

©William A Foster 2022

AERODYNAMICS FOR PILOTS

A SYSTEMS VIEW TO HOW LIFT IS CREATED

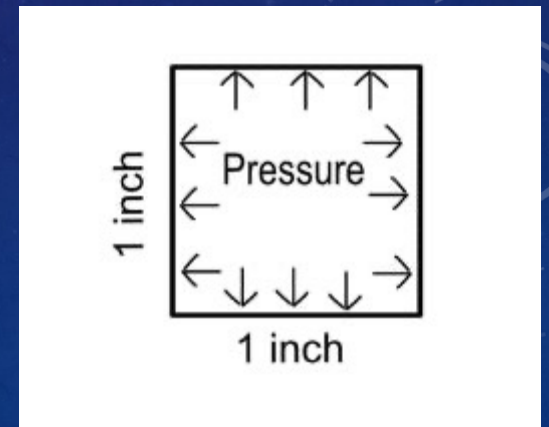
Andy Foster, CFI-S, AGI, BAE

Before we start talking about aerodynamics, let's talk about air.

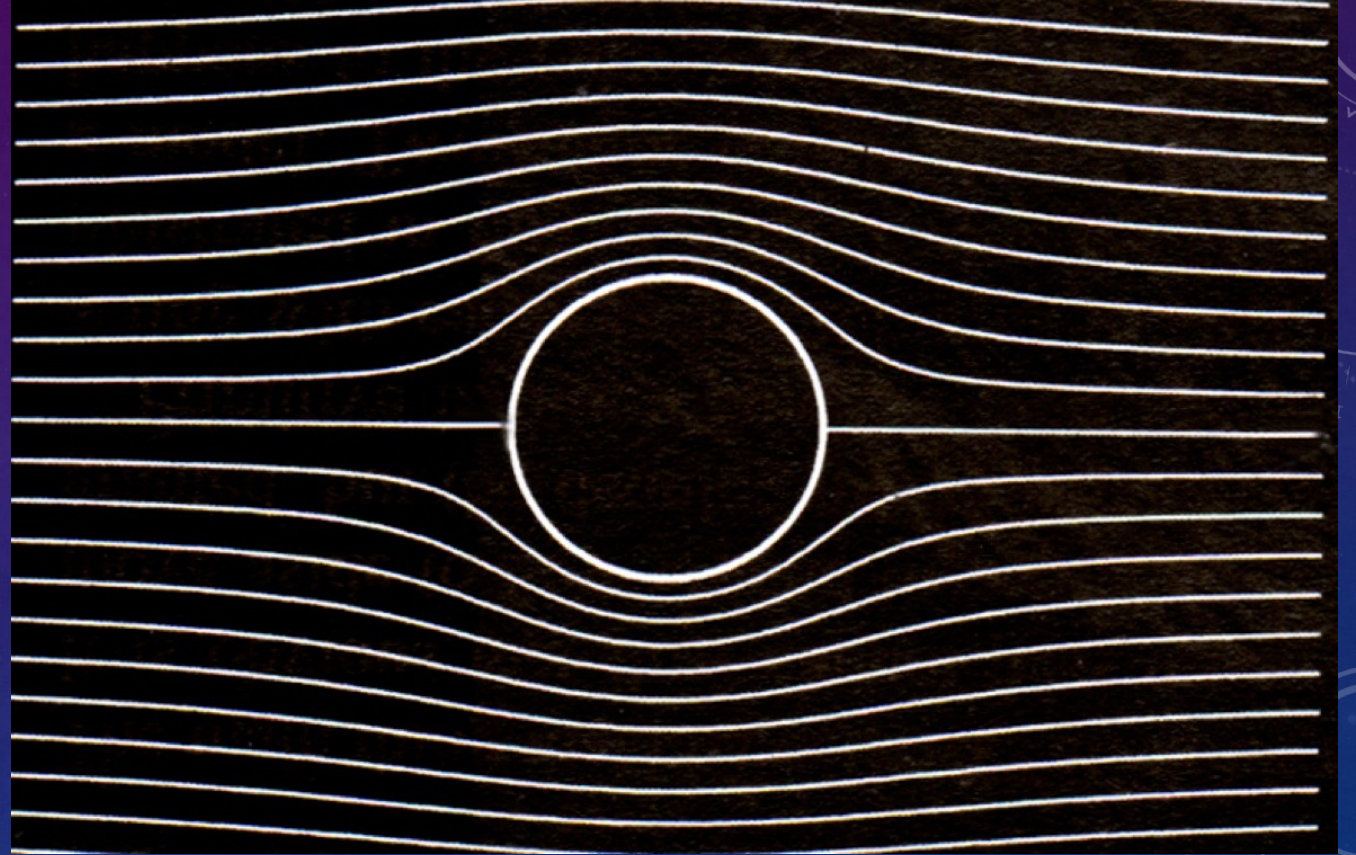
- Air is a molecular gas made up of 78% nitrogen, 21% oxygen, and 1% trace elements) atoms.
- Its molecules are constantly moving, even when we call the air “still”.
 - The molecular movements are why air “fills in” around something we move into it.
- Air exerts force on an object.
 - One way to measure that force is to use “pressure”.
 - Pressure is measured per unit area, i.e. lbs. per square inch (English system).

Pressure is the force per unit area.

In the English system and at sea level, standard atmospheric pressure is 14.7 lbs/square inch.



- We need a way to see and understand how air flowing around something acts. One way of doing that is to use “streamlines”.
- If we put our pen on a molecule and draw a line tracing its direction of movement at each point in an airflow, we’d make a series of streamlines.
- This depiction shows streamlines created by air flowing from left to right around a smooth, non-moving ball placed in the center of the area we’re looking.



- We can use this approach to allow us to see the relative speed of the air molecules to each other.
- Streamlines that squeeze together vertically show us the air is accelerating (i.e., moving to a higher velocity).
- Streamlines moving apart show us where the air is slowing down (i.e., velocity is decreasing).
- Streamlines that are equally spaced show us where the speed of the air is NOT changing (constant velocity).



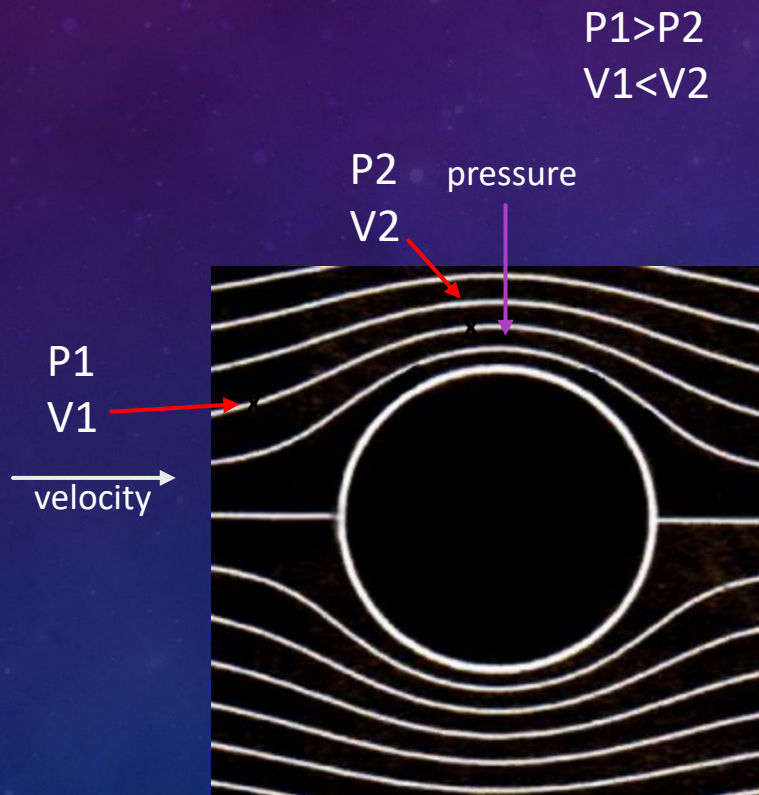
The point where the air hits and “stops” is called the stagnation point.

- Notice that even before the air reaches the ball the streamlines start moving apart.
- The presence of the ball affects the flow (velocity and pressure) even before it reaches it.
- The velocity at each point in the flow field affects its pressure which affects the pressures and velocities on either side of it. This happens at every point in the flow field, so every place in the field is influenced by what is happening at every other place and vice versa.



The point where the air hits and "stops" is called the stagnation point. "Stops" means the average velocity is "zero".

- At any point on a streamline, we can calculate its pressure and velocity relationships by using Bernoulli's Equation.



Bernoulli's Equation

$$P + \rho V^2 / 2 = \text{constant}$$

P = static pressure

ρ = density

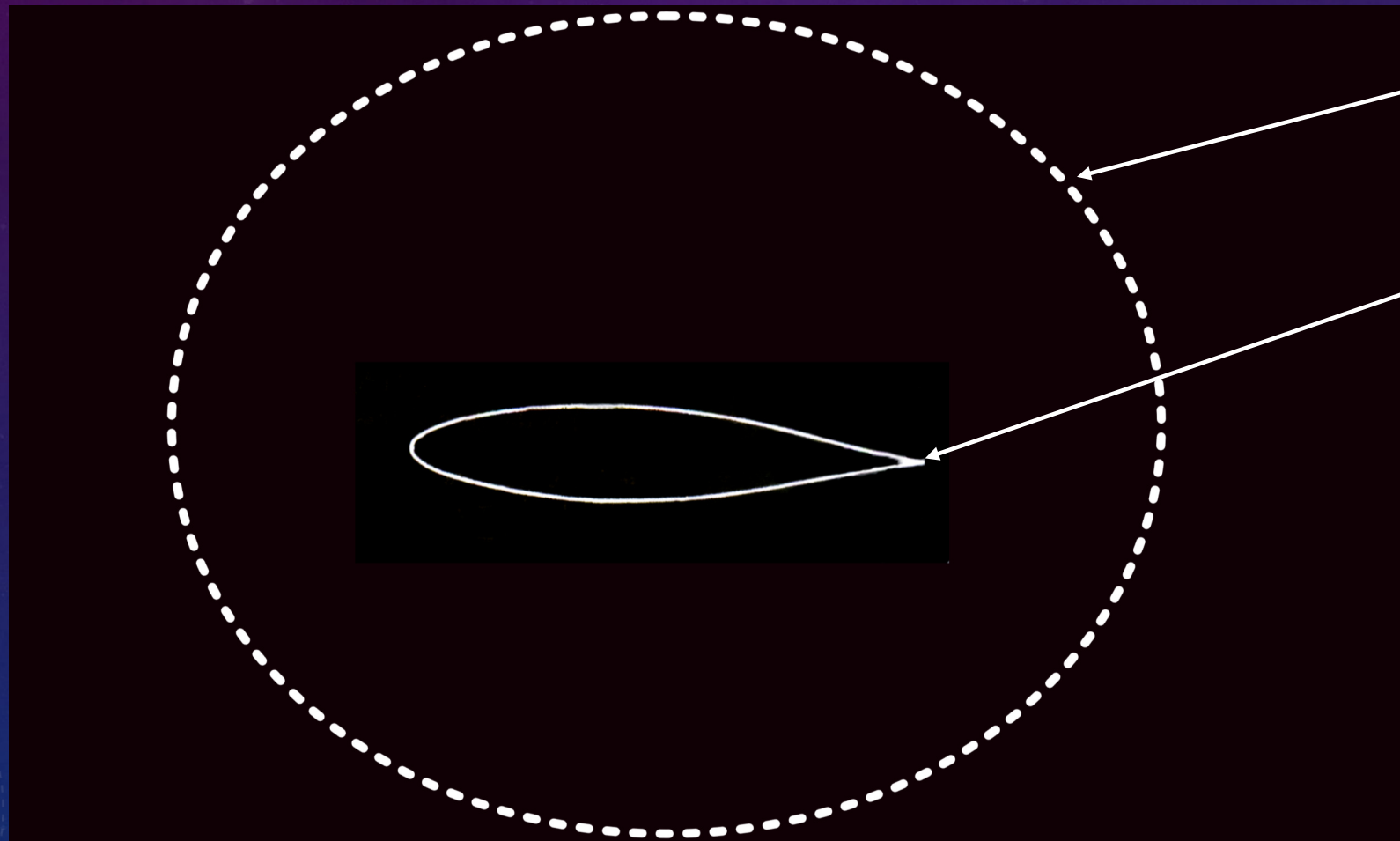
V = velocity

$\frac{\rho V^2}{2}$ is called "dynamic pressure"

and is often referred to as "q" or "q - bar". This is the pressure measured in the direction of the flow (i.e. hitting you in the face).

P or static pressure is pressure measured in a direction perpendicular to the flow.

As we said earlier, anything we place in the air is going to affect what happens to both it and the air around it. So, that means that the object and the air form a **SYSTEM**. The system we are going to use to talk about how an airfoil create lift is shown below:

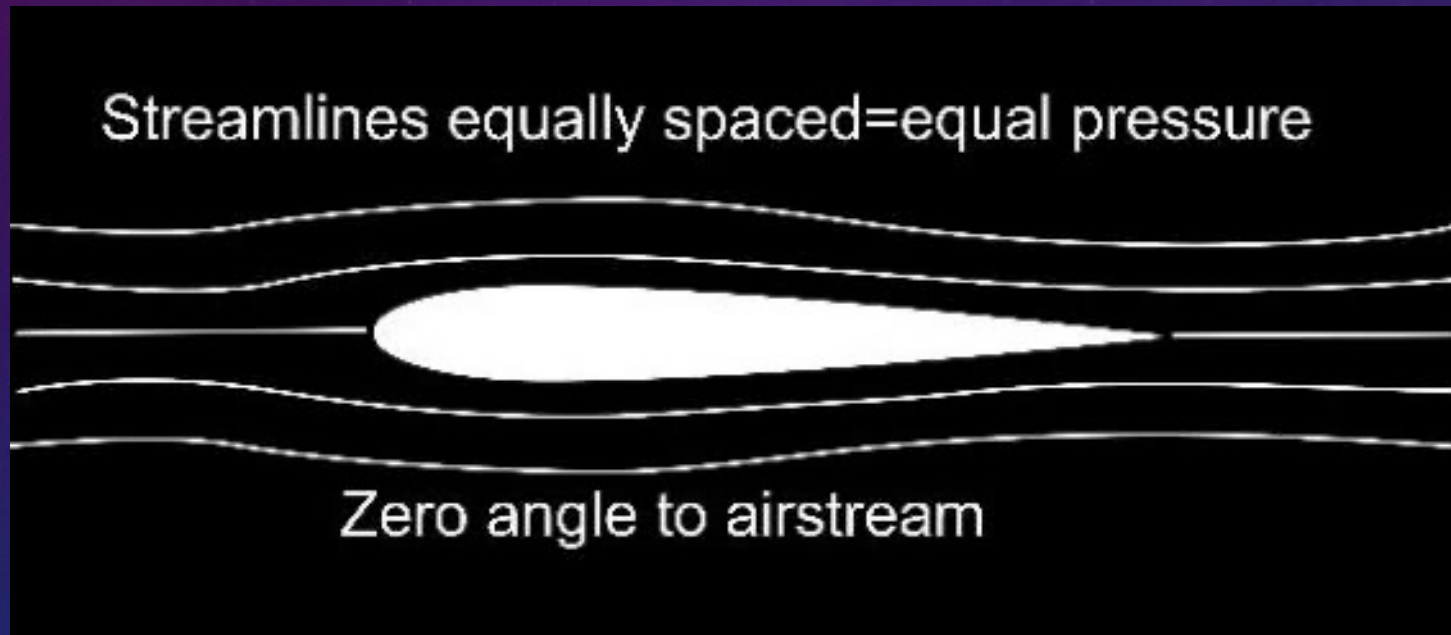


System Boundary

Outside it, the air is in equilibrium.

Symmetrical Airfoil
with the same top and bottom halves.

- Let's zoom in to look at the airfoil (i.e., a cross-section of a wing) and what happens when air moves past it using the streamlines we talked about earlier.
- We're going to use our symmetrical airfoil and put in the airstream so it's perfectly aligned with the flow.

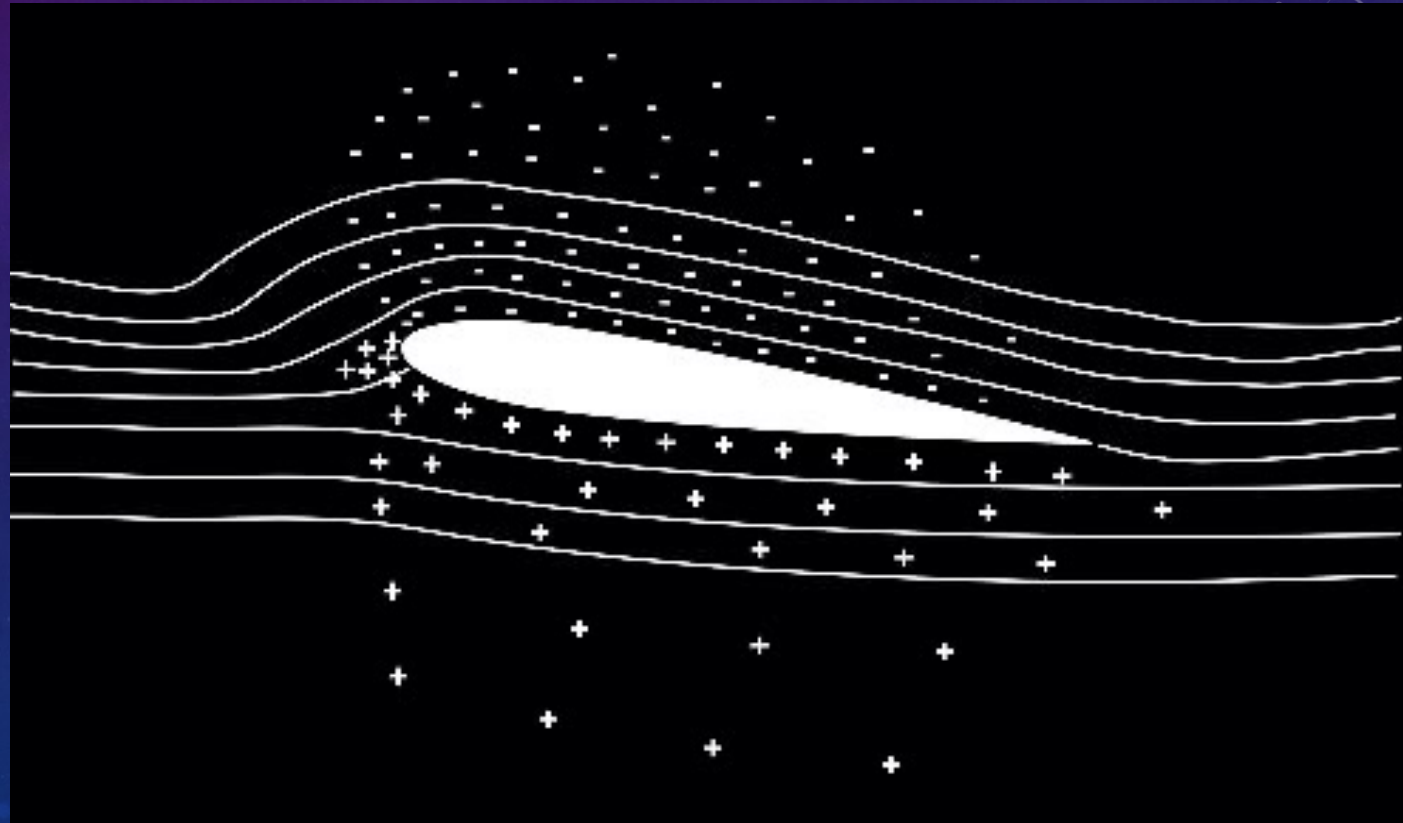


- Since the pressures and velocities above and below the airfoil are equal, there is no differential force pushing the airfoil up or down.
- Reminder: Pressure always pushes on an object.

- If we incline the airfoil, we cause it to deflect the air and create a diffuse and very different flowfield.
- The changes in the flowfield cause pressure, velocity, and momentum changes that result in other pressure and velocity changes in the air flowing through it everywhere.
- The different pressure forces that are created are what the airfoil “feels” and reacts to.

If we plot the static pressure over the streamlines (with – for lower static pressure and + for higher, we’d get something that looks like this.

There is a diffuse velocity-pressure field created for some distance around the airfoil, with the strongest effects at its surface.



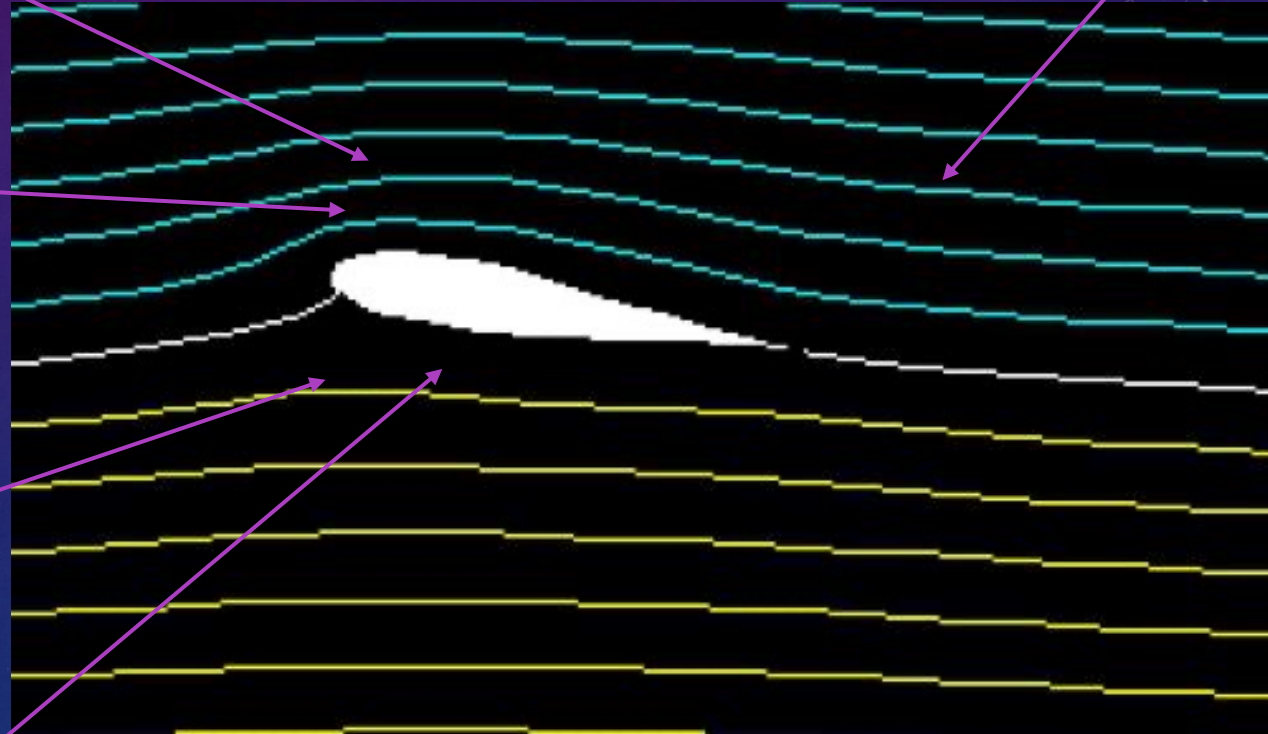
- If we look closer at some of those pressure and velocity relationships, we will see:

Lower static pressure helps
“accelerate” the air coming in.

Higher static pressure helps
“decelerate” the air coming in.

Streamlines bunch together
indicating higher velocity and
lower static pressure.

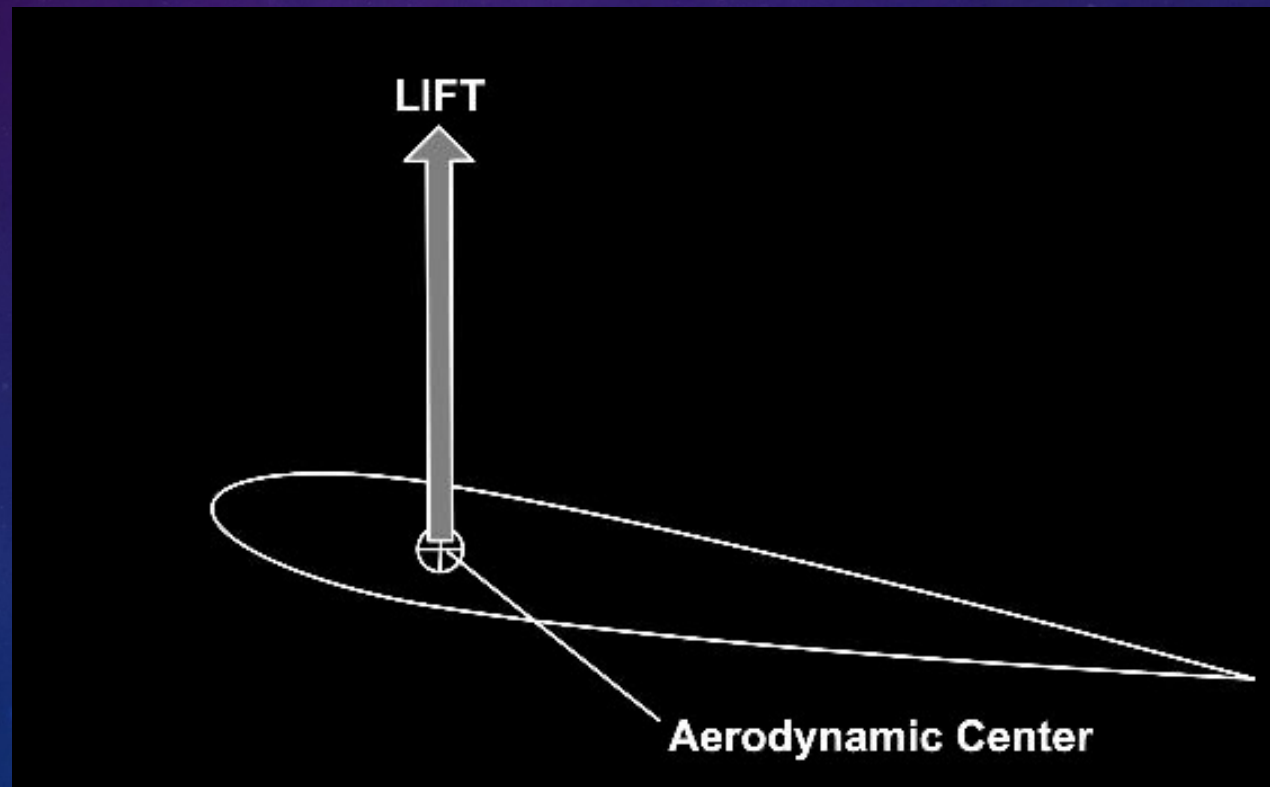
Streamlines don’t curve as
much and spread out a little,
indicating lower velocity and
higher pressure.



Higher static pressure helps
“decelerate” the air coming in.

Modified Screenshot from NASA FoilSim

- LIFT is the resultant force that arises from the summation of the pressures acting on the airfoil in the pressure-velocity field.
- It is the result of the changes in air velocity, pressure, AND the deflection of air, all of which create and sustain the pressure-velocity field.
- Lift cannot occur without *circulation*, i.e., a “circular” spin to the airflow around it caused by the deflection of air, which results in an overall “downward” (i.e., relative to the airfoil) momentum imparted to the air.



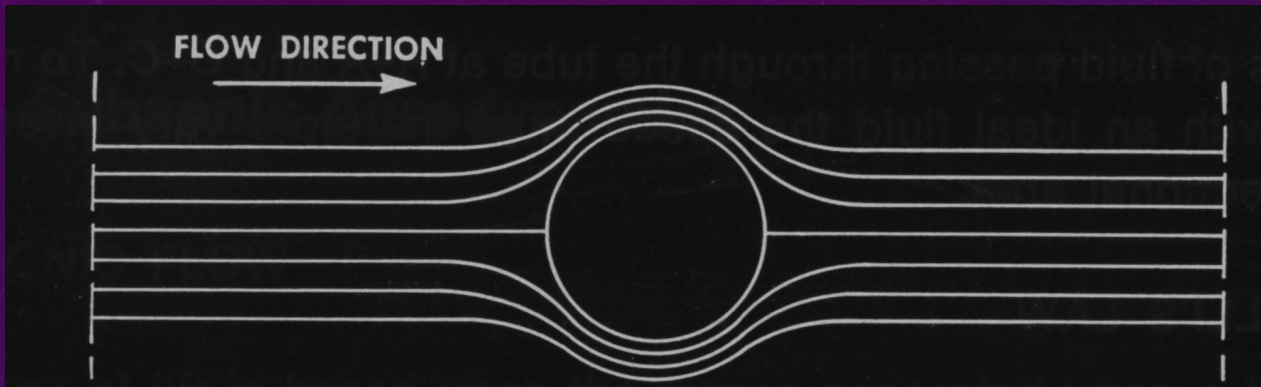


Figure 2.6 Ideal flow past a circular cylinder.

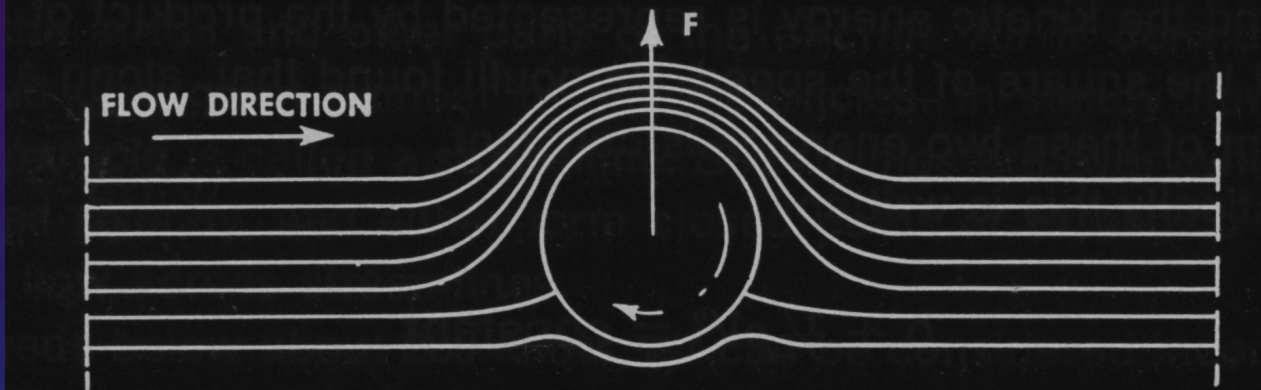
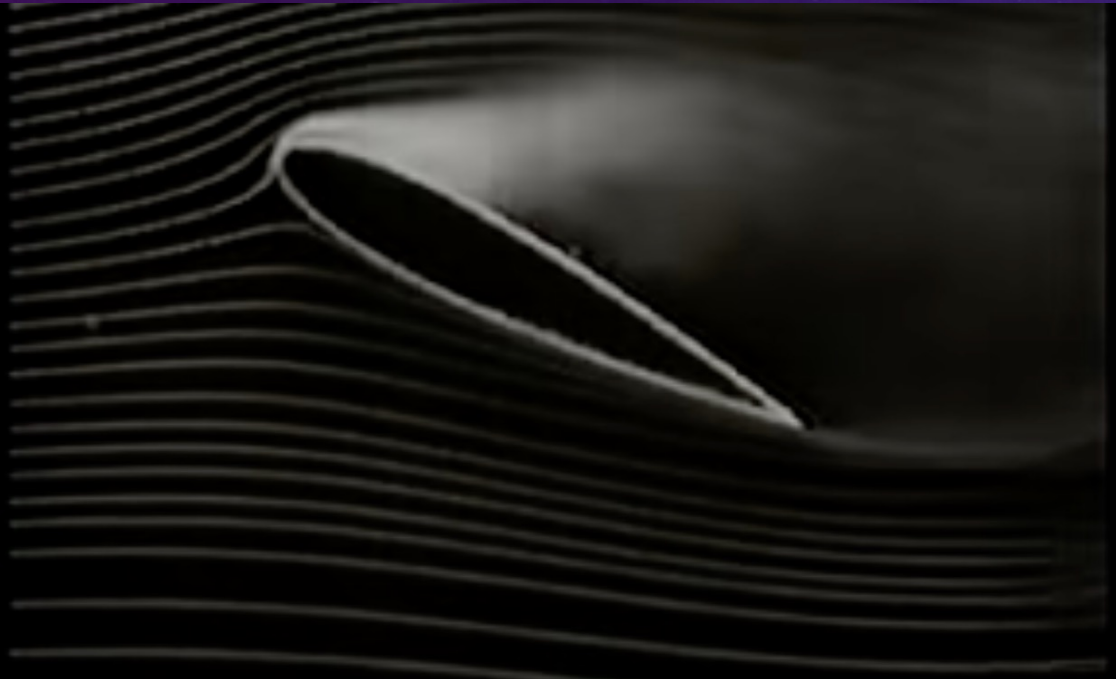


Figure 2.7 Ideal flow past a rotating cylinder.

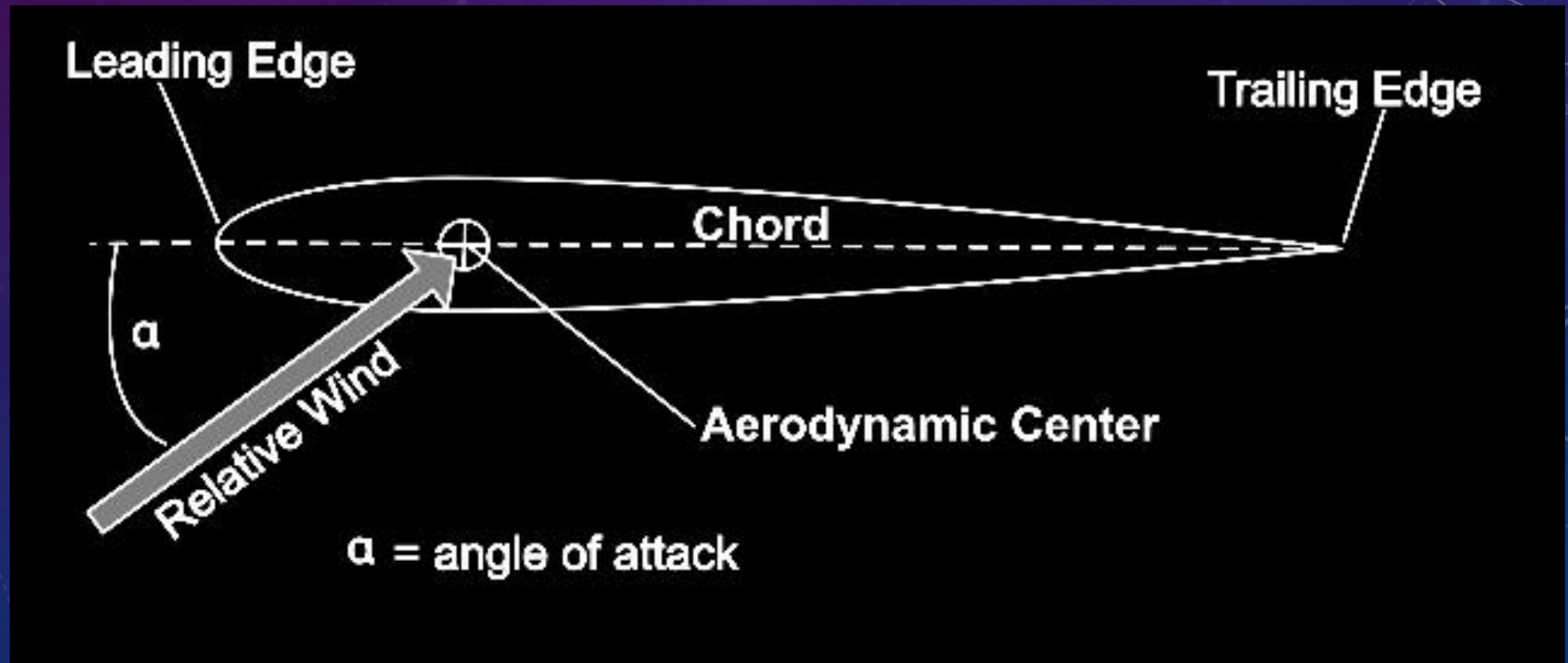
- To understand how *circulation* works, let's look at the *Magnus effect*.
- The top illustration shows a non-spinning ball in a fluid flow.
 - On the ball's top and bottom the streamlines are the same.
 - Pressure above and below is equal.
- The bottom illustration shows a ball spinning clockwise in the same flow.
 - The spin drags fluid with it.
 - This induces a faster flow over the top and a slower flow on the bottom.
 - The pressure imbalance creates a force that moves the ball toward the crowded streamlines.
 - An airfoil creates the same type of a flow.

- As the angle of inclination of the airfoil increases, the circulation and the lift increases...but only to a point.
- The pressures around the airfoil also change, and as its angle increases, the pressure along the top surface and at the back edge of it increase.
- At some angle, the pressure at the surface gets so high and creeps forward until it literally pushes the air away from the airfoil's surface, separating the flow which degrades the circulation.

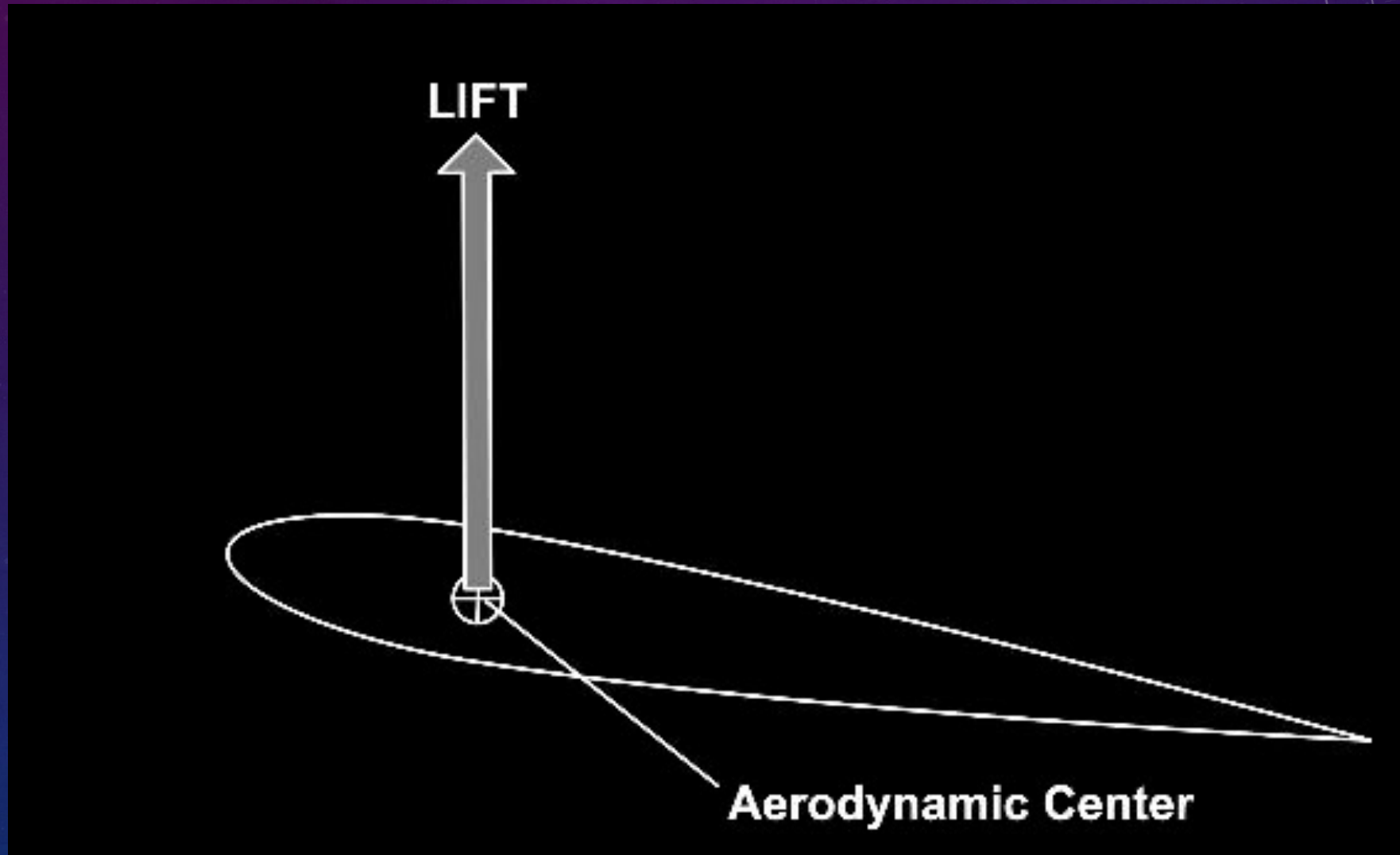


- This DESTROYS most of the upward lifting force.
- This is what we call a “stall”.
- The ONLY thing that controls whether a stall occurs is the angle of inclination.
- The angle the airfoil is inclined to the airflow is called the “angle of attack”.
- The ONLY way to get out of the stall is to reduce that angle.

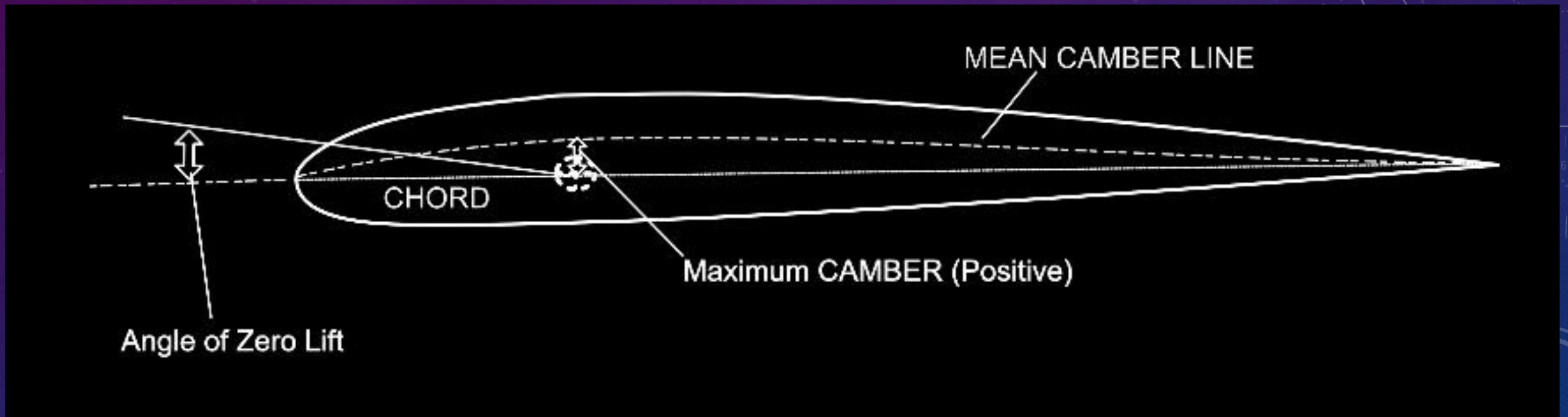
- The chord line of an airfoil is defined as a line from the leading edge to the trailing edge of the airfoil.
- The “relative wind” is defined as the direction of the airflow that collides with the airfoil.
- The “angle of attack” is the angle between the chord line and the relative wind. It is shown here as the angle “ α ” (alpha).



- LIFT acts through a point on the airfoil we call the “aerodynamic center”.
- For the subsonic airfoils most of us fly with, it’s at about the 25% of the chord point.

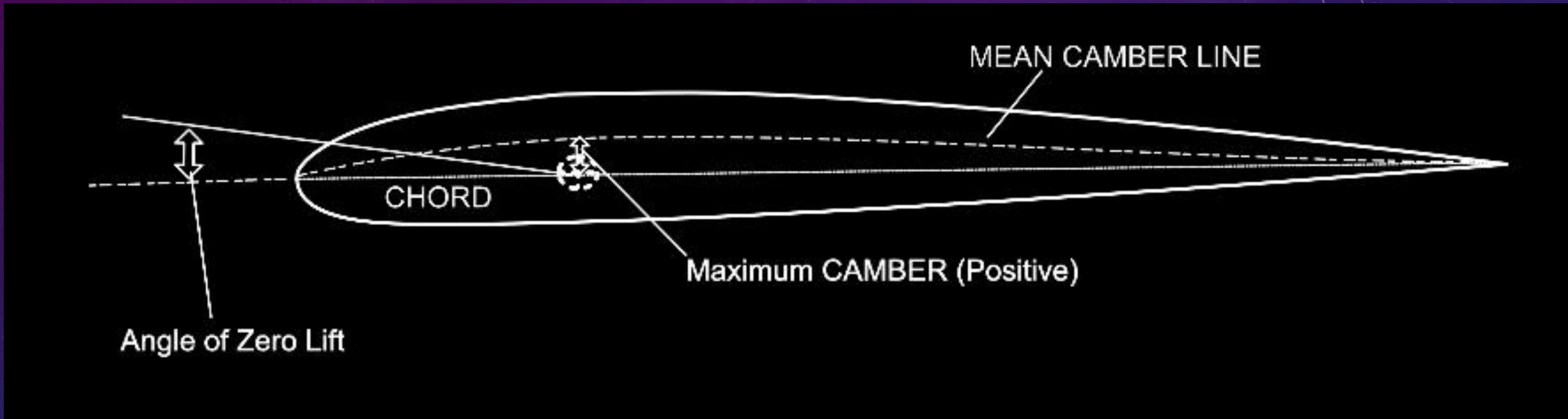


- So far, we have used a “symmetrical airfoil” in our discussion.
- Most of us don’t fly with those. Most small aircraft wings use positively cambered airfoils.
- To understand that, we must define what “camber” is.



- Camber is the distance between the chord line and the “mean camber line”, i.e., a line drawn at the midpoint between the top and bottom surfaces of the airfoil.

- Since for a symmetrical airfoil, the mean camber line and the chord line are the same, the camber is zero.
- If we take that same airfoil and curve its top surface and flatten out its bottom, we will increase the camber (as shown)



- Increasing camber (overall curvature) increases the circulation and, therefore, the lift.
- A positively cambered airfoil mounted level on a fuselage will be at a positive angle of attack and create more lift than a symmetrical airfoil at the same angle.

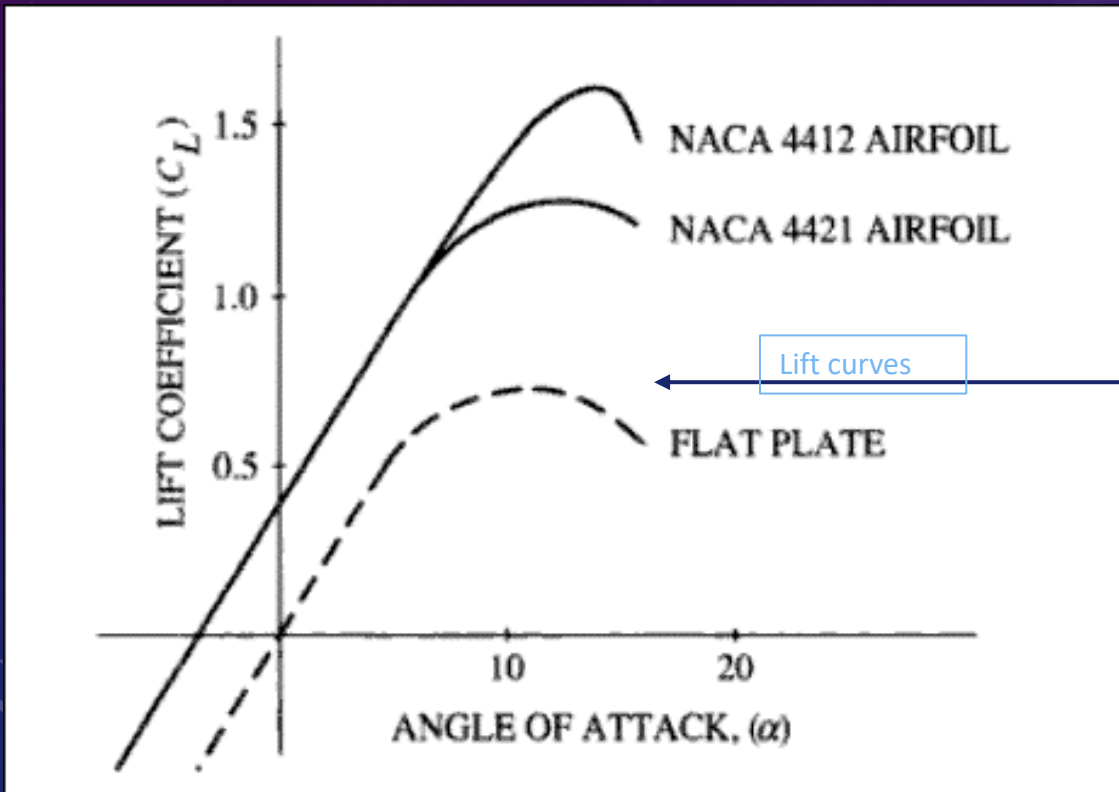
- We can calculate how much lift an airfoil produces by using this formula where L = Lift:

$$L = \frac{1}{2} \rho C_L V^2$$

ρ = air density

C_L = coefficient of lift (determined by the shape of the airfoil and the circulation it produces)

V = speed of the air/airplane



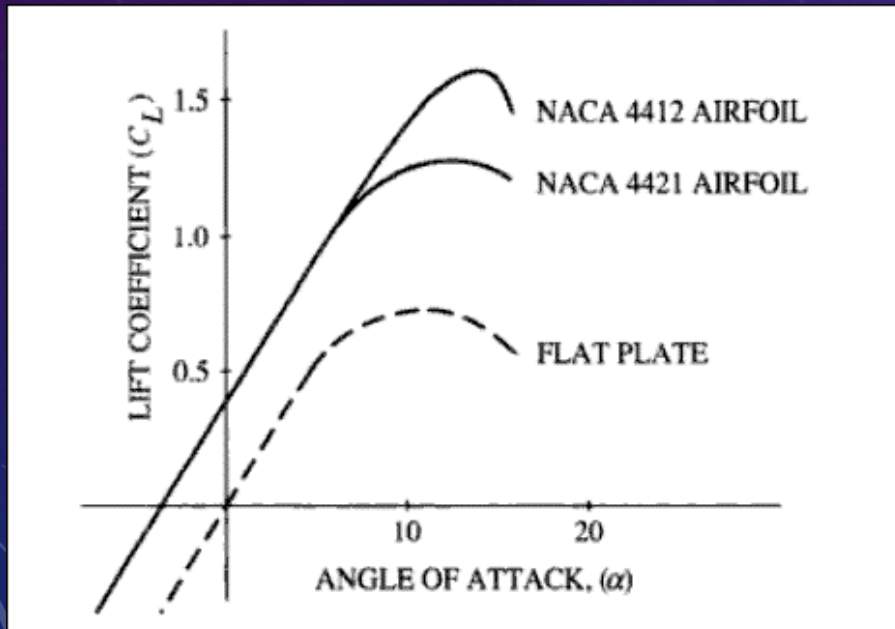
Modified screenshot from <https://www.quora.com>

- The graphic shows the lift coefficient of two airfoils and a flat plate plotted versus angle of attack.
- The lines show two positively cambered airfoils.
- Notice that C_L is ONLY a function of angle of attack.
- The point where each curve peaks and falls off is IS the angle of attack where the wing “stalls” and is called the “Critical Angle of Attack”.

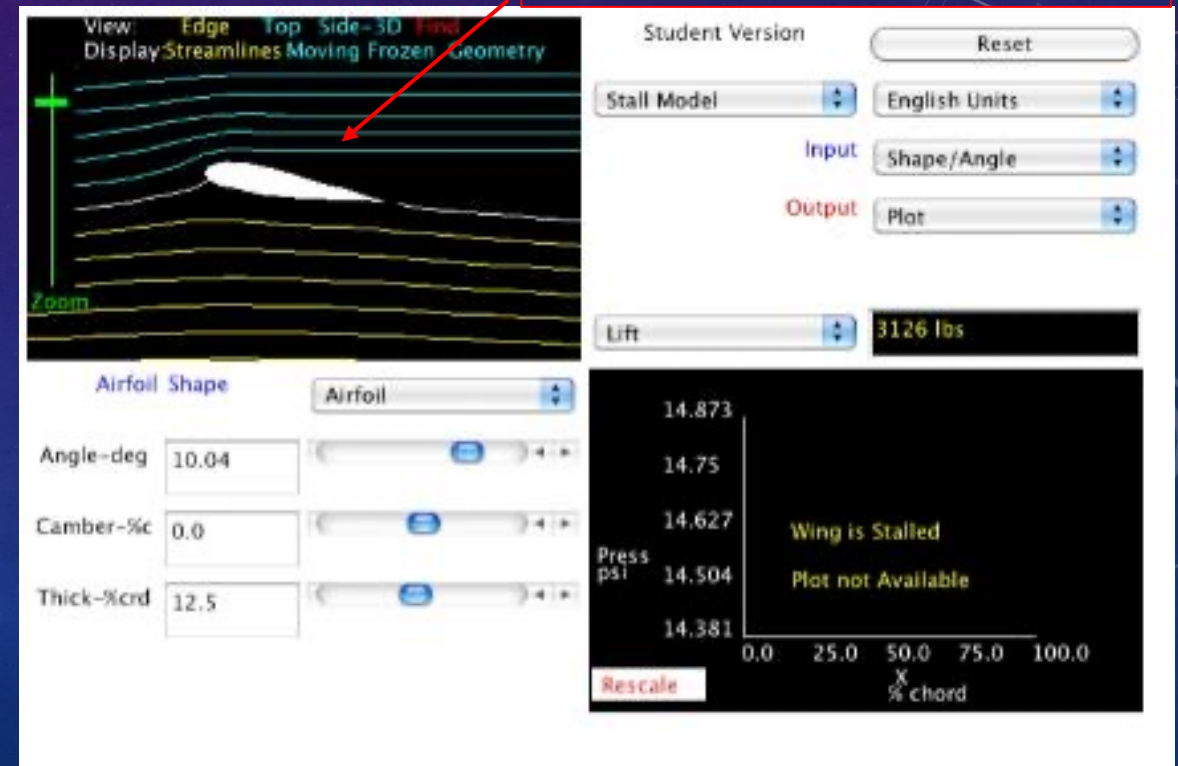
$$\text{Since } L = \frac{1}{2} \rho C_L V^2$$

- For any amount of lift keeping you flying, as you slow down, you must increase C_L (i.e., angle of attack).
- The equation and the lift curves also tell you an airplane can stall at ANY SPEED!

The streamlines show the airflow over the top breaking away (no downward deflection or bunching of streamlines) and all that beautiful low pressure (and LIFT!) going with it.



Modified screenshot from <https://www.quora.com>



Screenshot from NASA FoilSim

- This means an airplane can be STALLED AT ANY AIRSPEED OR ATTITUDE!
 - ATTITUDE and ANGLE OF ATTACK are NOT the same!
- Most small airplanes don't have angle of attack indicators.
- Most only have an airspeed indicator... which is a "better than nothing" indirect indication of angle of attack under specific sets of conditions (i.e., bank angle, G G-force, specific weight, flap settings).

Analog Airspeed Indicator

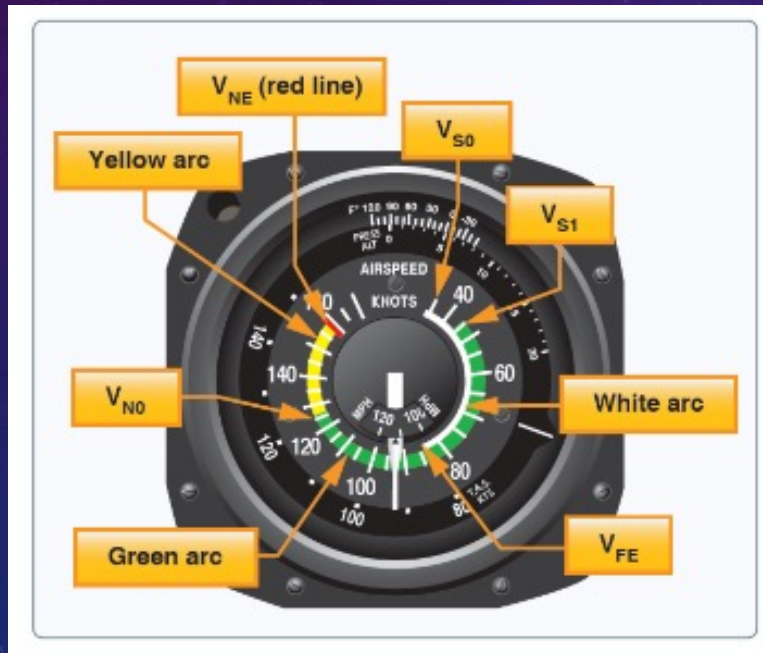
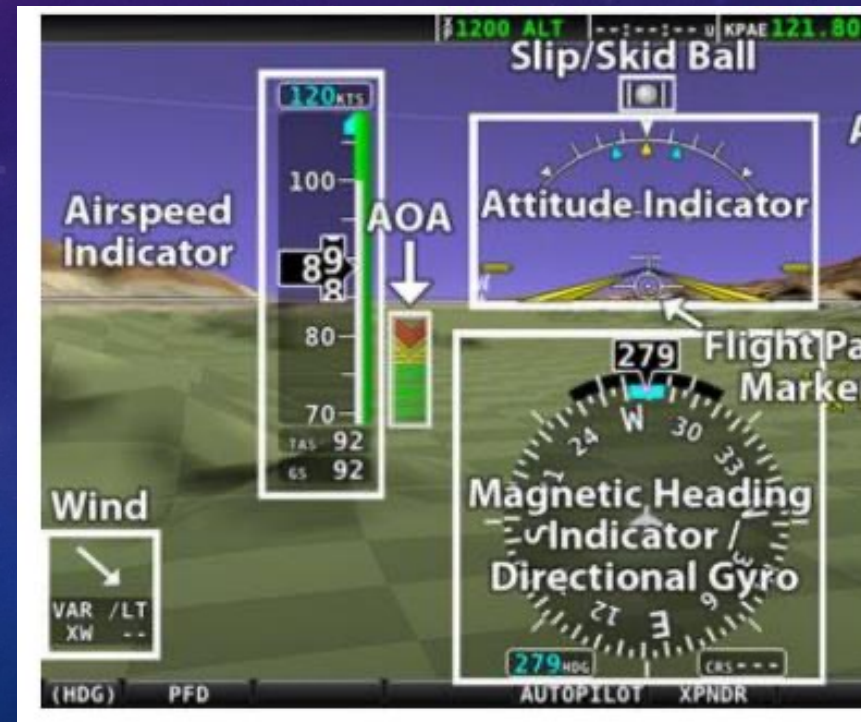


Image from FAA-H-8083-25B, p. 8-9

Dynon Skyview PFD



Screenshot from Dynon Skyview Classic and Touch Pilot's User Guide, Figure 9, Skyview PFD

- Flying AOA works **independently** of the aircraft weight while stall speed **increases** as the weight does.
 - A stall always occurs at the same (critical) angle of attack.
- Navy pilots don't fly airspeed during landing but units of ANGLE OF ATTACK (AOA). In fact, AOA references are used for EVERY flight phase.

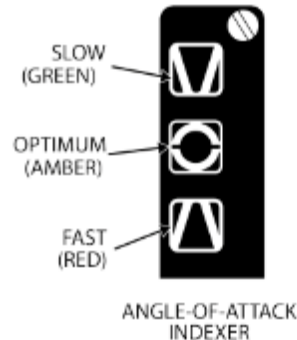
F-14 AOA Indicator
(units)



Screenshot from Heatblur F-14A/B Tomcat Documentation, Release 1.0 p 51

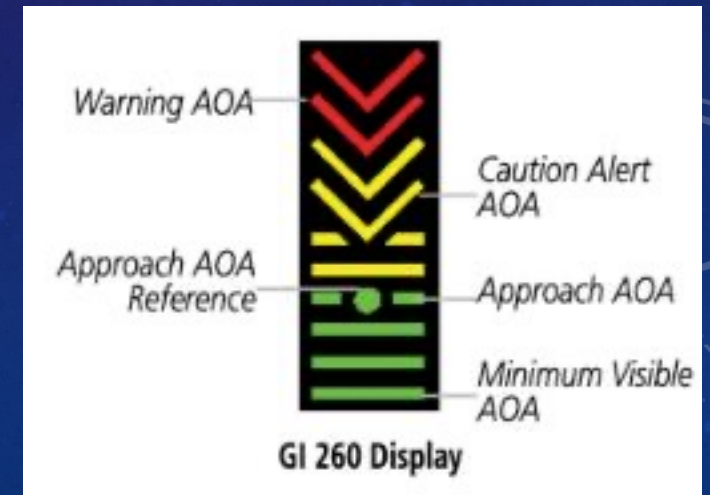
F-14 AOA Indexer
(Pilot-in cockpit/Landing only)

APPROACH LIGHT	INDEXER	ANGLE -OF- ATTACK UNITS	AIRSPD
GREEN 		16 TO 30	SLOW
AMBER 		15.5 TO 16	SLIGHTLY SLOW
AMBER 		14.5 TO 15.5	OPTIMUM ON SPEED
AMBER 		14.0 TO 14.5	SLIGHTLY FAST
RED 		0 TO 14	FAST

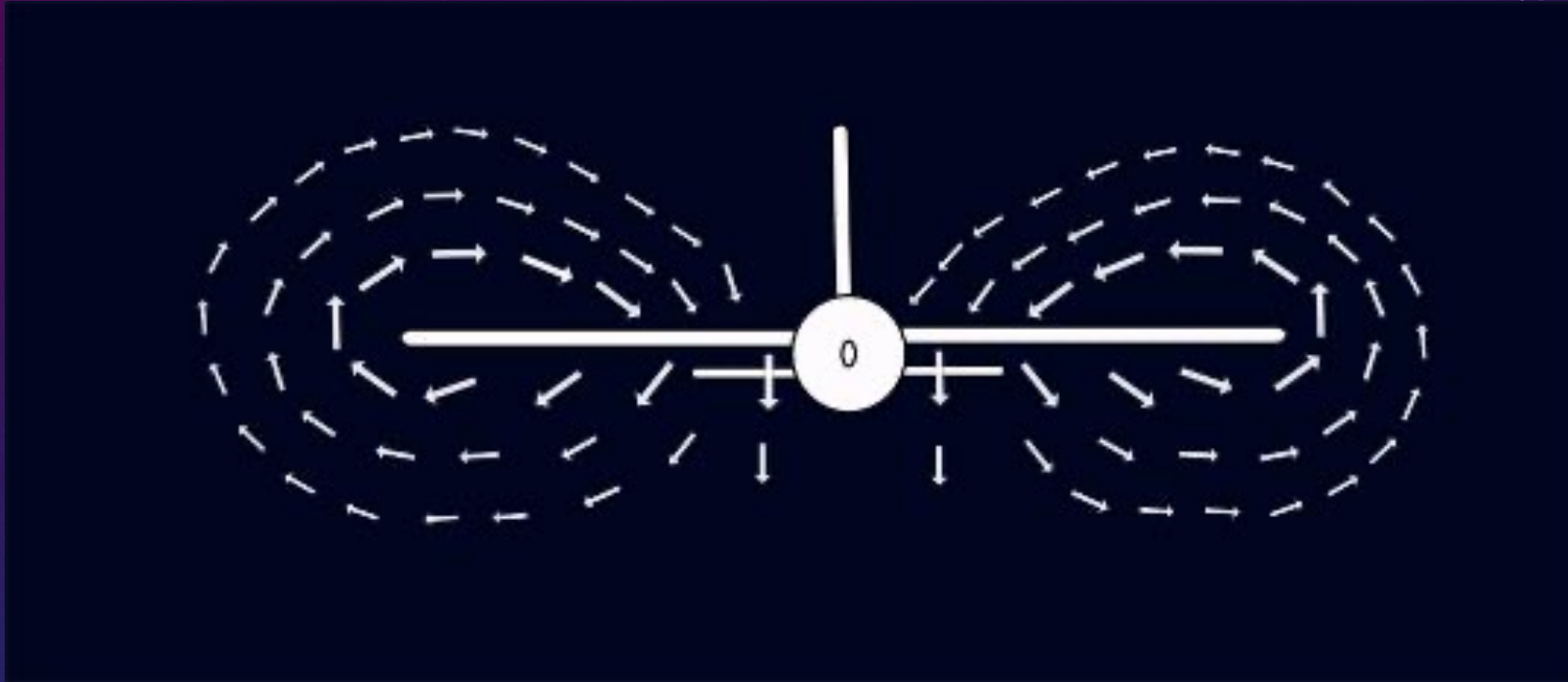


Screenshot from Heatblur F-14A/B Tomcat Documentation, Release 1.0 p 52

Garmin GI 260 AOA Display
(Typical General Aviation Usage:
Warning AOA flashes and audio
warning of approaching stall.)

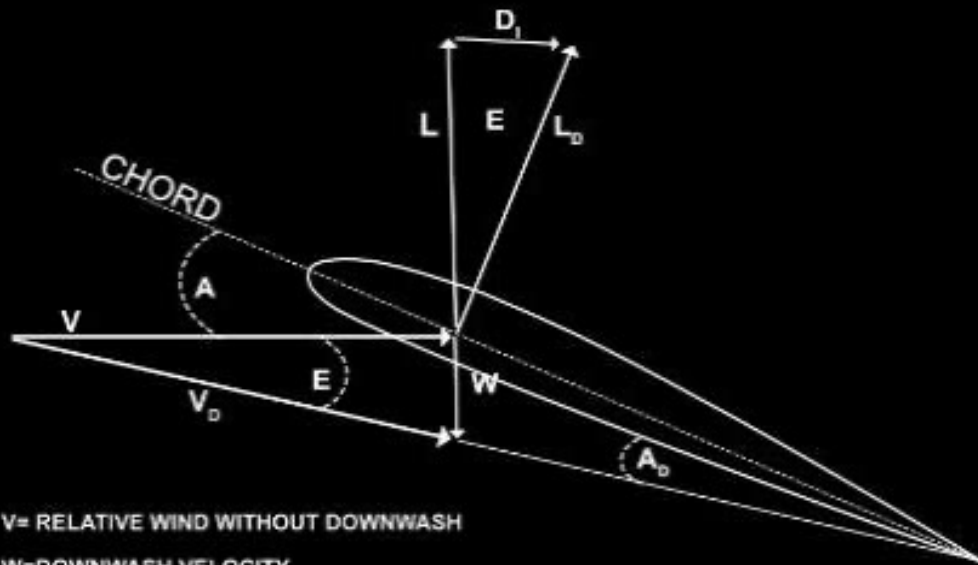


- And while we are speaking about flying...
- There are a couple of things that directly affect it due to the airflows of wings.



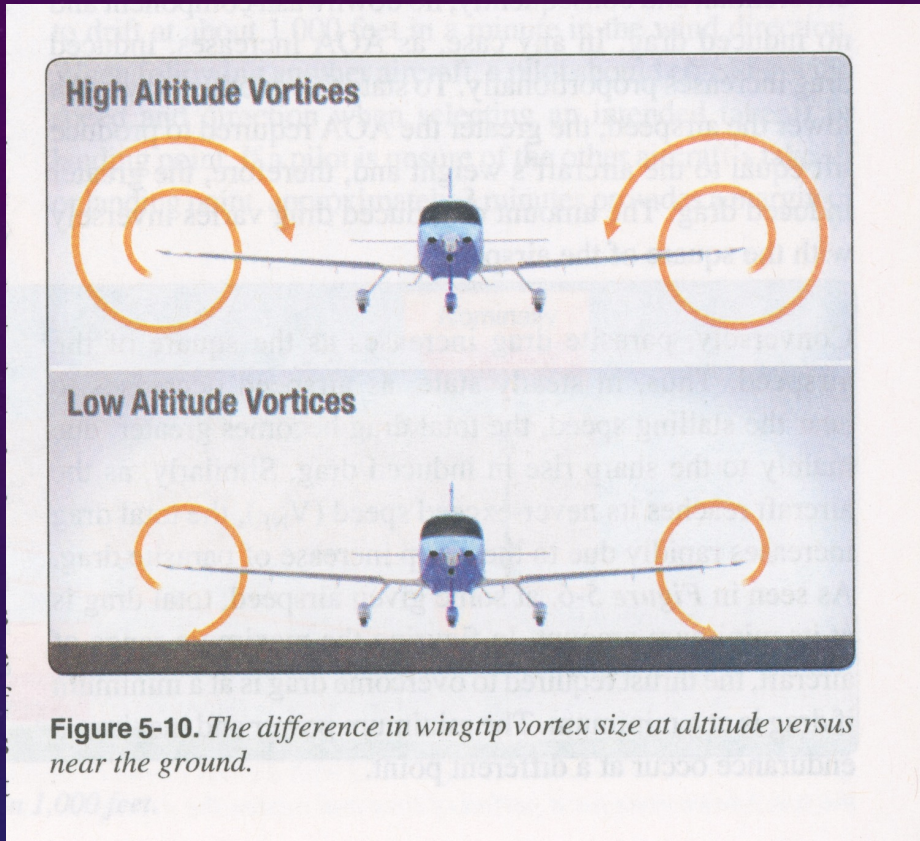
When generating lift, the high-pressure air under the wing attempts to equalize with the low pressure area above which creates a swirling flow around the wingtips, like two horizontal tornadoes that spin toward the fuselage.

- This swirling air combines with the air flowing OVER the wing (as shown in the earlier airfoil diagrams) and changes its flow.
- This affects the angle of attack and the aerodynamic forces the wing creates.



V = RELATIVE WIND WITHOUT DOWNWASH
 W = DOWNWASH VELOCITY
 V_D = RELATIVE WIND AFTER DOWNWASH
 L = LIFT VECTOR BEFORE DOWNWASH
 L_D = LIFT VECTOR AFTER DOWNWASH
 A = ANGLE OF ATTACK BEFORE DOWNWASH
 A_D = ANGLE OF ATTACK AFTER DOWNWASH
 E = DOWNWASH ANGLE
 D_I = INDUCED DRAG

- Lift acts perpendicular to the Relative Wind (i.e., velocity vector) which is rotated downward.
- The airflow around the wingtips causes a **decrease in the angle of attack** (A to A_D) which **rotates the lift vector rearward** (L_D). This **decreases LIFT** and **increases DRAG**.
- This drag due to lift is called **induced drag** (D_I).



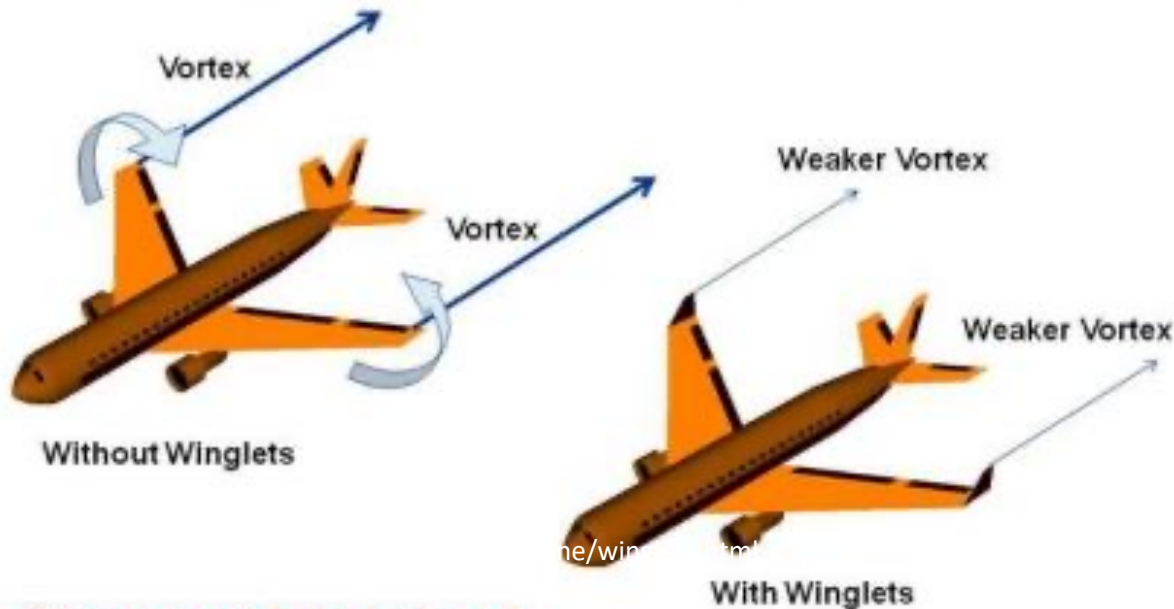
- When an aircraft is within a half-wingspan of the ground, the ground interferes with the full development of the wingtip vortices.
- They makes them weaker than they will be once the airplane is free of the ground's influences.
 - Lift is right at takeoff is higher than it will be once the airplane elevates a few feet.
 - Induced drag is lower than it will be when the airplane elevates a few feet.
- This can allow an overloaded airplane to get airborne but prevent it from climbing any higher than a very short distance above the ground.
- This is called flying in "ground effect".



Image from FAA-H-8083-25B, p. 5-7

- The wingtip vortices are also responsible for “**downwash**” that can sometimes be seen or felt!
 - It’s the “thump” you sometimes feel during practicing steep turns or performing aerobatics.
- The strength of their vorticity is directly proportional to the aircraft’s weight.
- The vortices exist anywhere an airplane is creating enough lift to fly.
 - They settle downward and downwind of the aircraft creating them.
- Flying a light airplane into a vortex created by a large airliner (e.g. 747) can be asking for a loss of control.
- The area of disturbed air is called “wake turbulence”.
 - See FAA Advisory Circular 90-23G.

Winglets



Winglets reduce induced drag component.

- The wingtip vorticity and its associated downwash is a RESULT of lift acting on a finite wingspan...NOT part of the mechanisms that CREATE lift.
- The extra drag and lift penalties they produce are something engineers work to *reduce*.
 - Winglets are one design solution that reduces the problem.

Misconceptions and Myths about Creating Lift

- **Myth:** Bernoulli's Principle and Newton's Third Law are mutually exclusive or competitive when talking about how lift is created.
- **What's wrong:**
 - *To create lift, the pressure and velocity changes explained by Bernoulli's principle must take place.*
 - *The deflection of air that induces circulation must also take place.*
 - *There is both upwash and downwash in the flowfield but there is an overall downward momentum to the air if you sum it all up.*
 - *It is this overall downward momentum shift that the airfoil is "reacting" to. (Newton's Third Law)*
 - *Can't really see it easily and intuitively which is why there so many incorrect explanations grabbing onto physical mechanisms not truly involved.*
 - *If the explanation doesn't match what the streamlines are telling you, it's wrong.*
 - *BTW, engineers and NASA understand all this quite well and aren't still debating it.*
 - *The debate about this resides in the educational community, whether in academia or the pilot world.*
 - *Social media loves fuzziness, so anything can be distorted.*
 - *Engineers just use the math.*

Misconceptions and Myths about Creating Lift (Continued)

- **Misconceptions:** Newton's Third Law is illustrated by: (1) the wing reacting to the air bouncing off its bottom, or (2) as a reaction to downwash associated with the wingtip vorticity, or (3) a magical reaction to air turning at the airfoil's trailing edge.
- **What's wrong:**
 - (1) *Fluids are composed of molecules, not bullets. Air is a fluid, and the bullet theory went out with a very long time ago. The physics is more sophisticated than that.*
 - (2) *This confuses the downwash associated with wingtip vortices with the overall downward deflection of air in the flowfield, i.e. a case of grabbing the wrong physical mechanism.*
 - (3) *The only thing happening at the trailing edge of an airfoil is the Kutta condition. Go look it up.*
- **Myth:** Air at the top of the airfoil goes faster over the top of the airfoil because it has to get there at the same time as the air on the bottom. (Equal Transit Theory)
- **What's wrong:**
 - *It's simply untrue. See: <https://www.youtube.com/watch?v=e0l31p6RlaY>.*
 - *Air moves because of the pressure gradients and air over the top arrives at the airfoil's trailing edge first (larger pressure drop; faster velocity).*

Misconceptions and Myths about Creating Lift (Continued)

- **Myth:** The Coanda Effect is necessary for air to follow the top curvature of an airfoil and therefore is involved in the creation of lift.
- **What's wrong:**
 - *The Coanda Effect is dependent upon a focused high stream jet of air (annular with a HIGHER pressure than the fluid around it) of close to an object that also involves subsequent air entrainment. This is not the same as freestream air around an airfoil (where pressure on top of the airfoil LOWERS as you approach the surface on the airfoil).*
 - *Freestream attachment of the boundary layer is dependent only on the viscous forces in the fluid and the degree of adverse pressure gradient at the surface.*
 - *Most water-based “demonstrations” illustrating the Coanda effect are actually driven by other things like molecular attraction and surface tension.*
 - *On an airfoil, molecular motion of the air, viscosity of the fluid, and pressure gradients are what cause the air to follow the airfoil's curvature...or not.*

SUMMARY

- The physics of lift require both an acceleration and a “downward” (relative to the airfoil) deflection of air to make flight possible.
- The wing and the air around it create a system that affect each other and that must be properly controlled to make things work.
- Angle of attack is the PRIMARY control of both lift and stall.
 - Angle of attack (AOA) is the BEST control you can use not only because it controls stall but it is independent of weight.
 - Without AOA indicators, a pilot MUST understand how speed, AOA, and weight relate to remain safe.
- Ground effect can get you into trouble on takeoff or landing if you push your aircraft and conditions too hard.
- Wake turbulence, its effects, and how to deal with it, are something every pilot needs to understand, especially in busy terminal environments where aircraft types mix.
- There is more misinformation than not about how lift is created and what the physics are behind it.
 - Learn the right stuff even if you have to test out and use a “myth” as your answer (and you will).
 - The best book on this subject is Doug McLean’s “Understanding Aerodynamics: Arguing from the Real Physics”.
 - Admittedly, it is a technical, college-level read but most folks can find what they need about where the truth lies in Chapter 7.

THANKS for participating!

If you have questions or comments, feel free to contact me
at: airandspaceflight@gmail.com

© William A Foster 2022
All rights reserved.