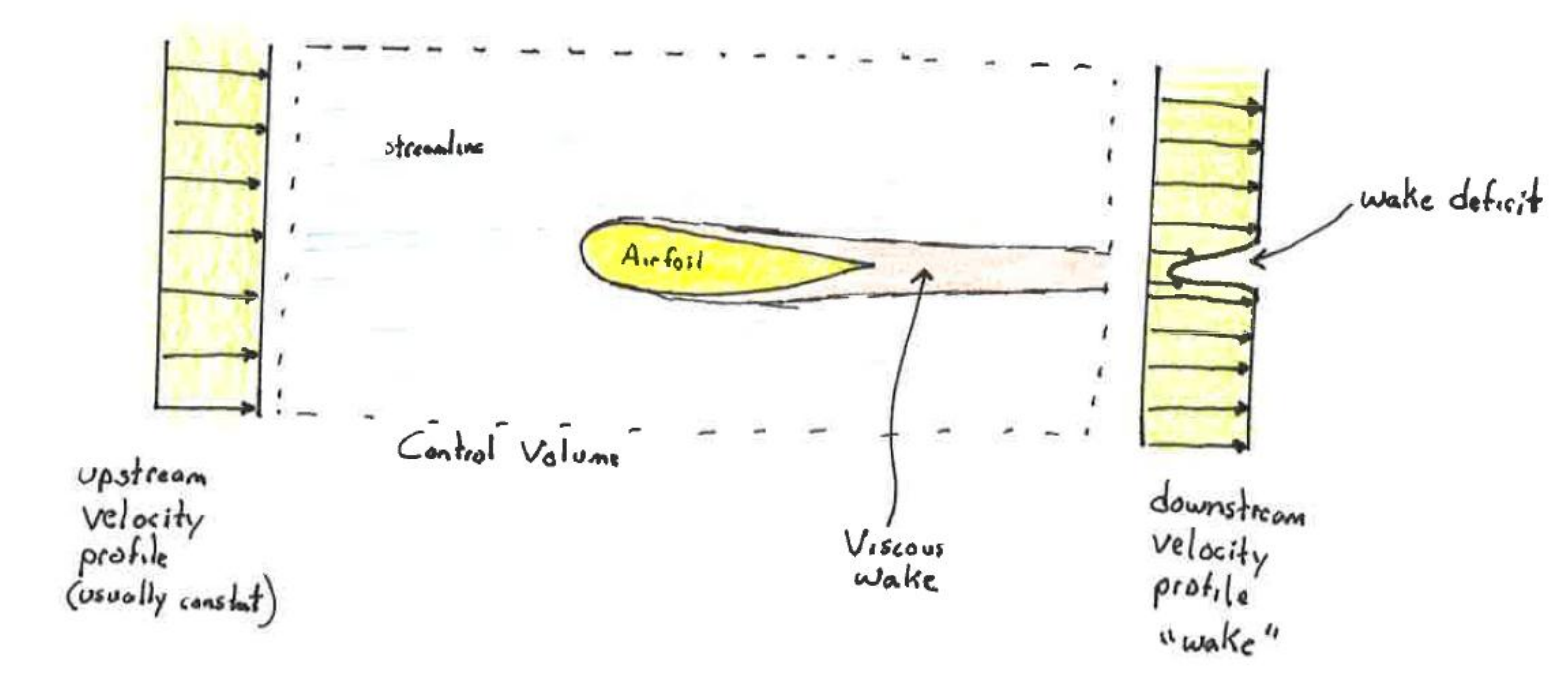
https://charles-oneill.com/blog/cherokee-tapered-wing-float/

Q: What are 3 forms of drag?



"Dragging fluid" "Create Rotating Flow" "Shocks"

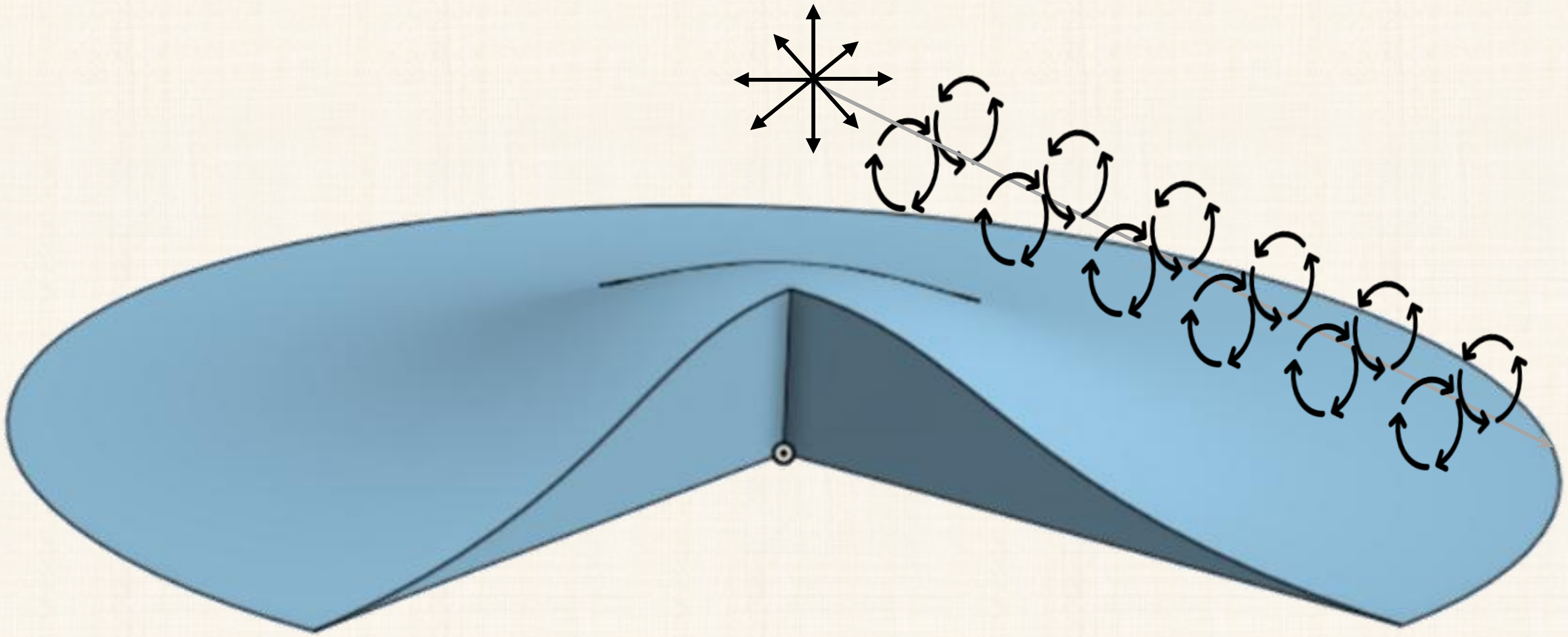
Airfoil Drag



Q: Can you weigh a flying aircraft?

https://www.youtube.com/watch?v=hnvtstq3ztl

Yes! Look at the zoomed-out pressure pattern of an aircraft, which we conceptually view as a freestream + doublet (aircraft shape) + vortices (lift).



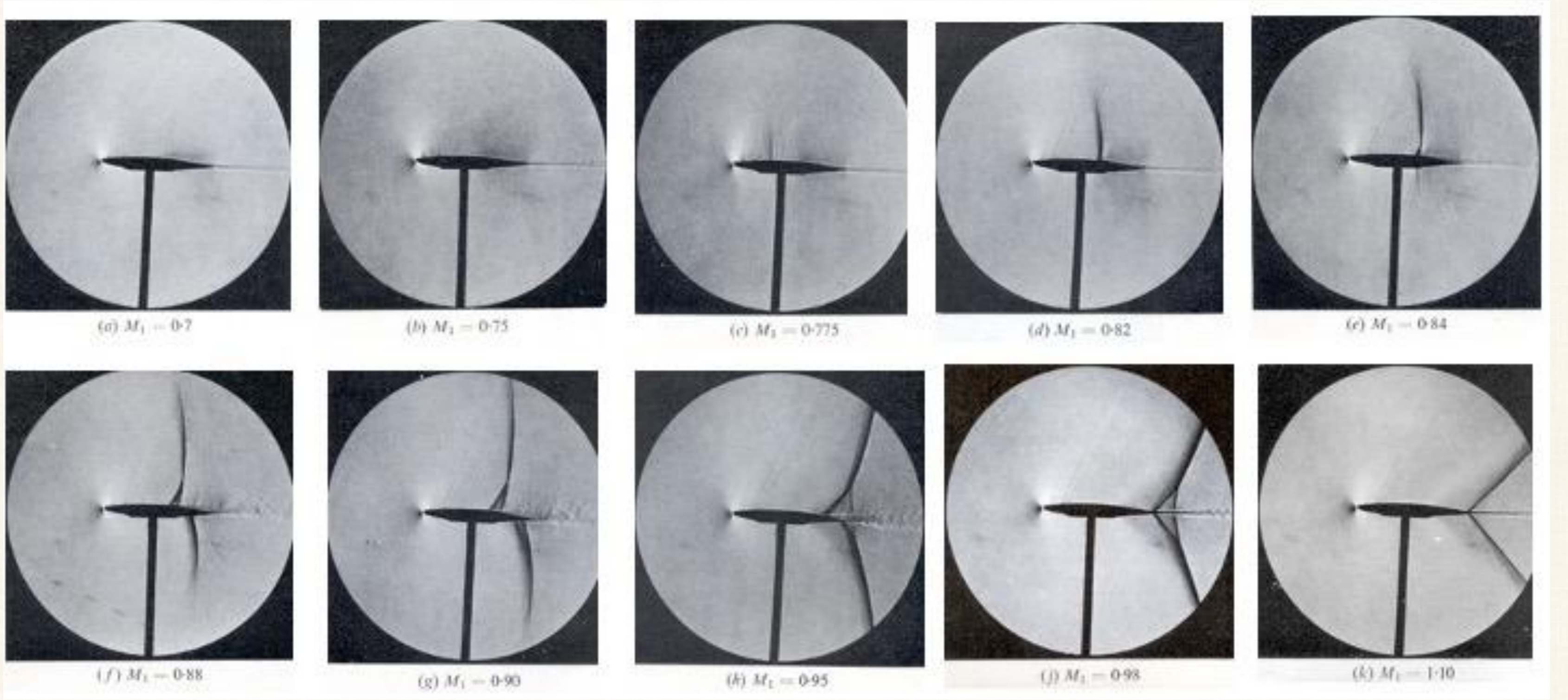
Overpressure on Ground: tiny but measurable!

Compressible Aerodynamics

Subsonic compressible flow is a variation of incompressible (Low Mach #) flow, but the density changes with velocity.

Density change: $\frac{\mathrm{d}\rho}{\rho} = -\frac{M^2}{V}\frac{dV}{ds}$

As the Mach number increases, the density rapidly varies. These variations eventually become shocks.



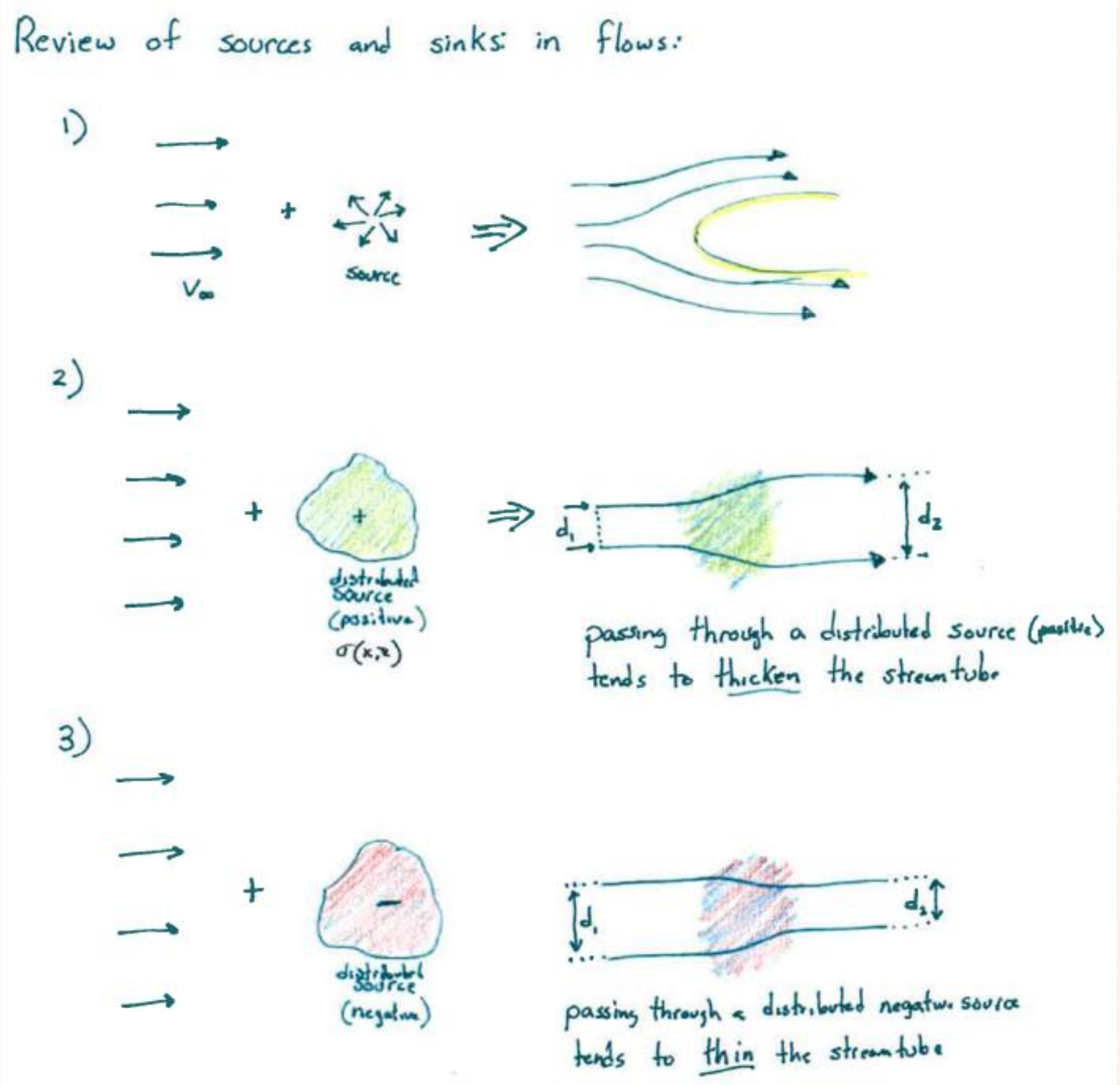
Mechanics of Fluids, Duncan, Thom, and Young.

The source/sink concept also applies! Some math from above:

Source Term: $\sigma = M^2 \frac{dV}{ds}$

When the air is accelerating (dV/ds > 0) the air behaves as if more flow is being added! This thickens the stream-tubes.

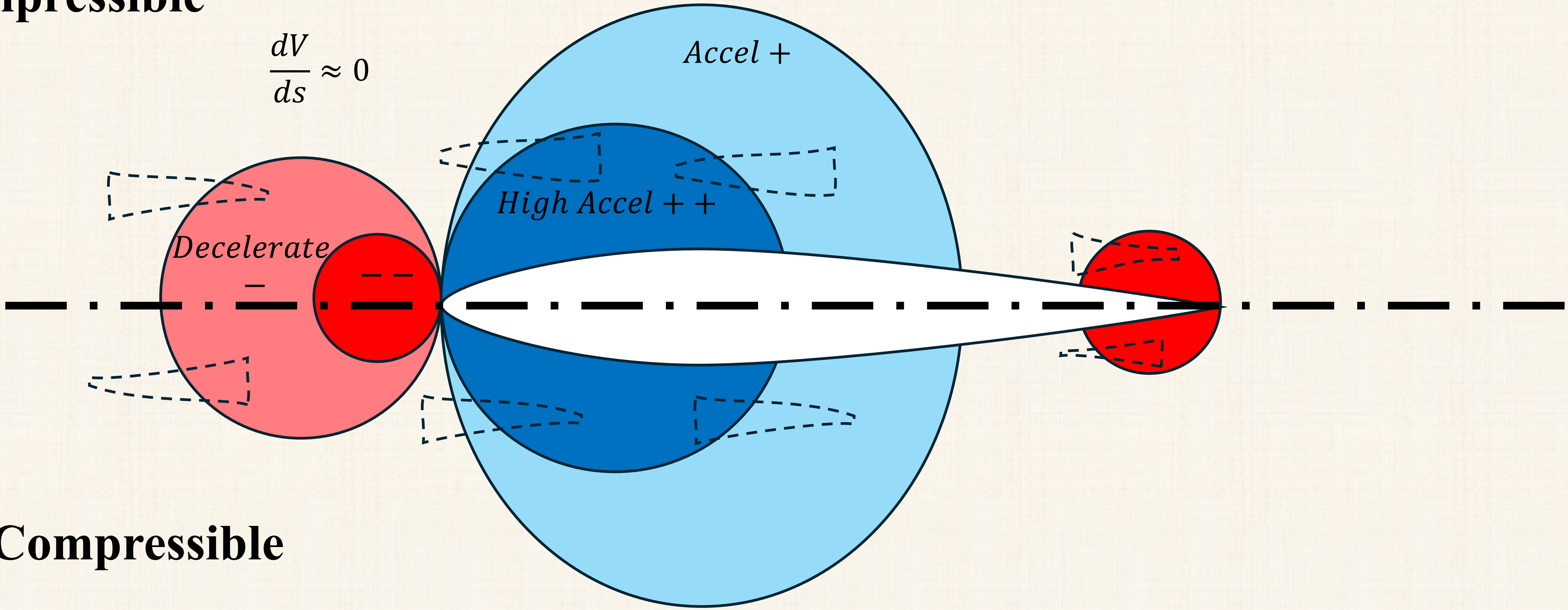
Generally, compressible flows tend to magnify both variations and the distance at which those variations act.



Conceptual Airfoil Velocity & Compressibility

$\sigma = M^2 \frac{dV}{ds}$ Says to add width when accelerating and remove width when decelerating

Compressible



In-Compressible

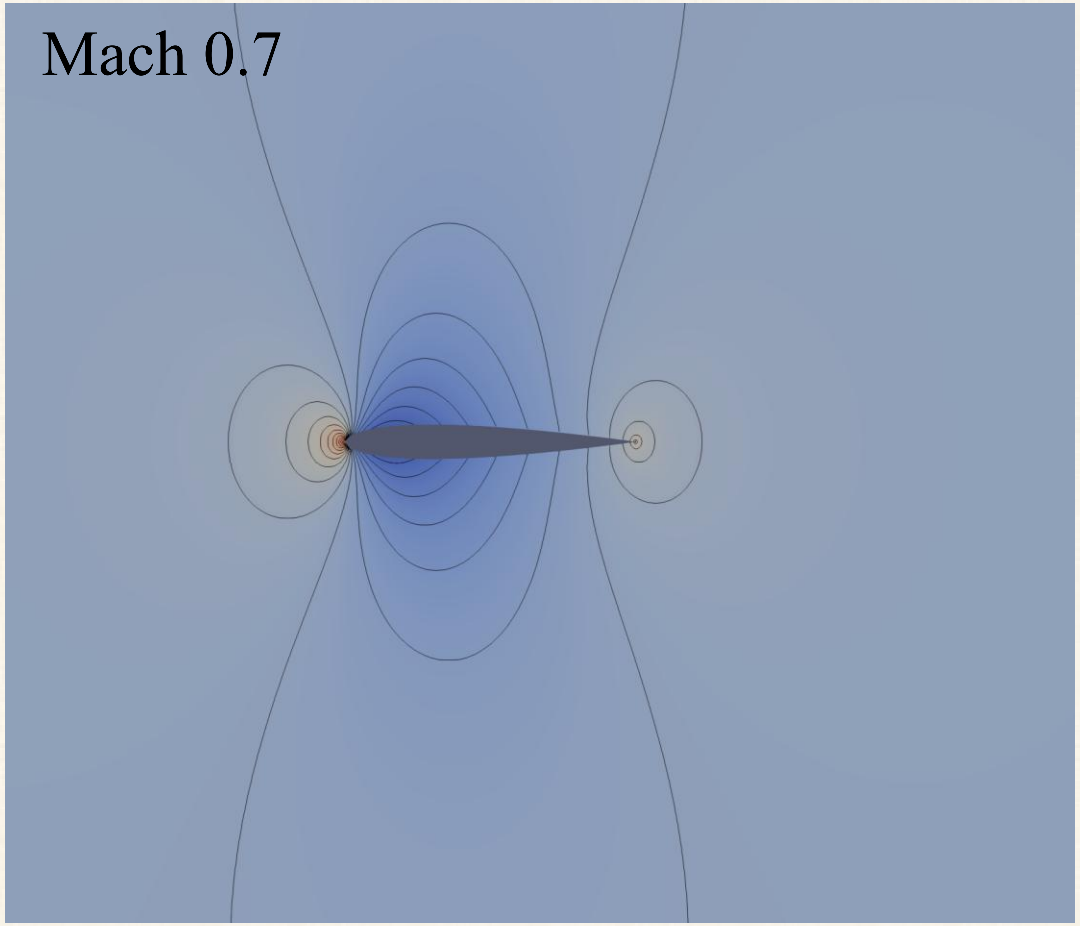
What is the net result to streamlines?

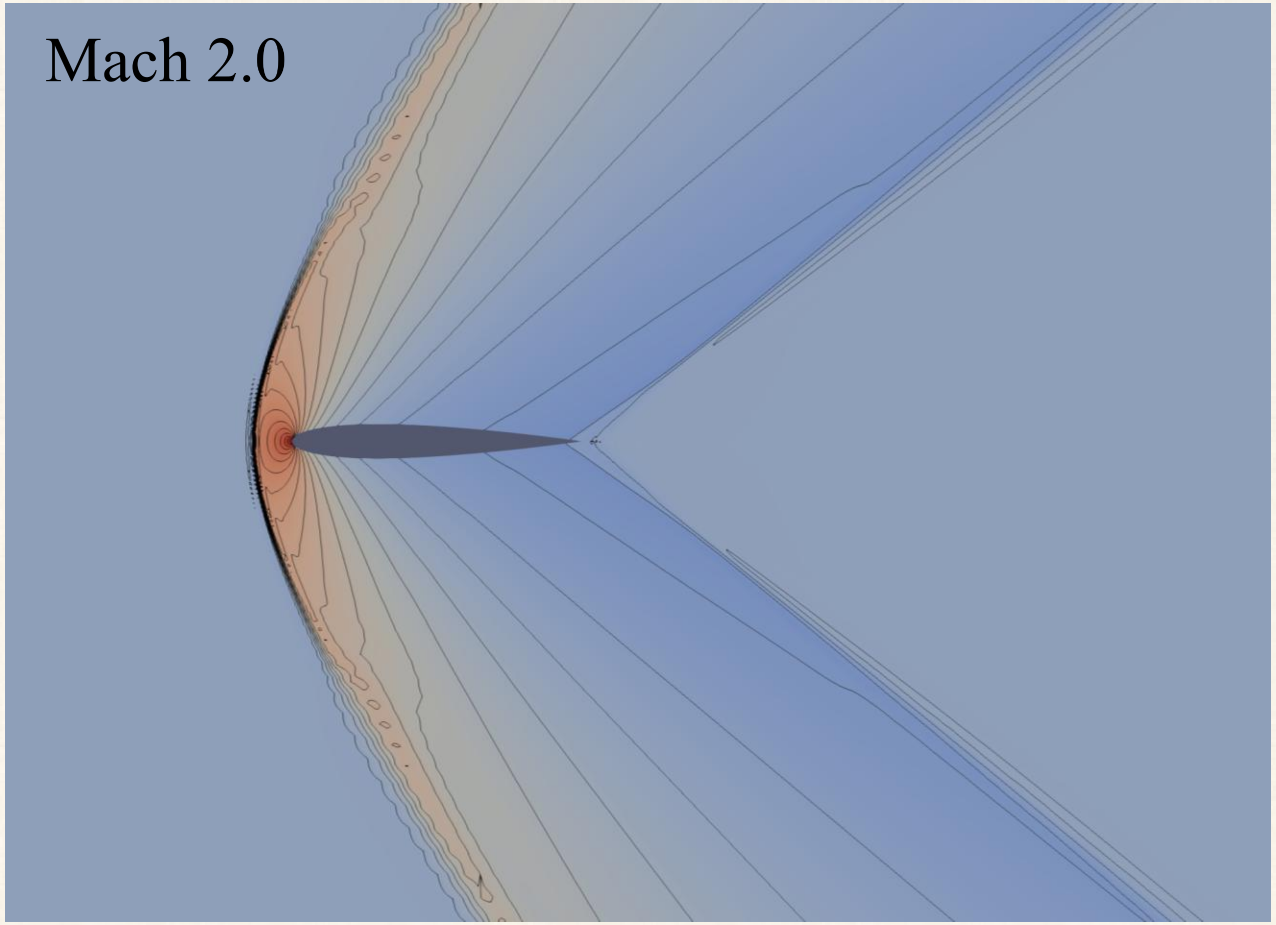
Supersonic Aerodynamics

Compressible stream-tubes can be considered

1) Less variable & more constant width
2) Stream-tubes are pushed away further.

When M>1, we find disturbances are pushed to infinity. Shock!

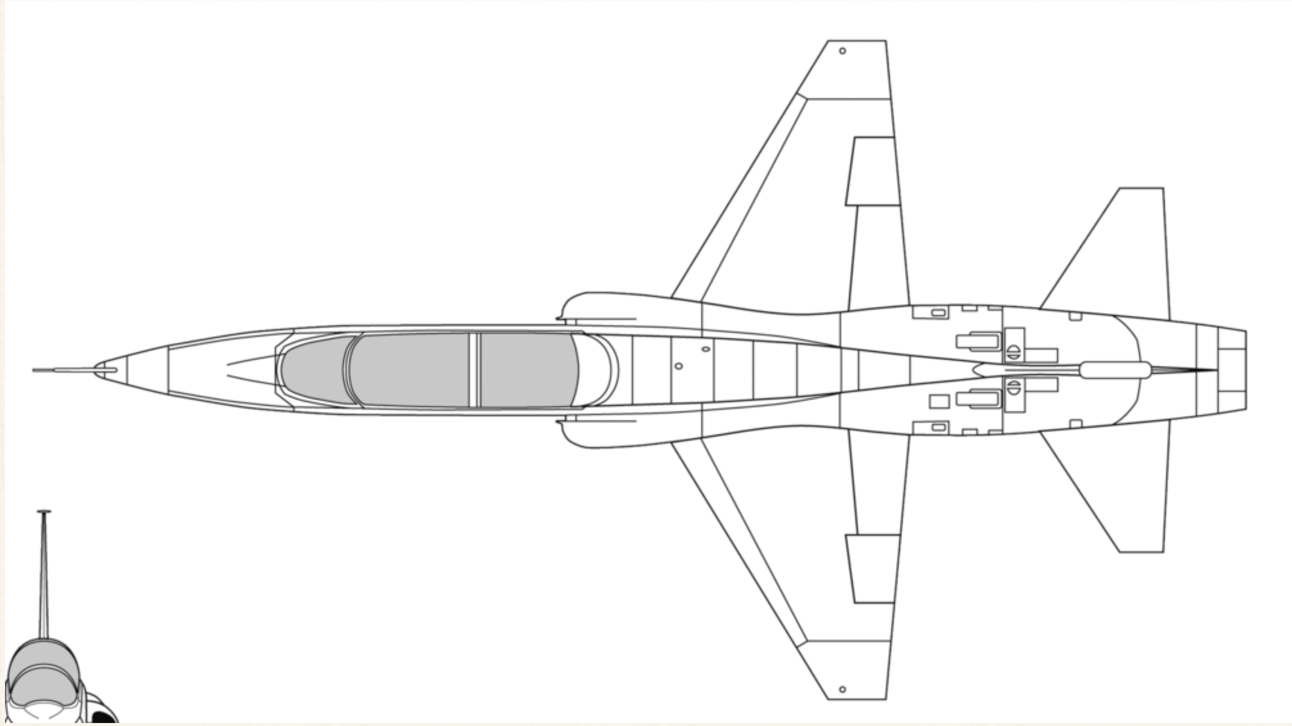




Area Ruled Aircraft

How can an engineer reduce the compressible “wave drag” of an aircraft? Whitcombe developed the “area rule”.

- Smoothly change the cross-sectional area of an aircraft.



In the T-38, the wing contributes to the cross-sectional area of the airplane, so the fuselage cross section is necked-down such that the overall cross-sectional area remains smooth.

This is a Mach 1+ airplane.

Cessna Citation X: Designed as a fast business jet (Mach 0.92)

By JetPix - Gallery page

In the Convair CV-990, rather than removing fuselage area, extra wing cross-sectional area was added!

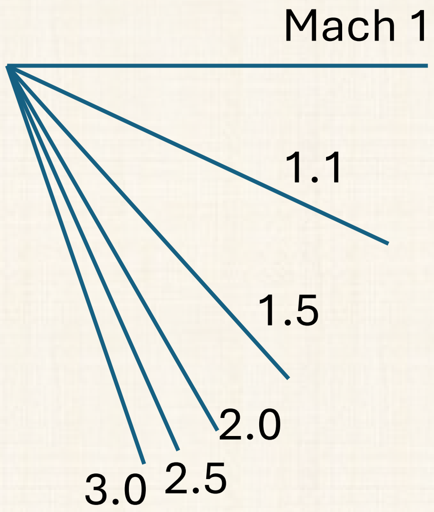
These are called “Küchemann Carrots” or “Anti-Shock Bodies”

The CV-990 cruised at Mach 0.89 (faster than contemporary).

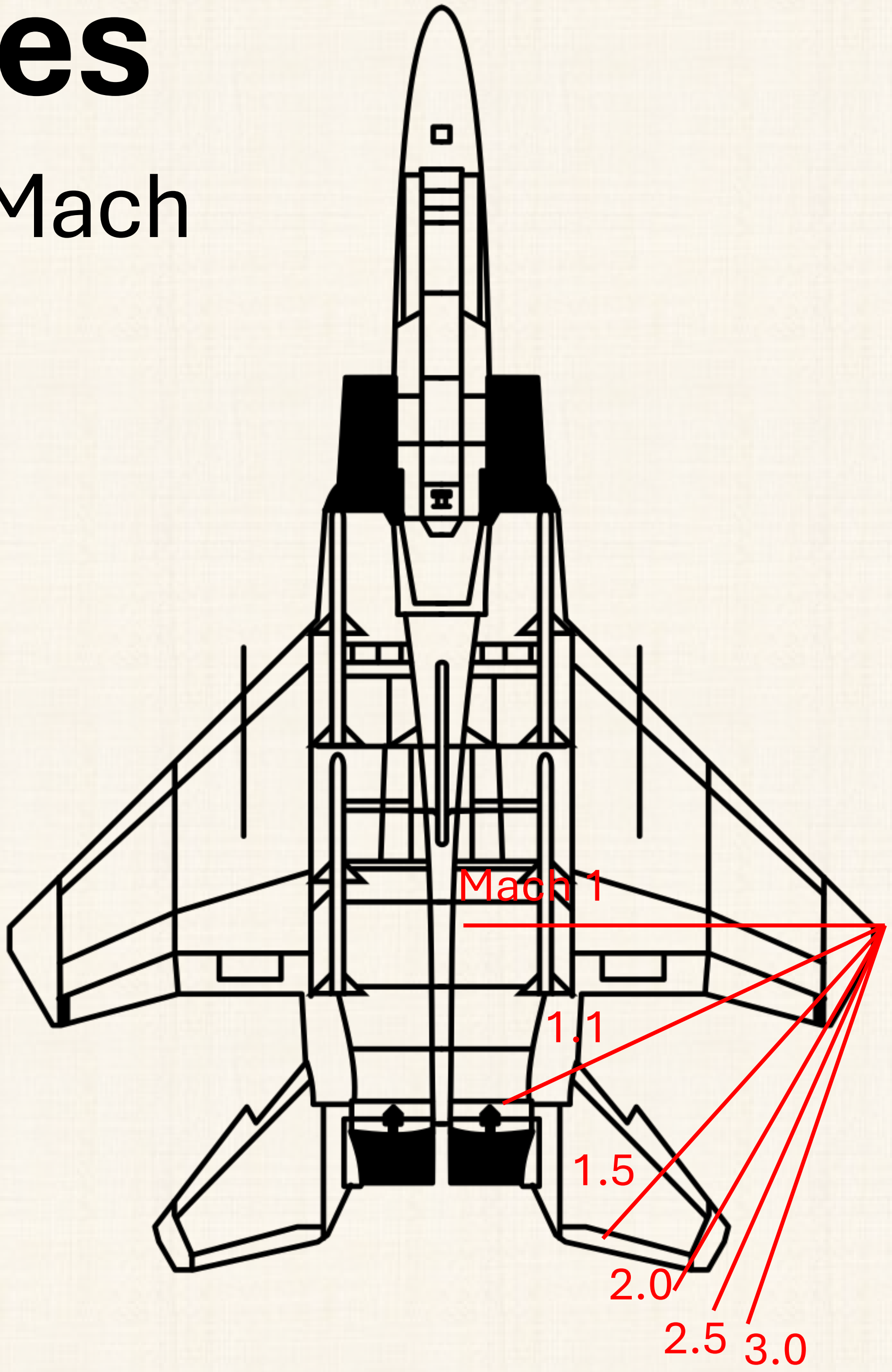
Mach Lines

The angle a small disturbance above Mach 1.0 makes is the Mach line.

$$\sin(\mu) = \frac{1}{M}$$



How fast is the F-15's design speed? Well, the angle from the wingtip to the horizontal is about Mach 2.2.



Aerodynamics Takeaways:

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1. Explaining Lift requires simultaneously conserving Mass, Momentum and Energy.

2. A simplified freestream, source/sink, and vortex model is useful for understanding.

3. Lift is bound vorticity;

   Induced drag is generated from trailing vortices changing the freestream AOA.

4. Compressible flows tend to magnify both variations and the distance at which those variations act.

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