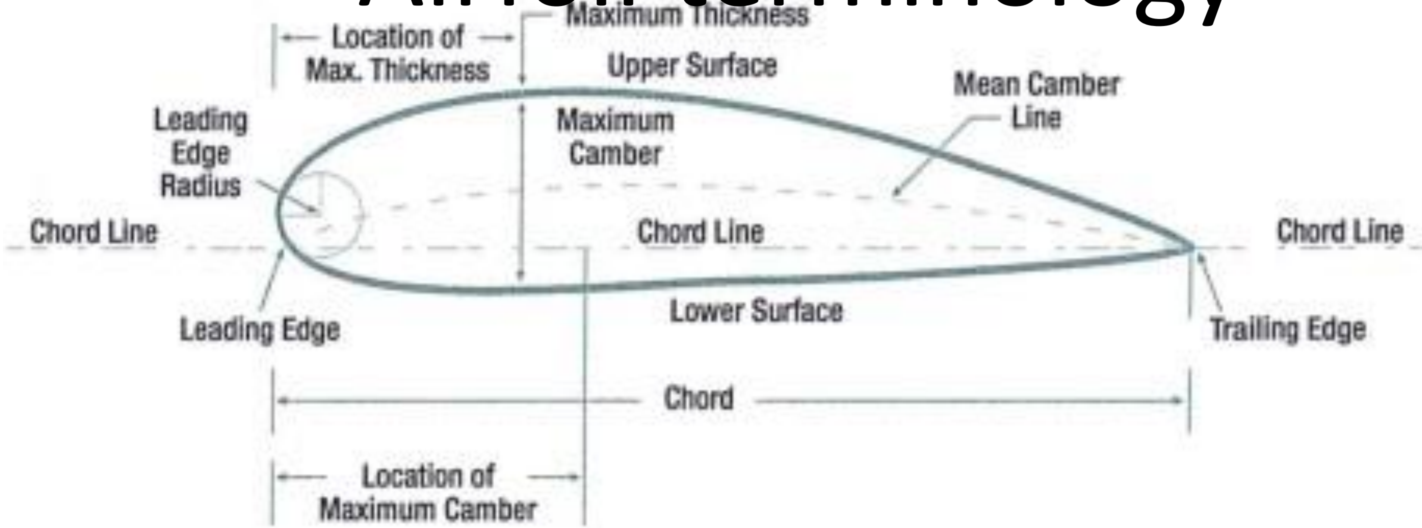
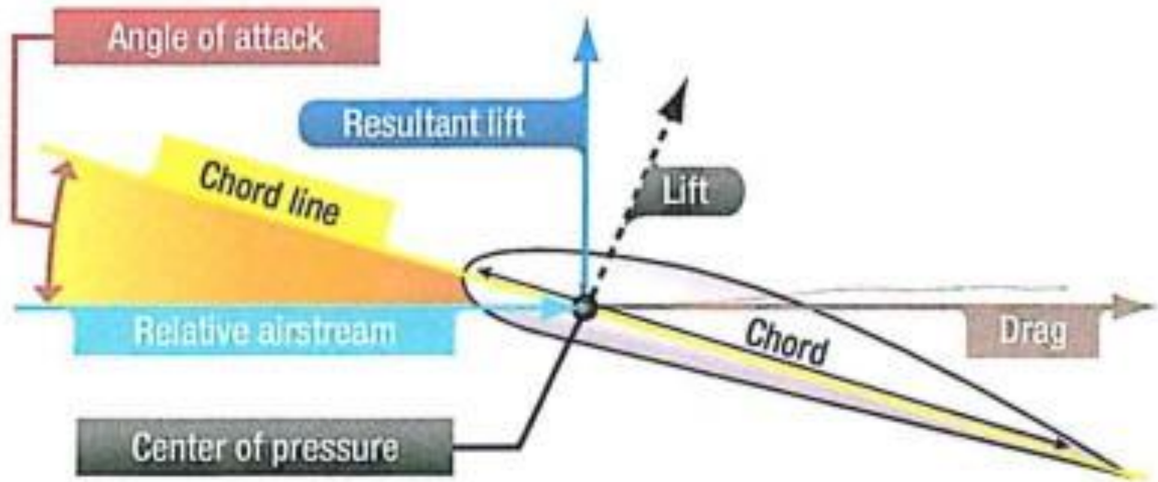
Aerodynamics of drones
Unit 2

Unit – II	08 Hrs
Aerodynamics of Drones: Airfoil nomenclature, Generation of Lift on Airfoils and Wings, Basic aerodynamics of fixed, rotary and flapping wing UAVs.	

Airfoil terminology





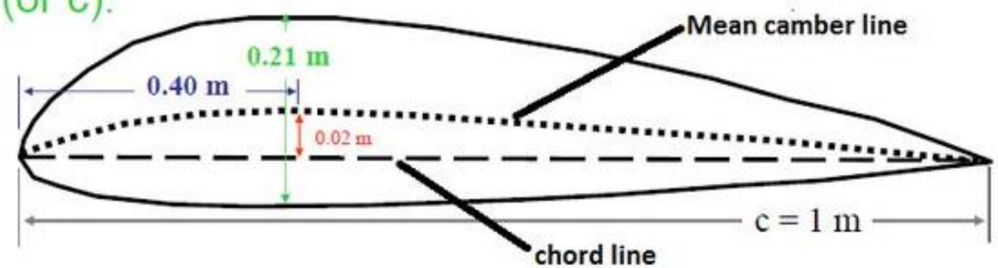
NACA Nomenclature

NACA 2421

1st Digit: Maximum camber is 2% of 2D airfoil chord length, c (or 3D wing mean chord length, $\overline{c}$).

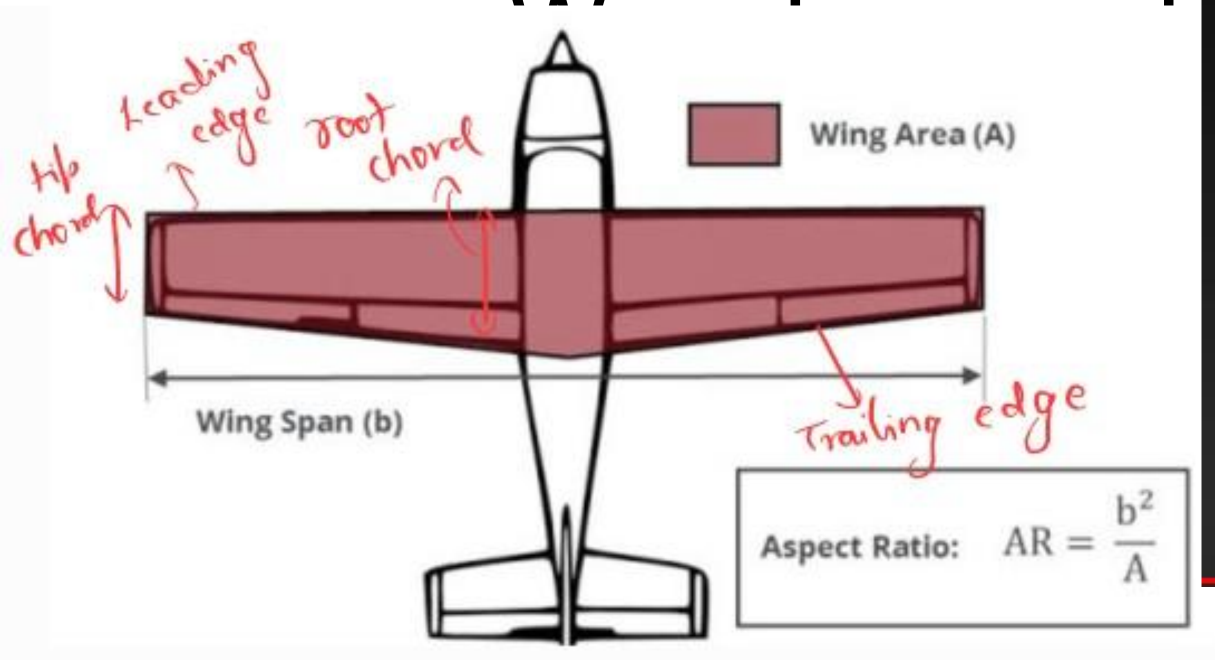
2nd Digit: Location of maximum camber is at 4/10ths (or 40%) of the chord line, from the LE.

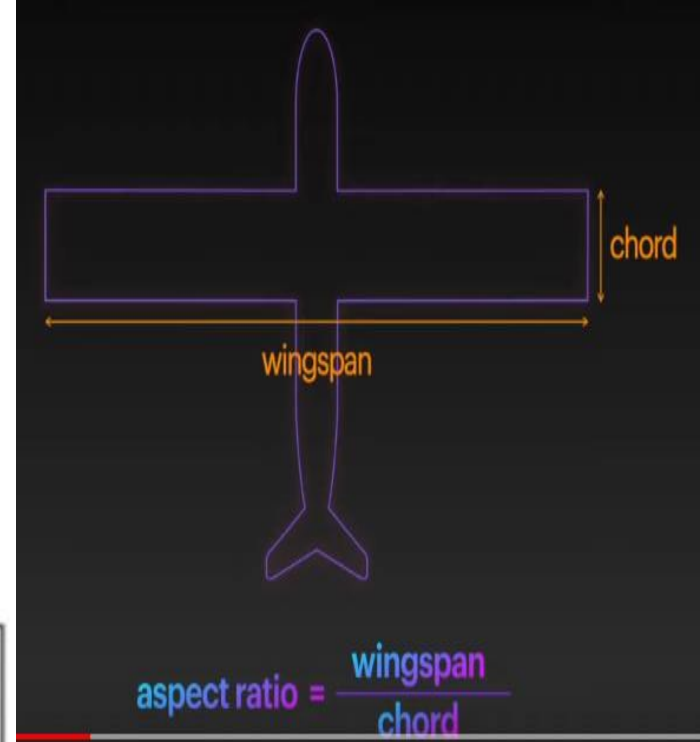
3rd & 4th Digits: Maximum thickness is 21% of c (or $\overline{c}$).

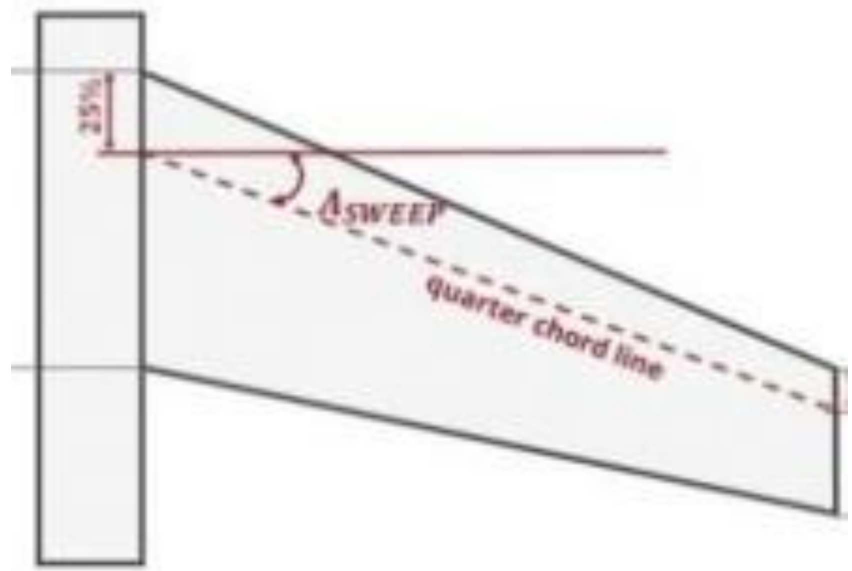


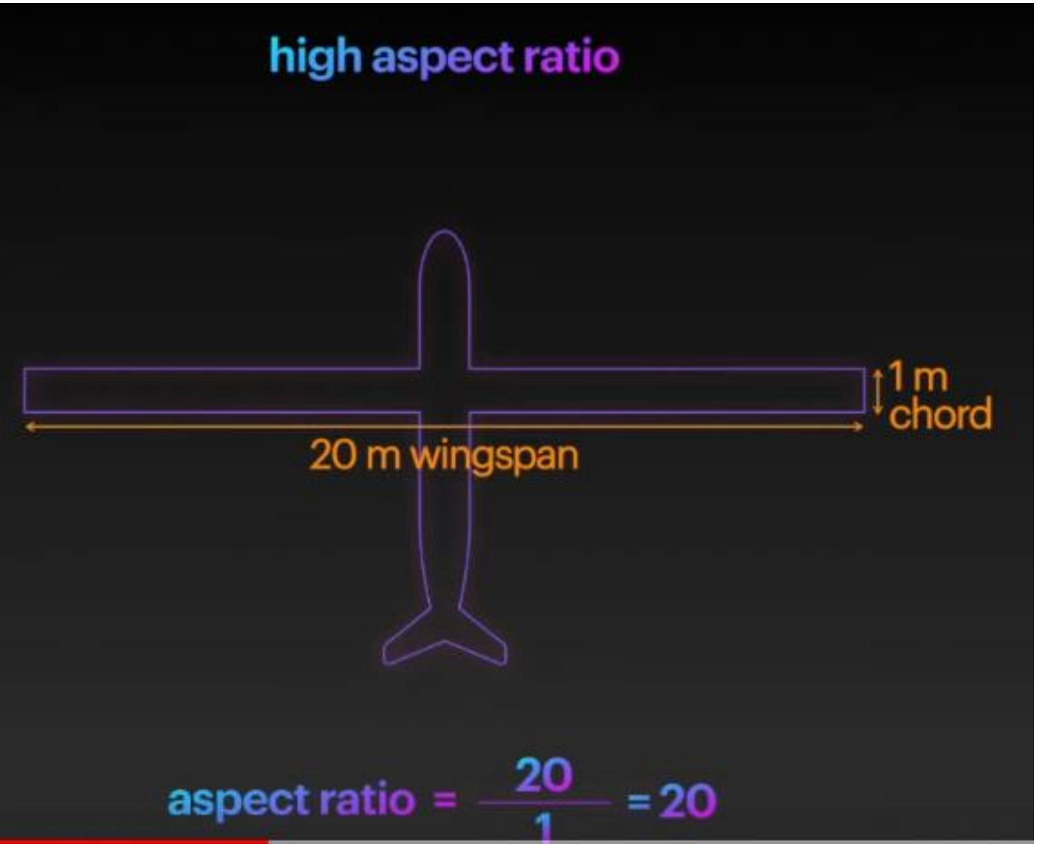
Airfoil terminology

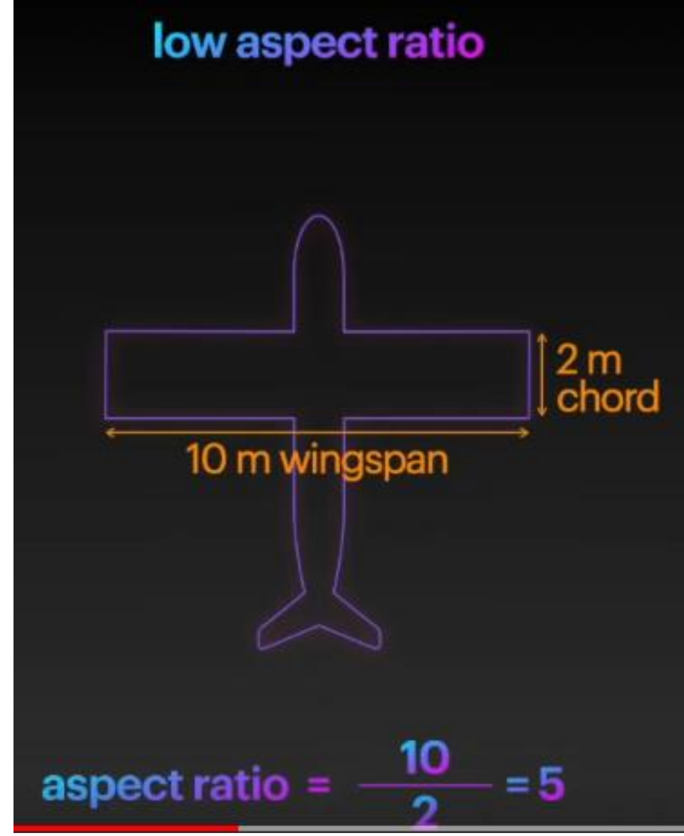
- Airfoil –The cross-sectional shape of the wing is called an airfoil
- Chord—the length of the chord line from leading edge to trailing edge; it is the characteristic longitudinal dimension of the airfoil section.
- Chord line—a straight line intersecting leading and trailing edges of the airfoil.
- Mean camber line—a line drawn halfway between the upper and lower surfaces of the airfoil.The shape of the mean camber is important for determining aerodynamic characteristics of an airfoil section.
- Camber: The maximum distance between the chord line and camber line.
- Thickness:it is the distance between upper and lower surface of an airfoil
- Leading edge—the front edge of an airfoil.
- Trailing edge—the rearmost edge of an airfoil.
- Angle of attack (AOA)—the angle measured between the resultant relative wind and chord line.
- Center of pressure—the point along the chord line of an airfoil through which all aerodynamic forces are considered to act

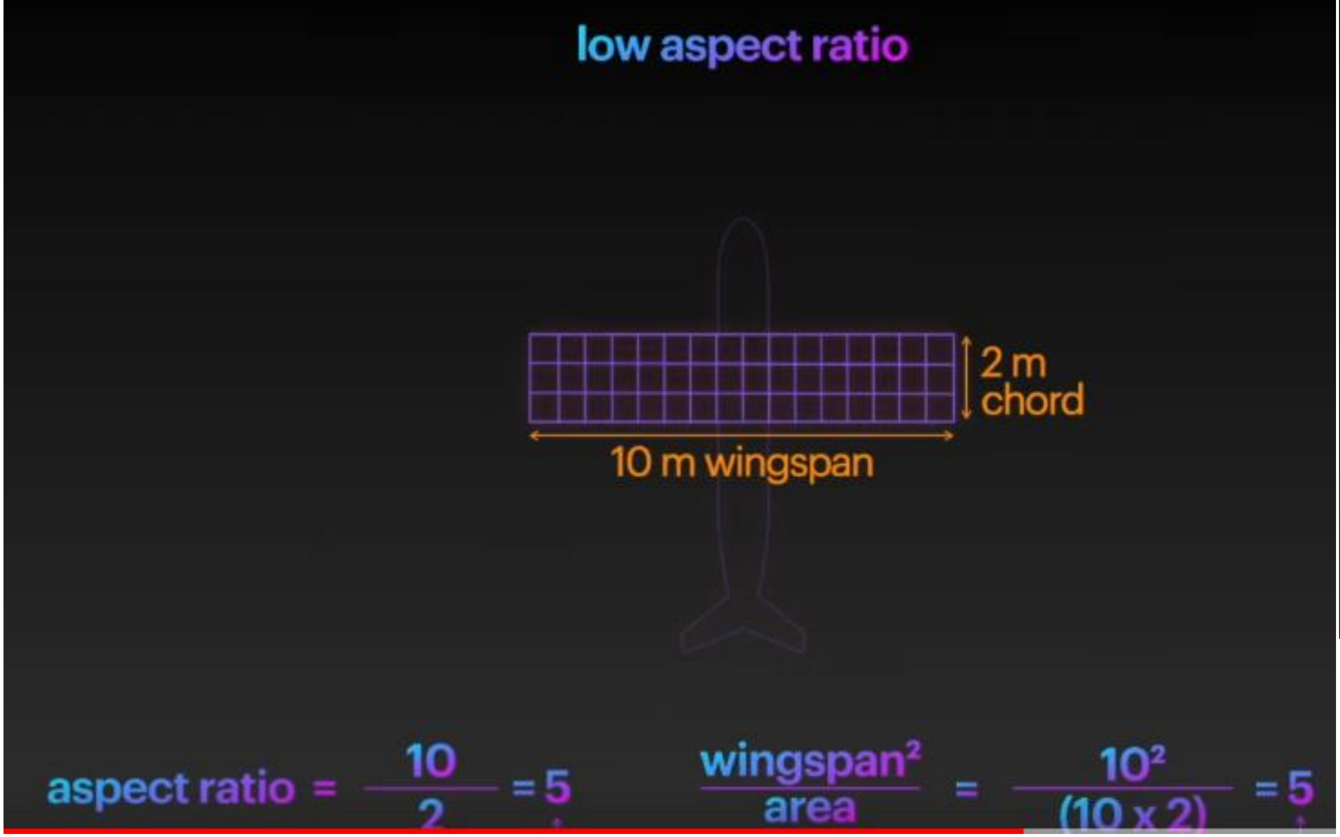

Leading edge
tip chord
root chord
Wing Area (A)
Wing Span (b)
Trailing edge
Aspect Ratio: $AR = \frac{b^2}{A}$

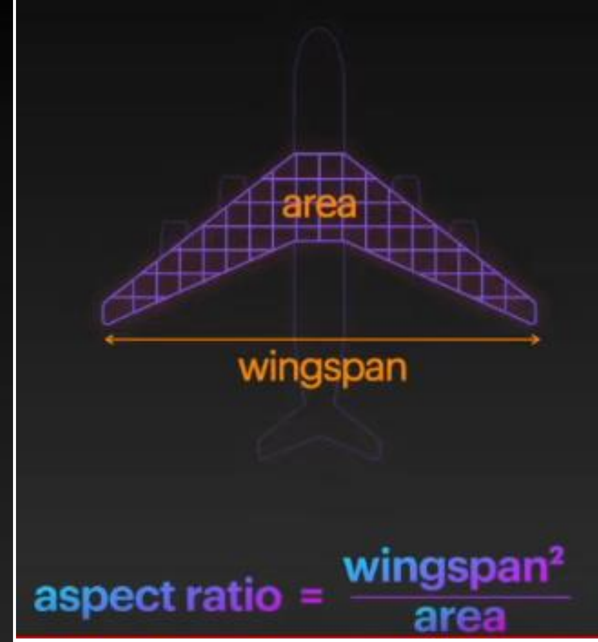

chord
wingspan
aspect ratio = $\frac{\text{wingspan}}{\text{chord}}$

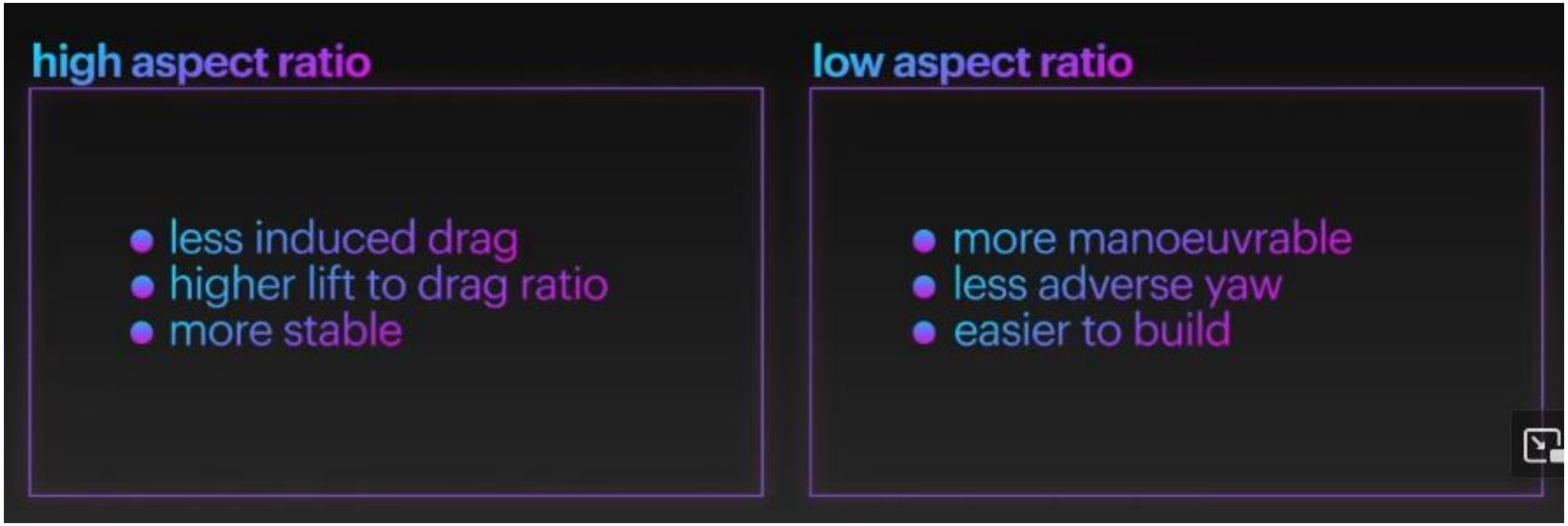

25%
Λ_{SWEEP}
quarter chord line


high aspect ratio
1 m
chord
20 m wingspan
aspect ratio = 20/1 = 20


low aspect ratio
2 m
chord
10 m wingspan
aspect ratio = 10/2 = 5

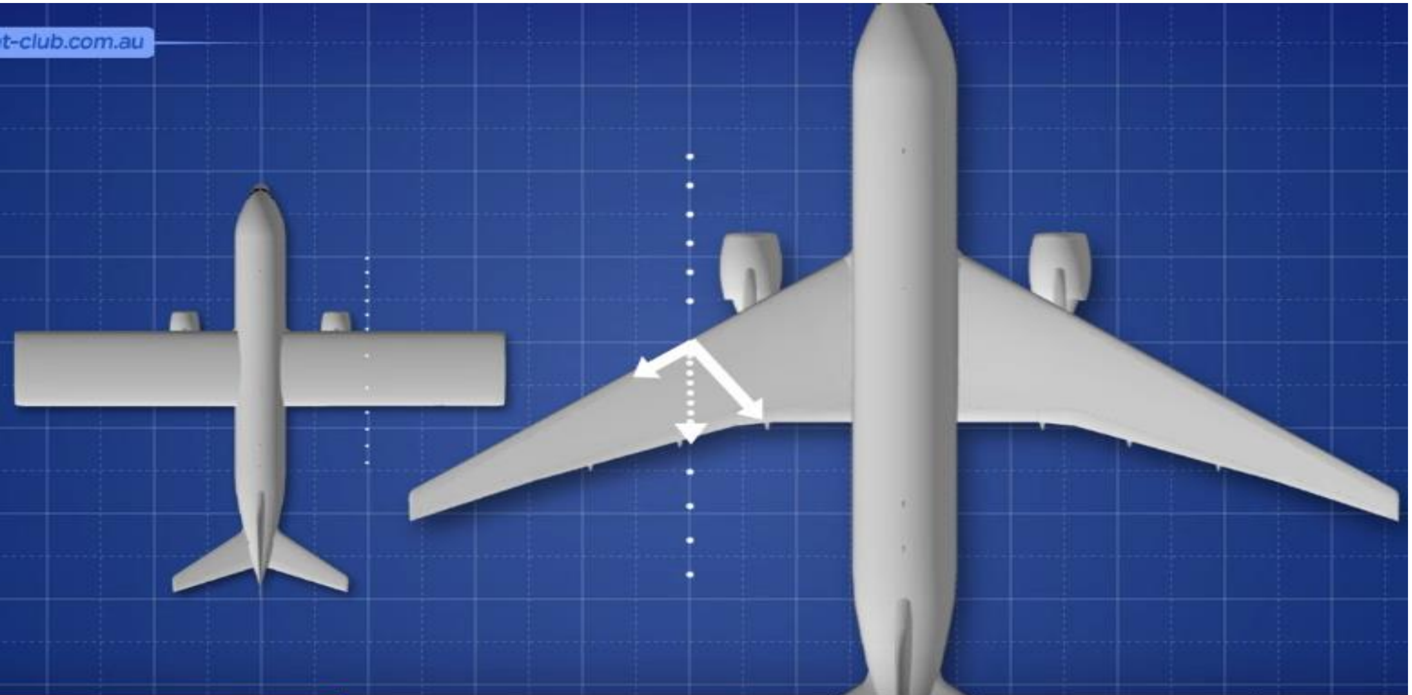

low aspect ratio
2 m
chord
10 m wingspan
aspect ratio = 10 / 2 = 5
wingspan² / area = 10² / (10 x 2) = 5


area
wingspan
aspect ratio = wingspan² / area


high aspect ratio
less induced drag
higher lift to drag ratio
more stable
low aspect ratio
more manoeuvrable
less adverse yaw
easier to build

- **Wing tips :**The ends of the wing are called the wing tips,
- **Wing span** :The distance from one wing tip to the other is called the span.
- **Wing planform:**The shape of the wing, when viewed from above looking down onto the wing, is called a planform.
- **The wing area** is the projected area of the planform and is bounded by the leading and trailing edges and the wing tips.
- **The total surface area** includes both upper and lower surfaces. The wing area is a projected area and is almost half of the total surface area
- **The aspect ratio** (AR) of a wing is defined to be the square of the span (b)divided by the wing area (A). Aspect ratio is a measure of how long and slender a wing is from tip to tip
- **Taper Ratio** :It is defined as the ratio between the tip chord (Ct) to the root chord (Cr).
- **Sweep angle** :The angle between a constant percentage chord line along the semispan of the wing and the lateral axis perpendicular to the aircraft centerline (y-axis) is called leading edge sweep (□LE).

For reference on swept wings: https://www.youtube.com/watch?v=11nz0YZSNxw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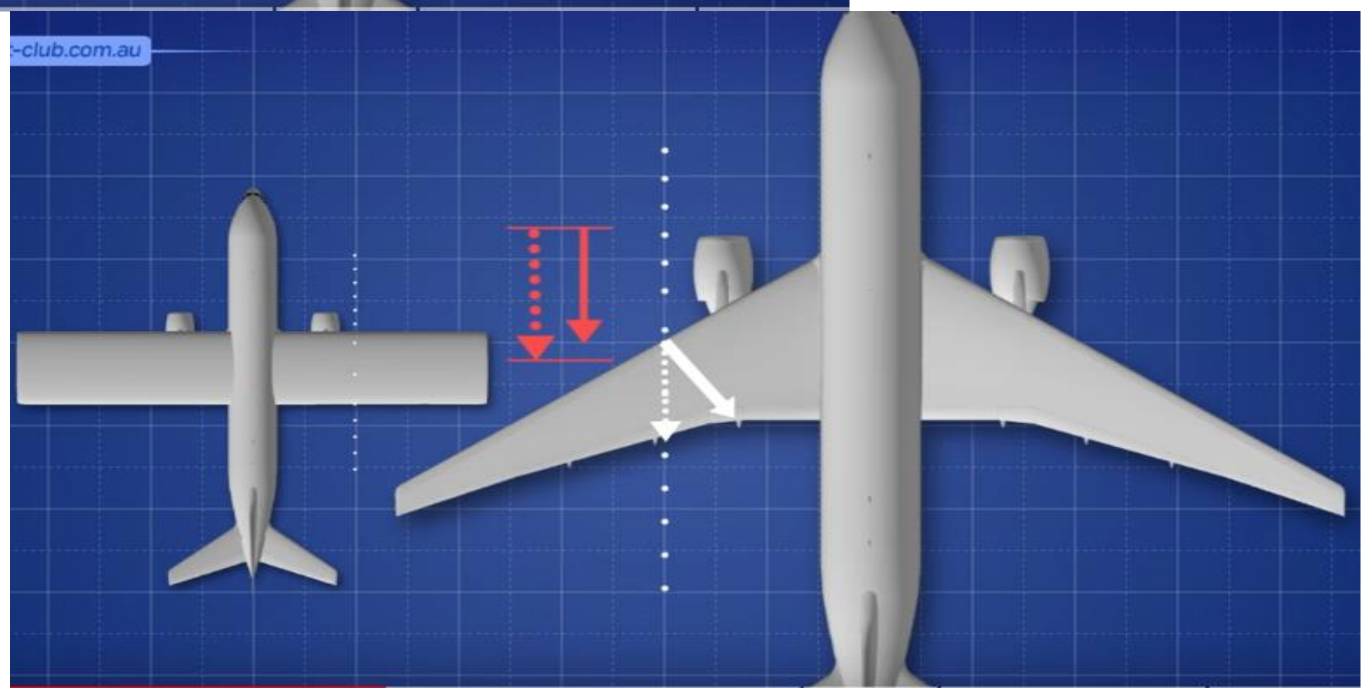
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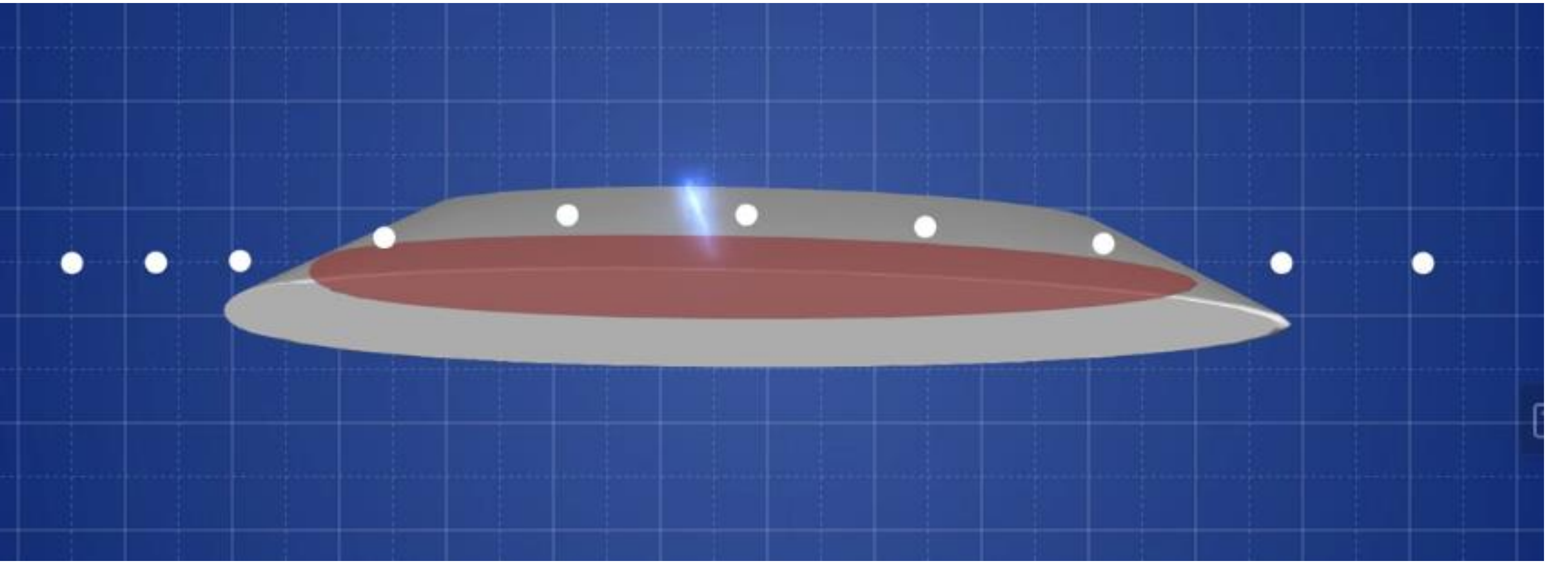
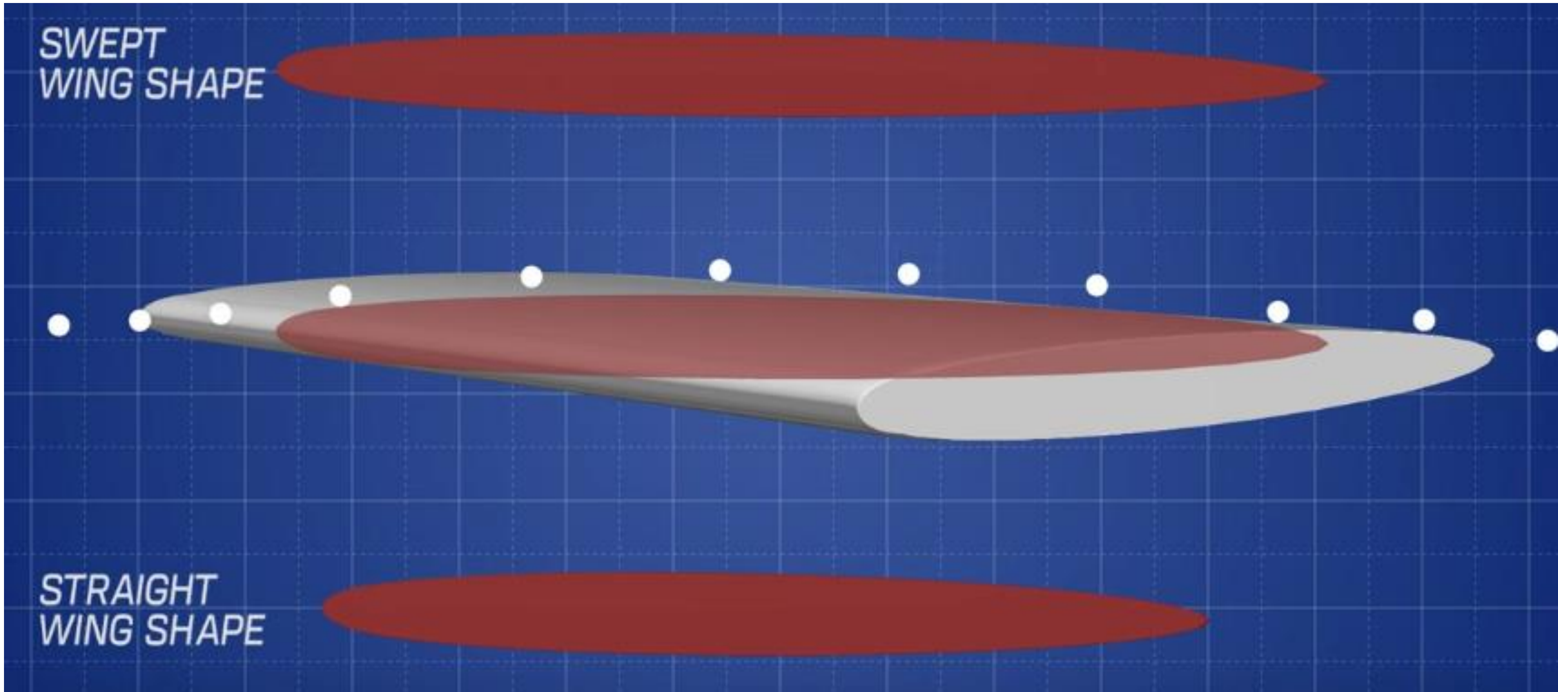
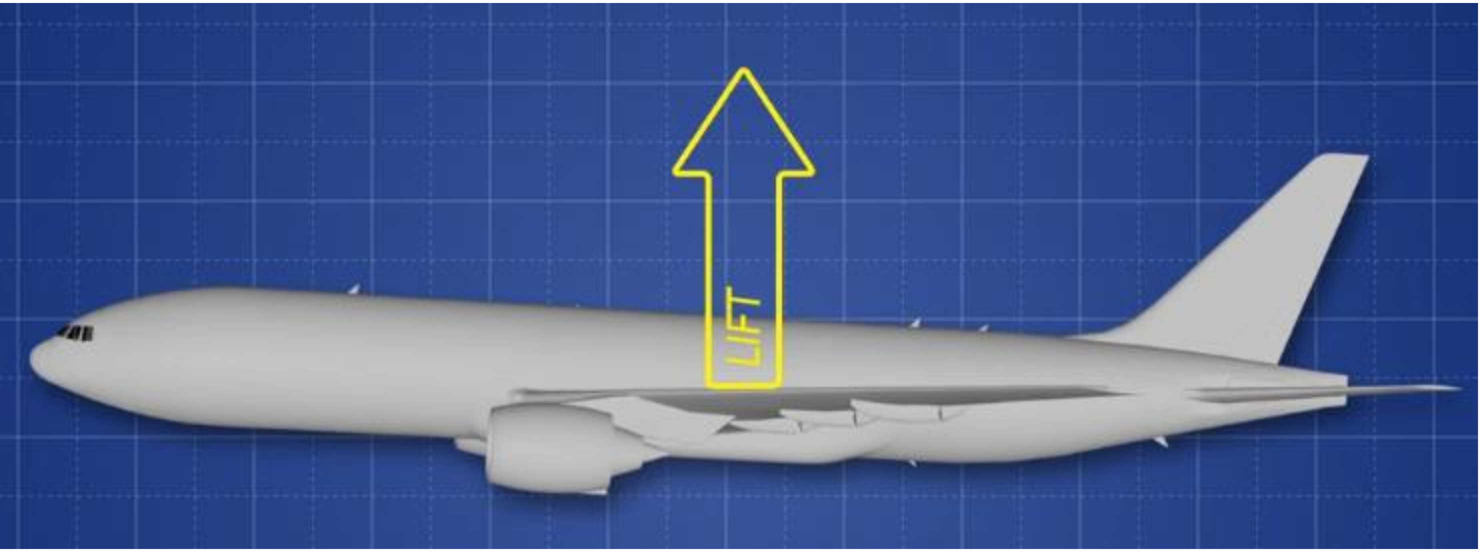
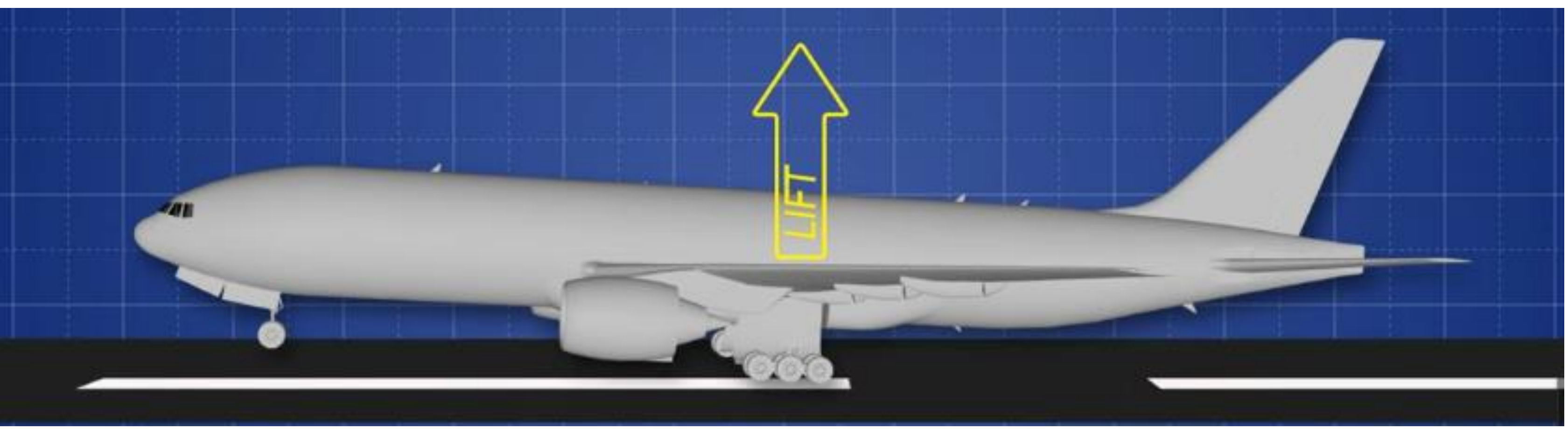



SWEPT
WING SHAPE
STRAIGHT
WING SHAPE

Lift for rectangular wing and swept wing (effect on take off distance)



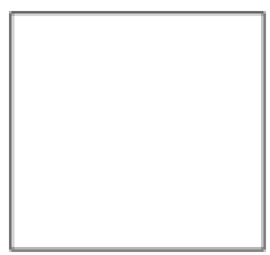


a. AR = 26.7

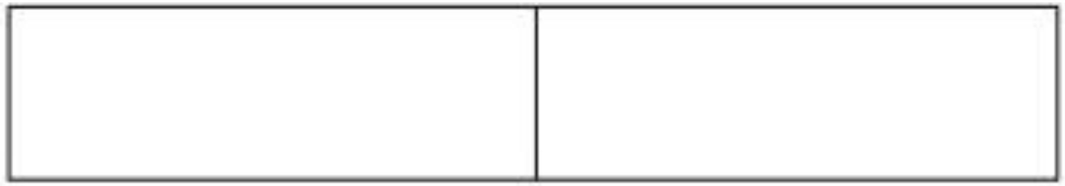
b. AR = 15

c. AR = 6.67

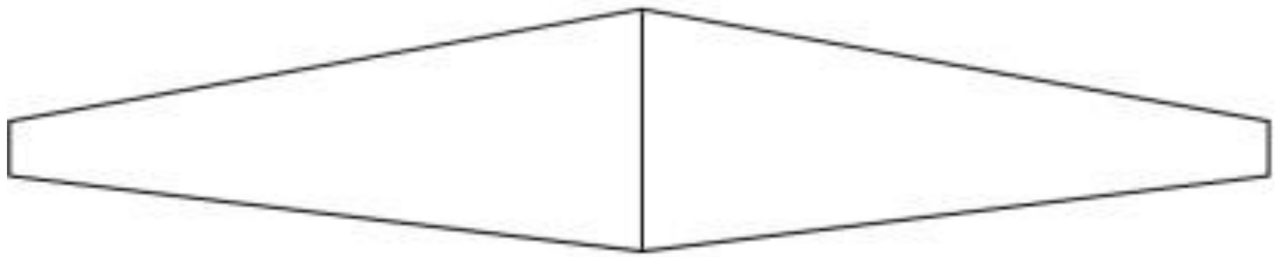
d. AR = 3.75



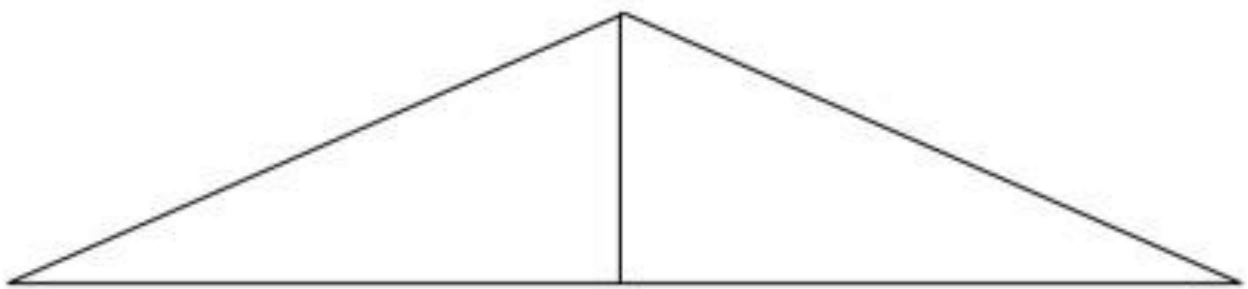
e. AR = 1



a. Rectangle (λ =1)



b. Trapezoid $0 < \lambda < 1$ (straight tapered)

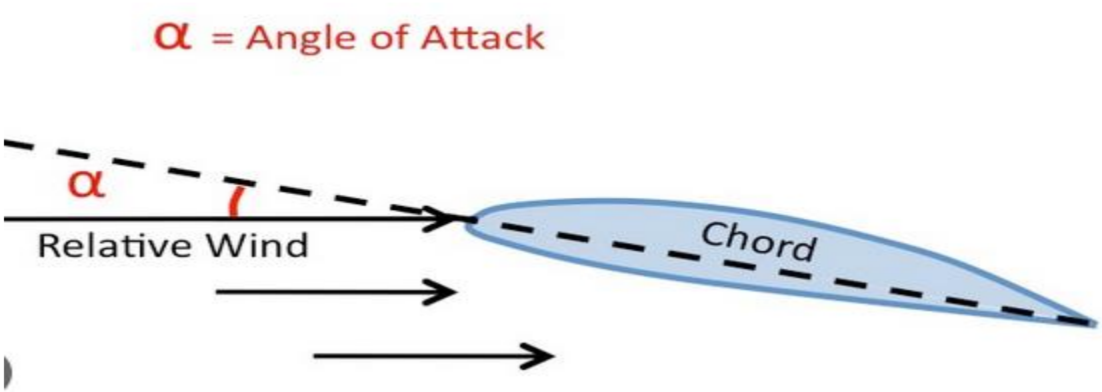


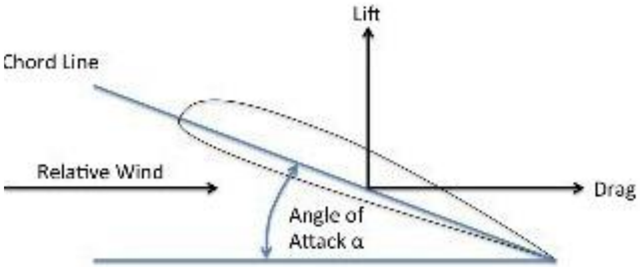
c. Triangle (delta) $\lambda = 0$

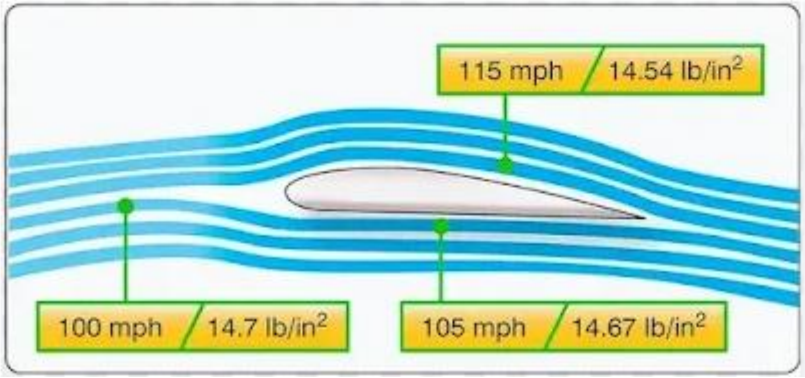
Aerodynamics of fixed wings

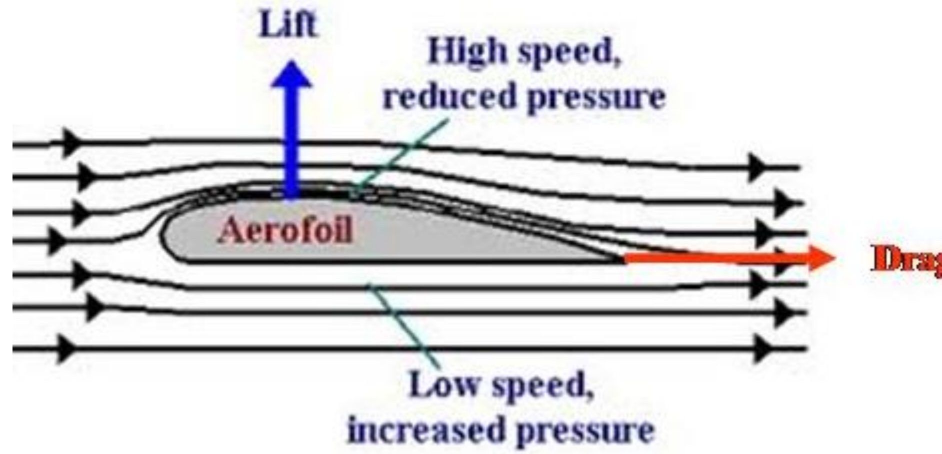
Lift

- Lift is a force that is produced by the dynamic effect of the air acting on the airfoil, and acts perpendicular to the flight path through the center of lift (CL) and perpendicular to the lateral axis.
- In level flight, lift opposes the downward force of weight.
- As the AOA increases, lift increases (all other factors being equal).
- Lift depends on the density of the air, the square of the velocity, the air's viscosity and compressibility, the surface area over which the air flows, the shape of the body, and the body's inclination to the flow

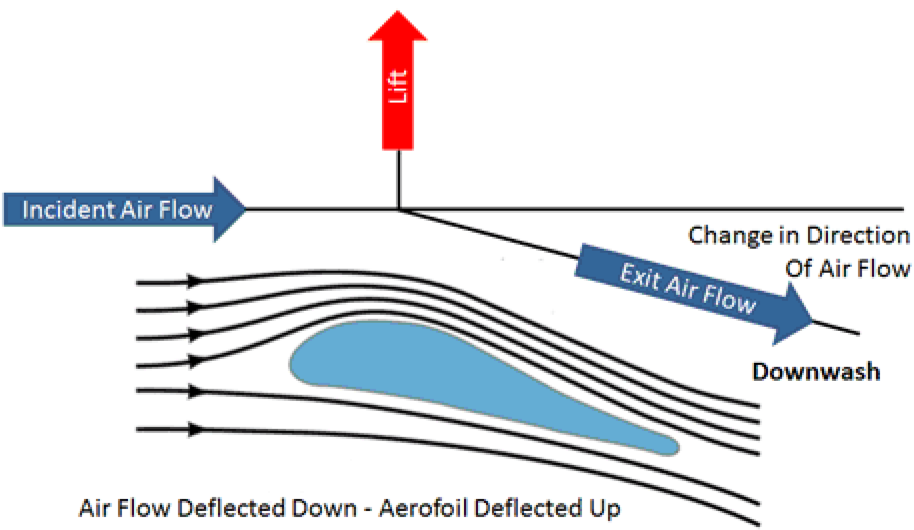








Aerodynamic Lift – Explained by Newton's Laws of Motion

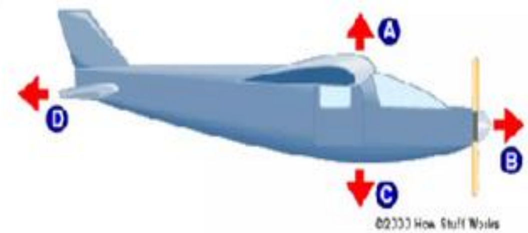


Lift occurs when a moving flow of air is turned by a solid object.
The flow is turned in one direction, and the lift is generated in the opposite directio
according to Newton's Third Law of action and reaction.
For an aircraft wing, both the upper and lower surfaces contribute to the flow turni
or the downwash.

Straight and Level Flight

In order for an airplane to fly straight and level, the following relationships must be true:

Thrust = Drag
Lift = Weight



Q1 - What would happen if Drag is greater than Thrust?

Q2 - What would happen if Lift is greater than Weight?

Lift Formula

$$F_L = \tfrac{1}{2} \rho v^2 C_l A$$

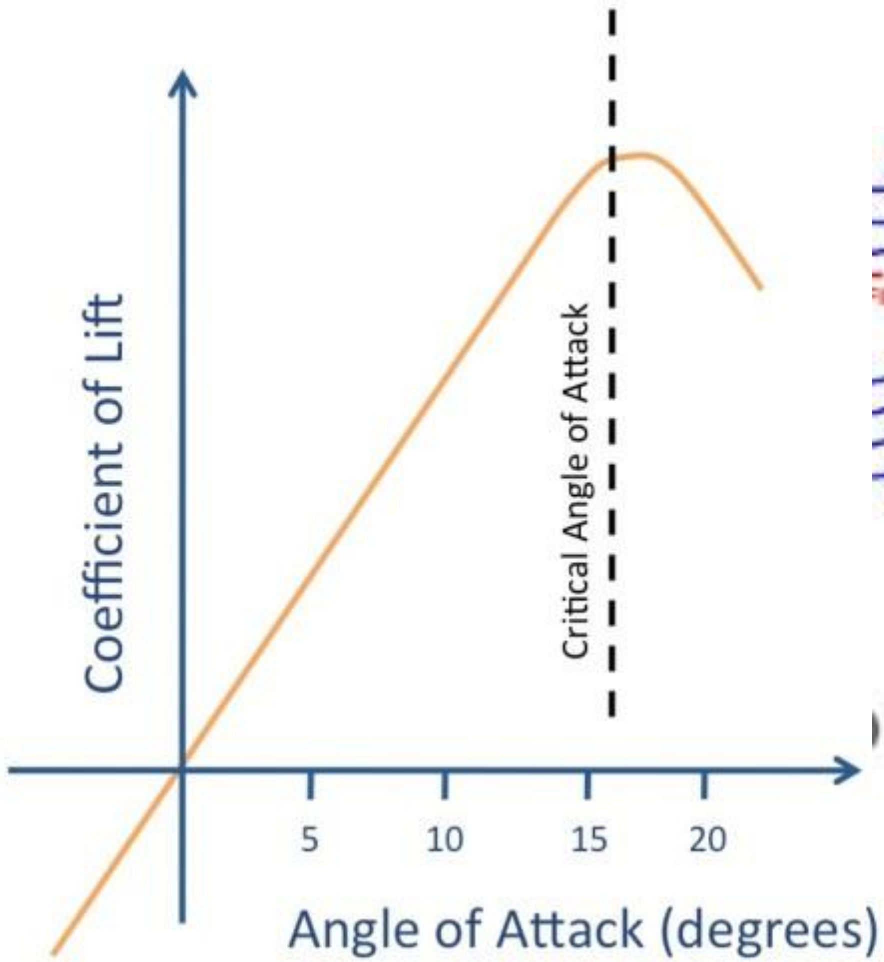
- F_L = Force of lift
- ρ = Density of air
- v = Velocity
- A = Total area of wings
- C_l = Coefficient of lift

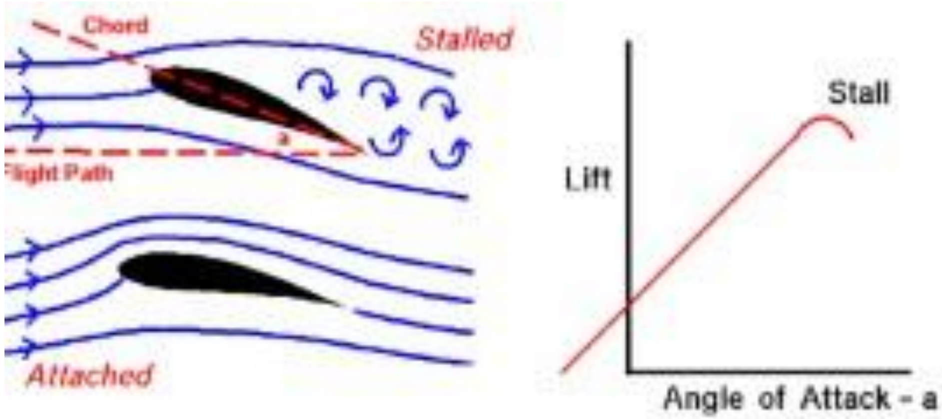
Lift coefficient

$$Cl = \frac{L}{\rho V^2 A / 2}$$

- The lift coefficient is a number that engineers use to model all of the complex dependencies of shape, inclination, and some flow conditions on lift.
- The lift coefficient then expresses the ratio of the lift force to the force produced by the dynamic pressure times the area.
- Engineers usually determine the value of the lift coefficient by using models in a wind tunnel. Within the tunnel we can set the velocity, density, and area of the model and measure the lift produced. Through division, we arrive at a value for the lift coefficient.

Cl vs AOA



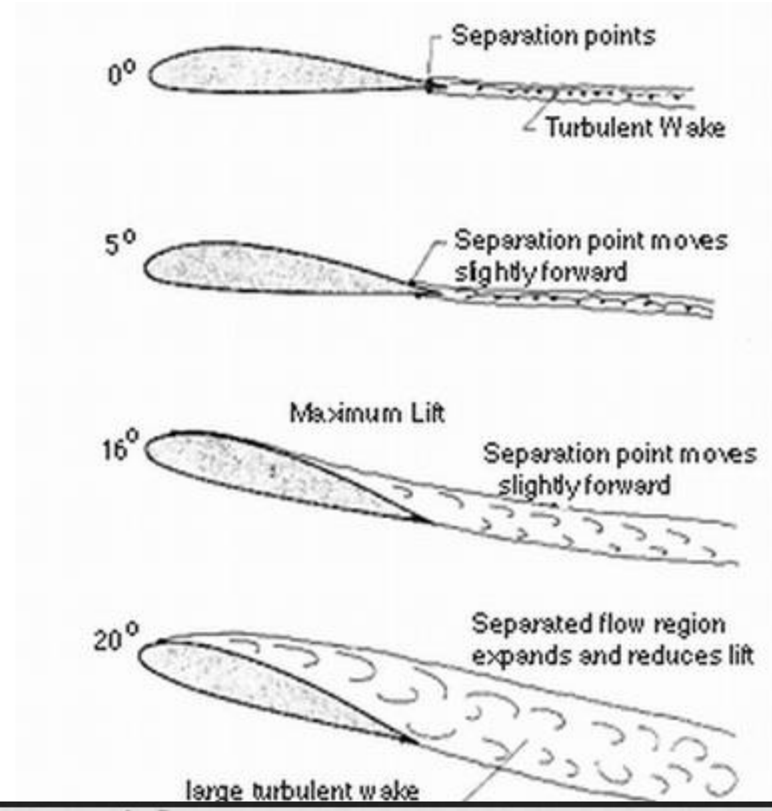


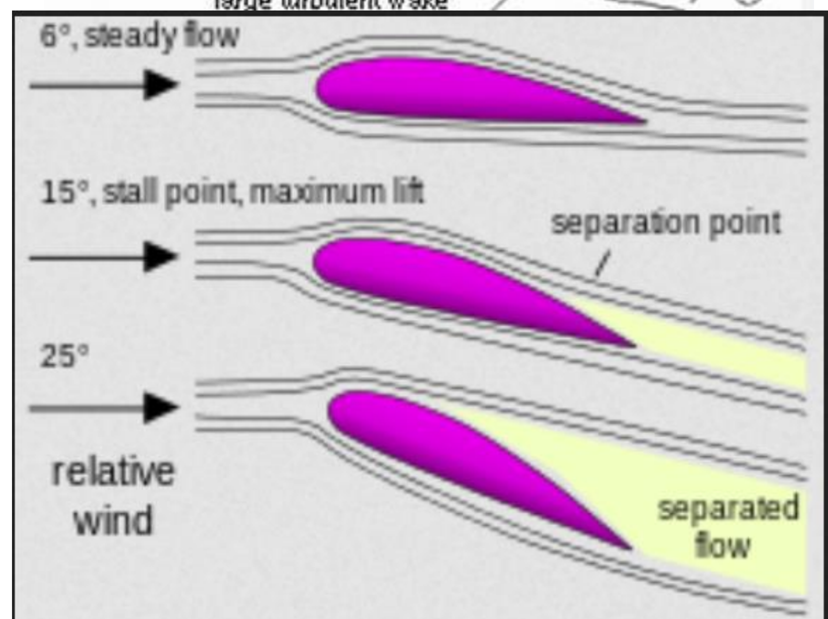
For small angles, lift is related to angle.
Greater Angle = Greater Lift

For larger angles, the lift relation is complex.
Included in Lift Coefficient

Stall

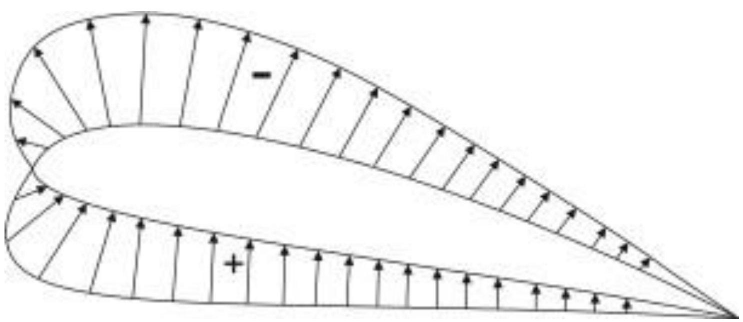
When the AOA is increased gradually toward a positive AOA, the lift component increases rapidly up to a certain point and then suddenly begins to drop off. During this action the drag component increases slowly at first, then rapidly as lift begins to drop off. When the AOA increases to the angle of maximum lift, the *burble point* is reached. This is known as the *critical angle*. When the critical angle is reached, the air ceases to flow smoothly over the top surface of the airfoil and begins to burble or eddy. This means that air breaks away from the upper camber line of the wing. What was formerly the area of decreased pressure is now filled by this burbling air. When this occurs, the amount of lift drops and drag becomes excessive. The force of gravity exerts itself, and the nose of the aircraft drops. This is a *stall*. Thus, the burble point is the stalling angle.



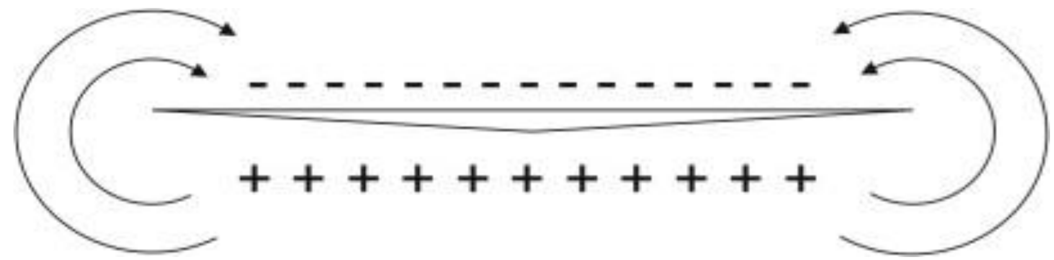


- Upwash means the upward movement of air just before the leading edge of the wing. A corresponding downwash occurs at the trailing edge

Pressure distribution over airfoil and wing



Over airfoil



Spanwise

- It is apparent that a wing would have positive pressure on its underside and negative (in a relative sense) pressure on the top. This is shown in Figure as plus signs on the bottom and minus signs on the top as viewed from the front or leading edge of the wing.

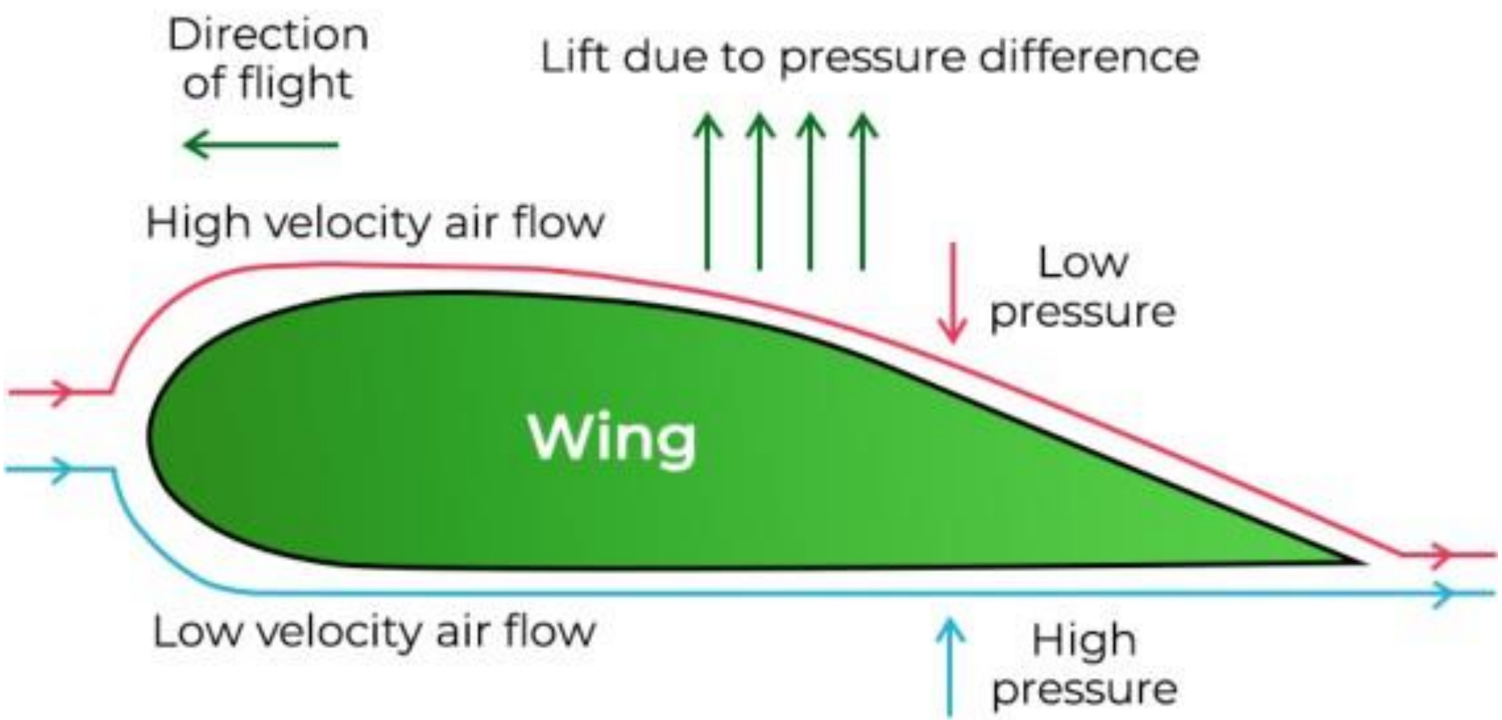
Mechanism of lift generation

Bernoulli's Principle

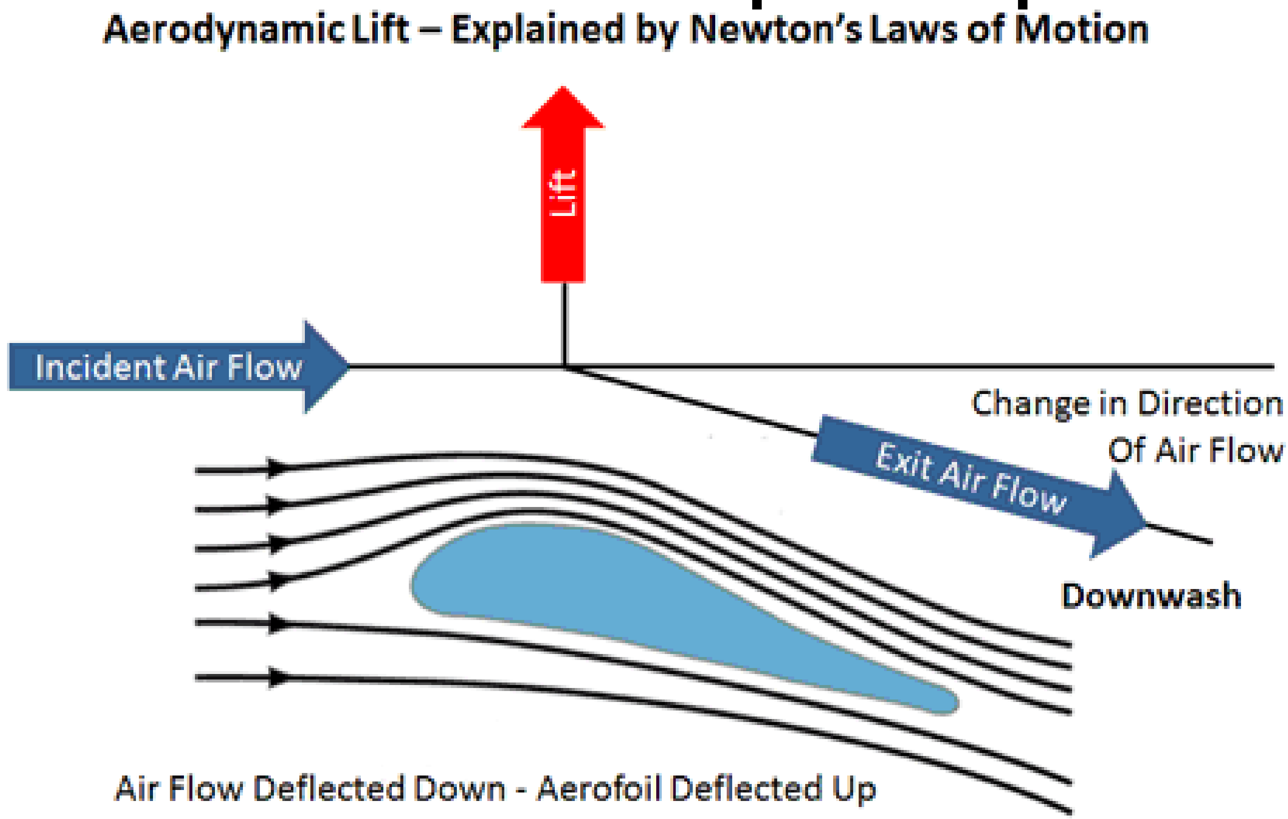
- Bernoulli's Principle provides the relationship between the pressure (P) and velocity of the fluid flowing.
- Bernoulli's Principle says that when a fluid is flowing horizontally, the points where the speed is higher exhibit low pressure, while the points where the speed is lower exhibit high pressure.
- Bernoulli's theorem governs the operation of airplanes. The plane's wings have a certain form. When the plane is moving, the air flows past it at a high rate, despite the plane's low surface wig. There is a variation in the flow of air above and below the wings due to Bernoulli's principle. As a result of the flow of air on the wing's up surface, this concept causes a change in pressure

Bernoulli's Principle Example

Lift of an Aircraft



Newton's principle



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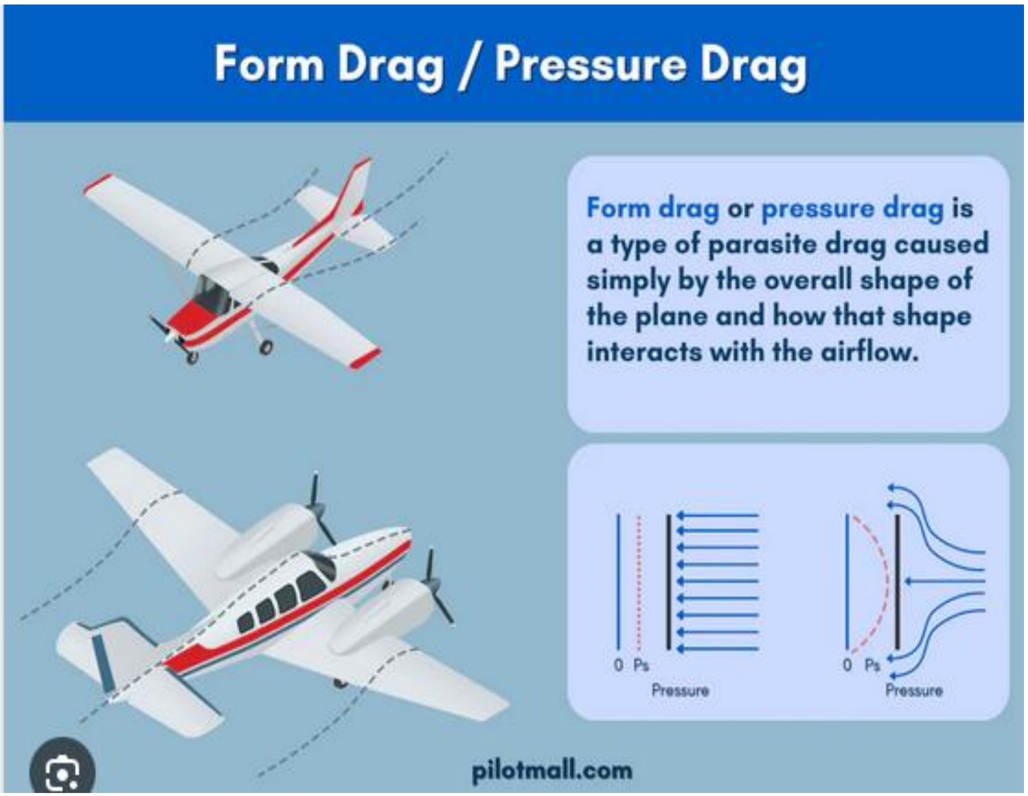
The flow is turned in one direction, and the lift is generated in the opposite direction, according to Newton's Third Law of action and reaction.
For an aircraft wing, both the upper and lower surfaces contribute to the flow turning or the downwash.

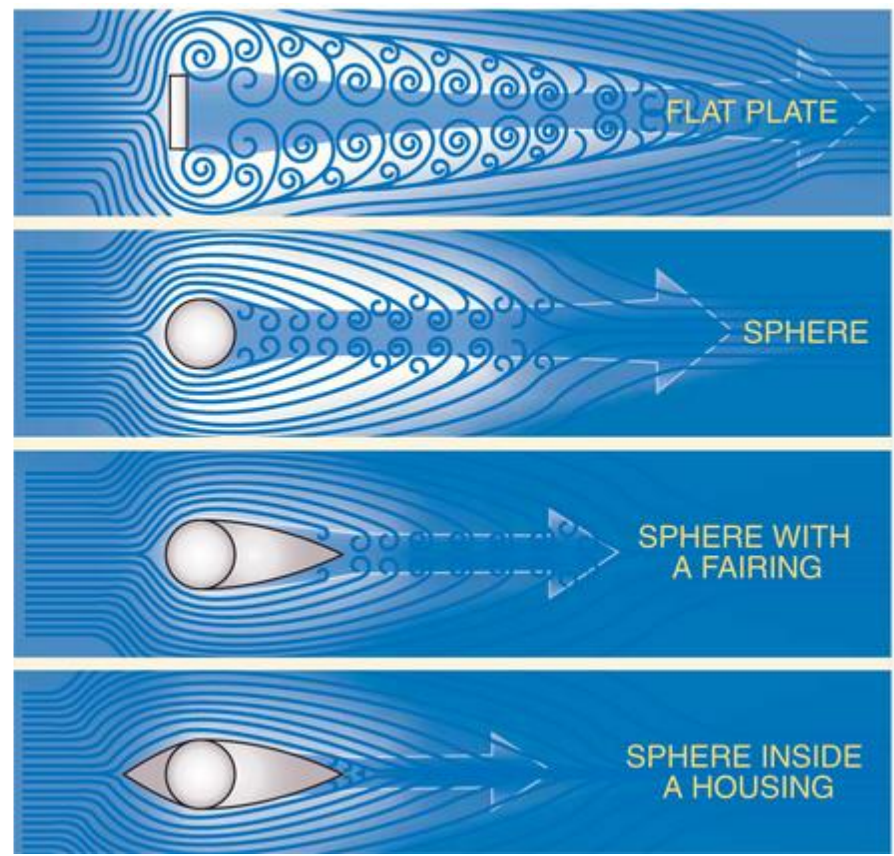
Drag

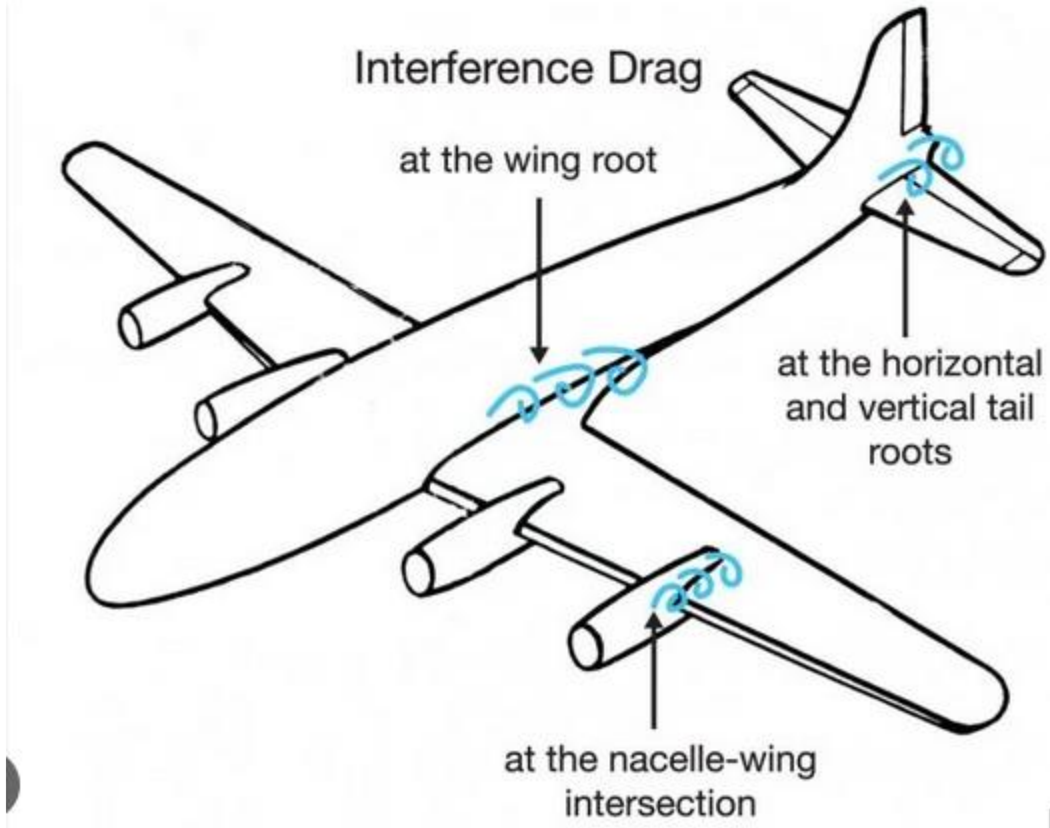
- Drag is the force that resists movement of an aircraft through the air.
- There are two basic types: parasite drag and induced drag.
- **Parasite Drag**:As the term parasite implies, it is the drag that is not associated with the production of lift. This includes the displacement of the air by the aircraft, turbulence generated in the airstream, or a hindrance of air moving over the surface of the aircraft and airfoil.
- There are three types of parasite drag: form drag, interference drag, and skin friction.
- **Form drag:**it is the portion of parasite drag generated by the aircraft due to its shape and airflow around it.
- **Interference Drag**:Interference drag comes from the intersection of airstreams that creates eddy currents, turbulence, or restricts smooth airflow.
- **Skin friction drag:** It is the aerodynamic resistance due to the contact of moving air with the surface of an aircraft

Induced drag: The second basic type of drag is induced drag.It is the drag caused due to generation of lift.

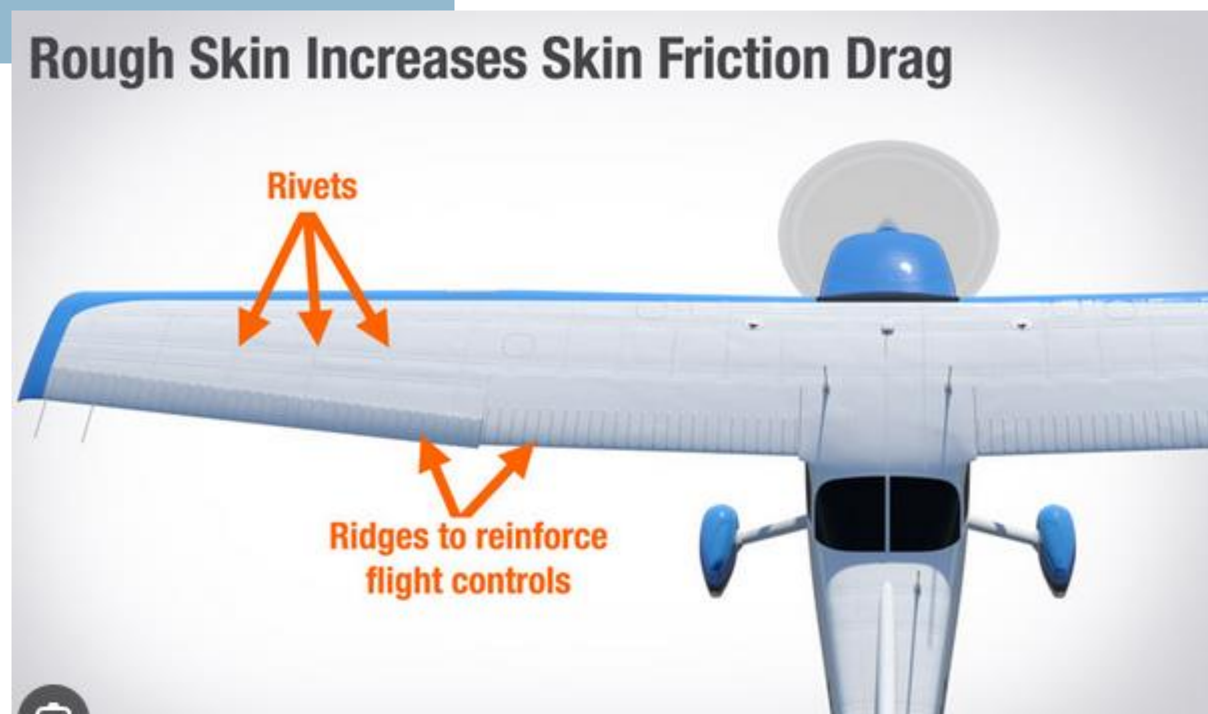
Wave drag: The drag caused due to formation of shock waves when an aircraft is travelling faster than the speed of sound.

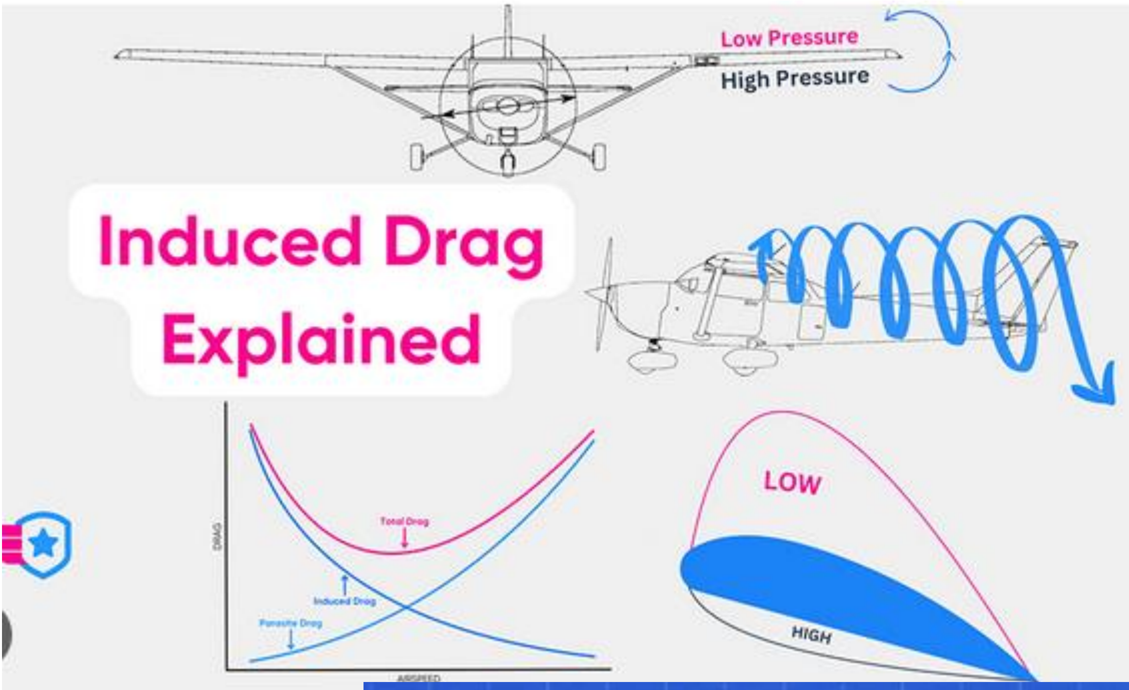

Form Drag / Pressure Drag
Form drag or pressure drag is a type of parasite drag caused simply by the overall shape of the plane and how that shape interacts with the airflow.
0 Ps
Pressure
0 Ps
Pressure
pilotmall.com


FLAT PLATE
SPHERE
SPHERE WITH A FAIRING
SPHERE INSIDE A HOUSING

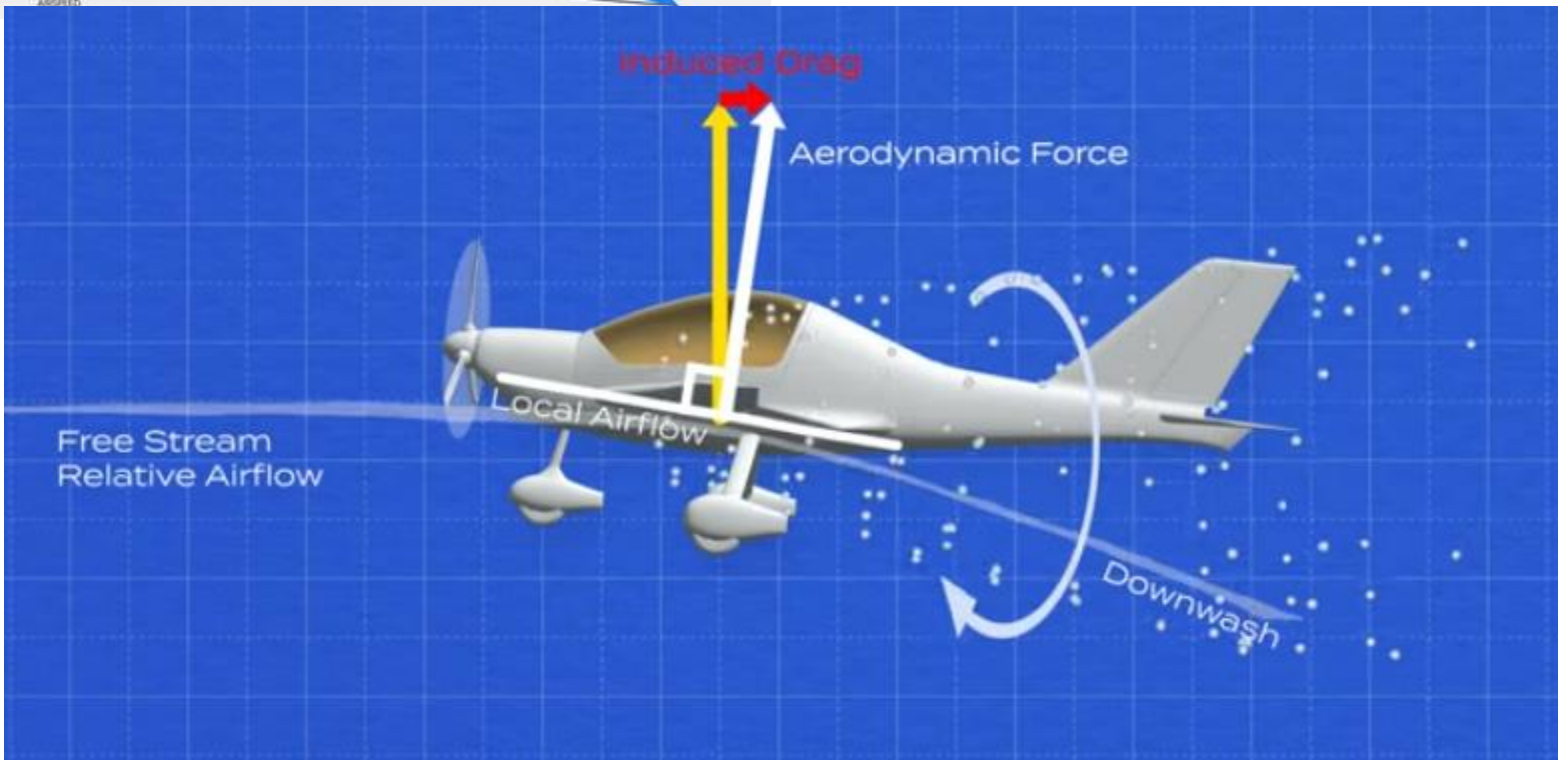

Interference Drag
at the wing root
at the horizontal
and vertical tail
roots
at the nacelle-wing
intersection


Skin Friction Drag
Skin friction drag is a type of parasite drag caused by rough spots on the skin of the plane.
Anything that takes away from a clean, smooth, perfectly aerodynamic surface causes skin friction drag.

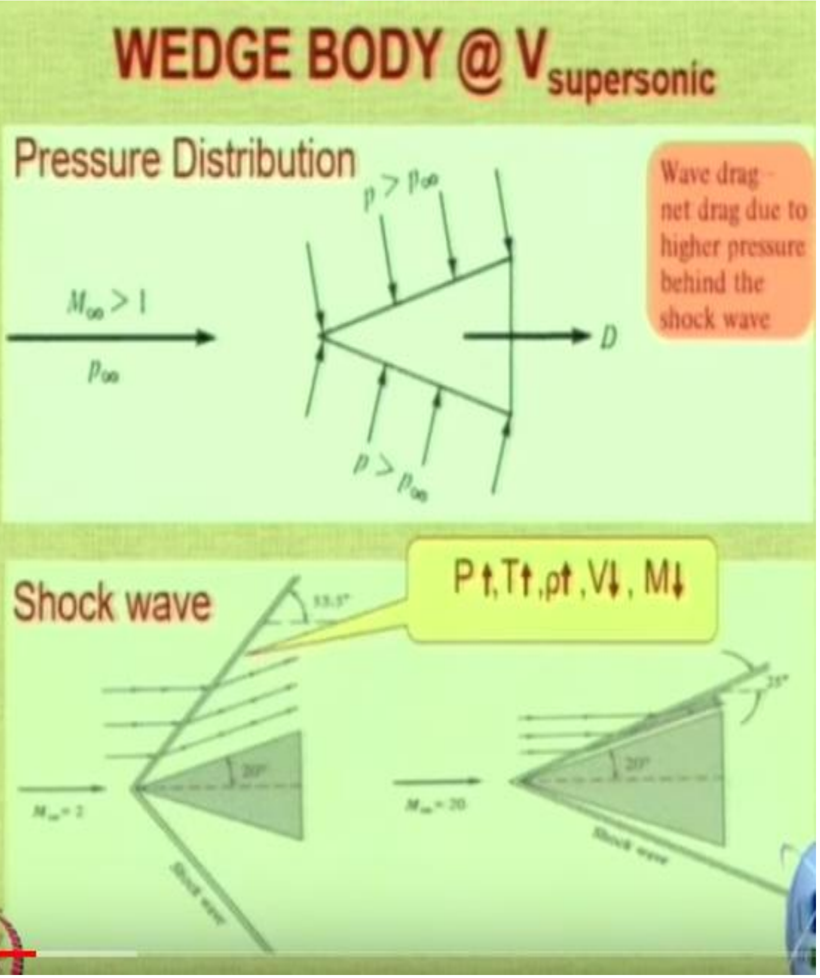

Rough Skin Increases Skin Friction Drag
Rivets
Ridges to reinforce flight controls

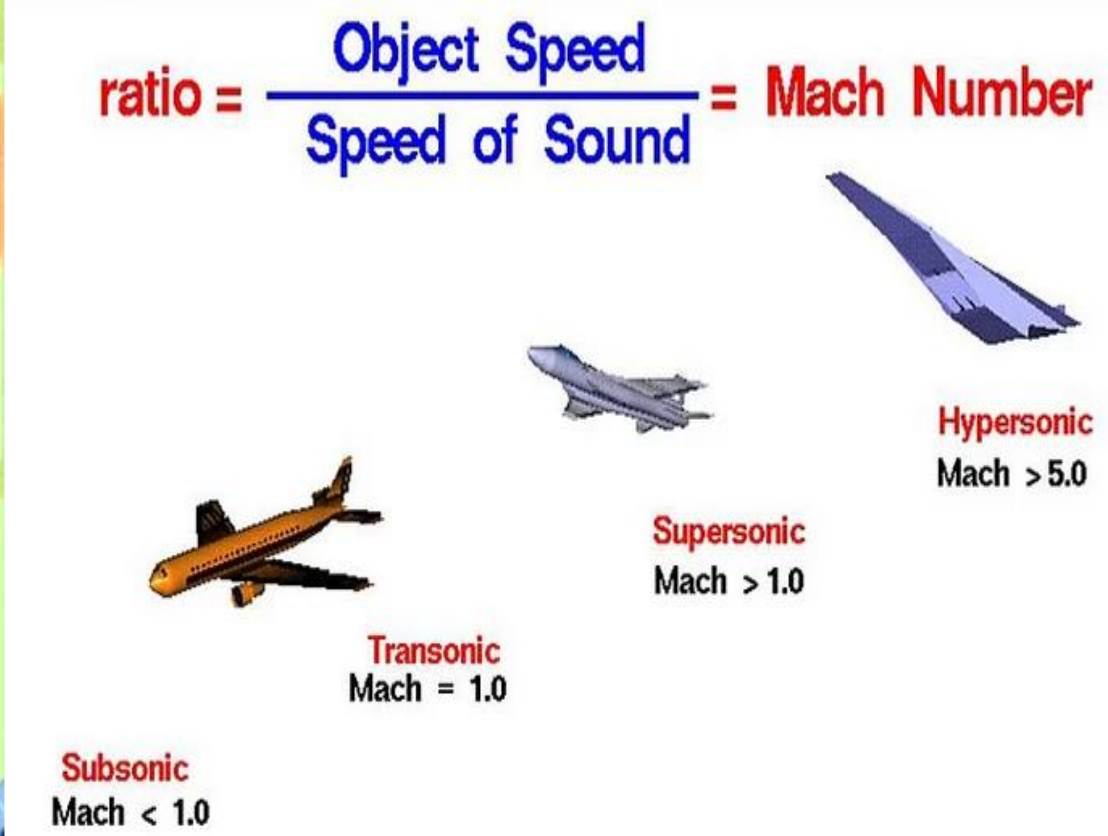


For more information:
https://www.youtube.com/watch?v=MnB6Lqr91Yc

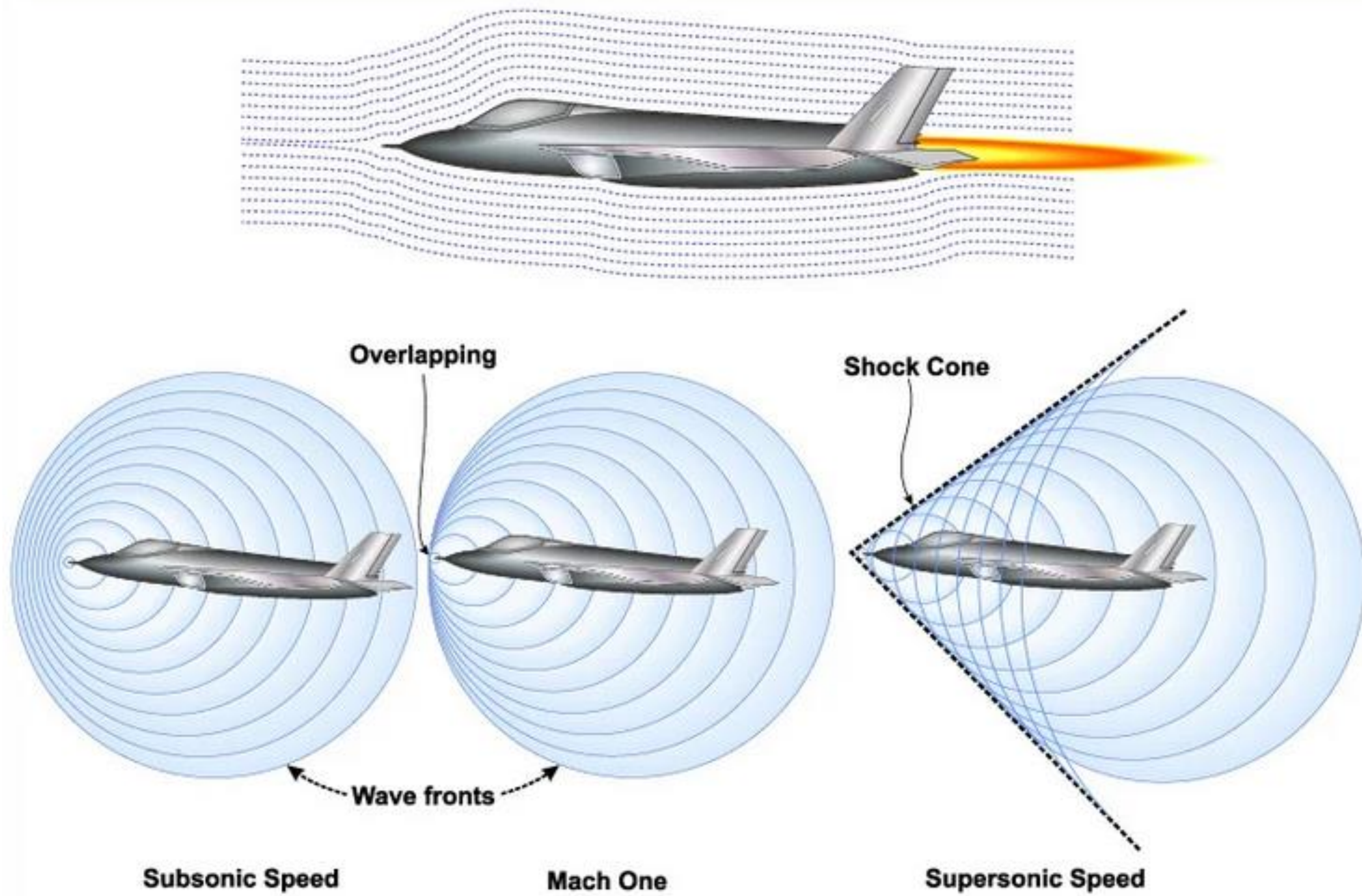


Wave drag





For further referece on wave drag: https://www.youtube.com/watch?v=Q5Amc5Vu3n8


Overlapping
Shock Cone
Wave fronts
Subsonic Speed
Mach One
Supersonic Speed

Drag formula

$$F_D = \frac{1}{2}\rho v^2 C_D A$$

where

F_D is the **drag force**,

ρ is the density of the fluid,[11]

v is the speed of the object relative to the fluid,

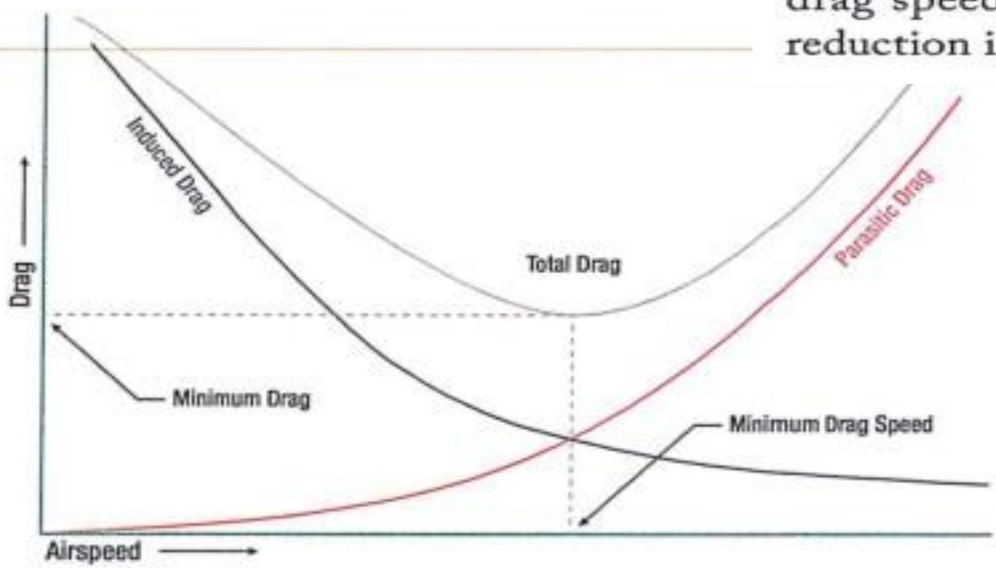
A is the cross sectional area, and

C_D is the drag coefficient – a dimensionless number.

Drag contd....

Parasitic Drag increases with the square of the airspeed, while induced drag, being a function of lift, is greatest when maximum lift is being developed, usually at low speeds. ***Figure 2–21*** shows the relationship of parasitic drag and induced drag to each other and to total drag.

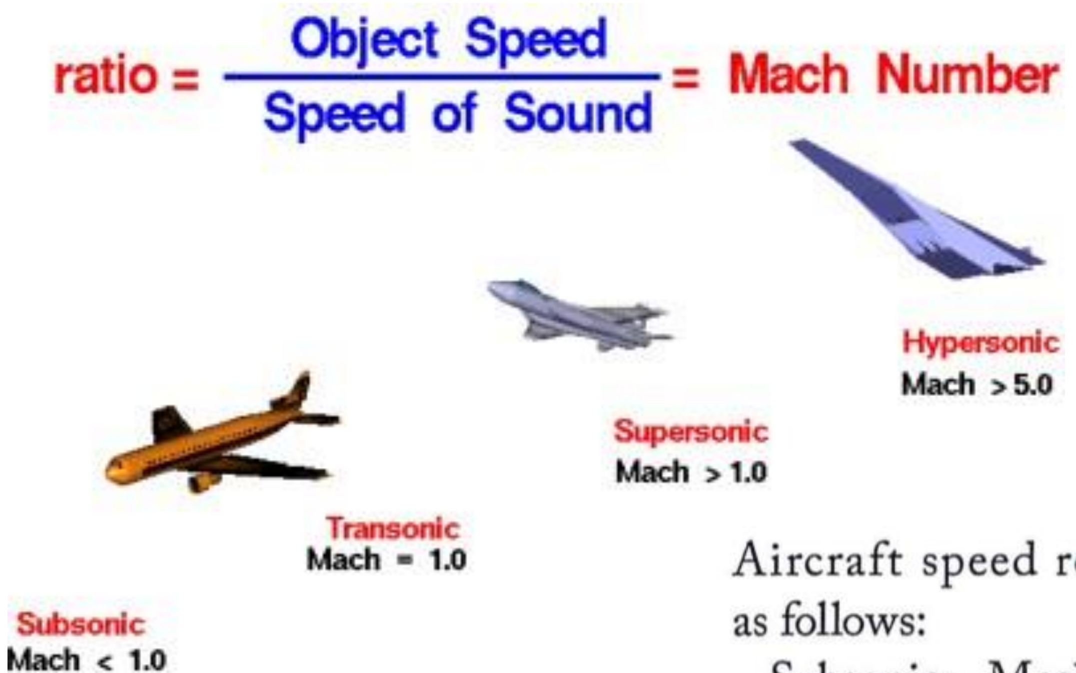
There is an airspeed at which drag is minimum, and in theory, this is the maximum range speed. However, flight at this speed is unstable because a small decrease in speed results in an increase in drag, and a further fall in speed. In practice, for stable flight, maximum range is achieved at a speed a little above the minimum drag speed where a small speed decrease results in a reduction in drag.



Induced drag decreases with increasing speed (for a constant lift force). This is because, **as speed increases, the downwash caused by the tip vortices becomes less significant, the rearward inclination of the lift is less, and therefore induced drag is less**.

Speed ranges

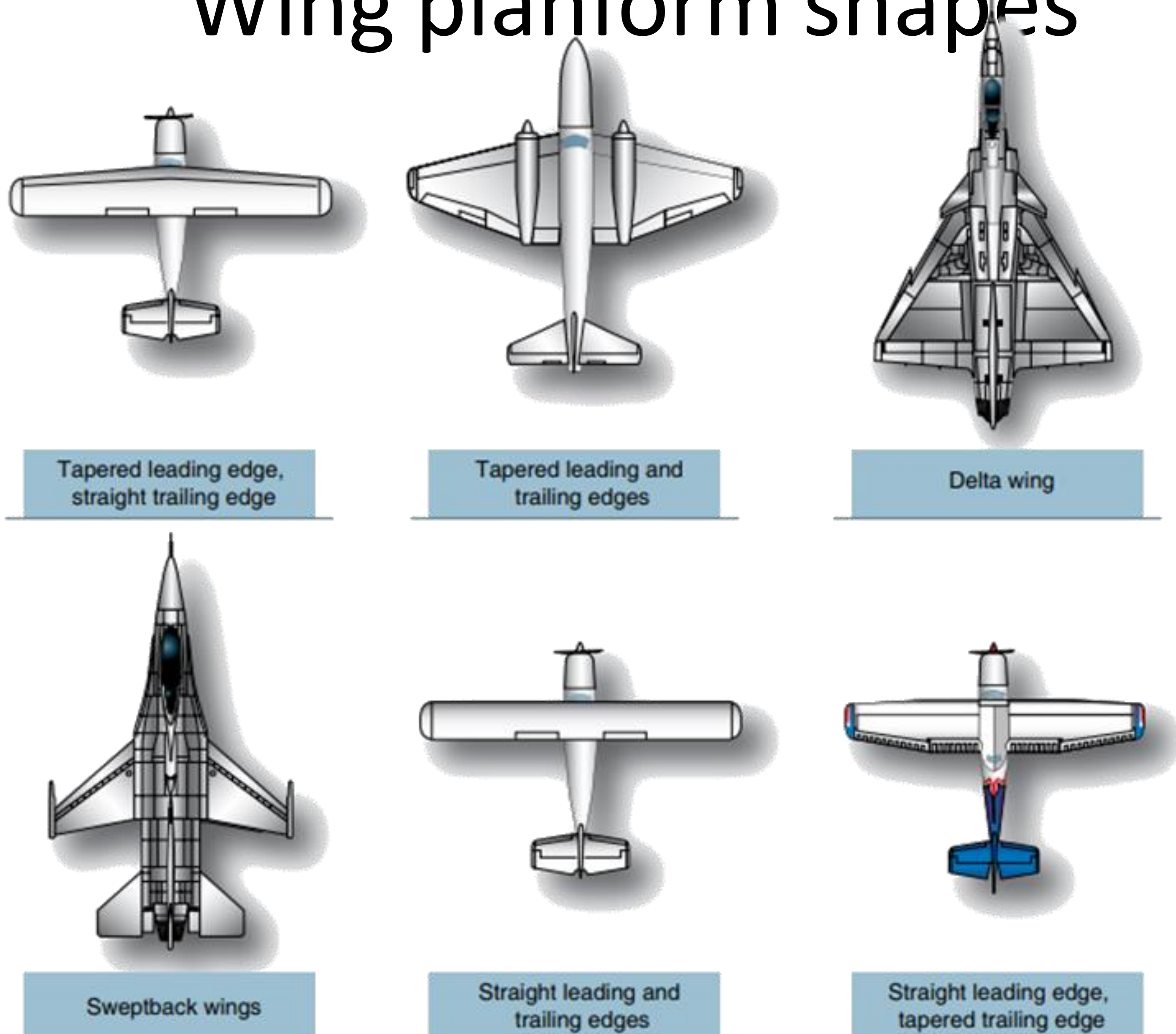
- Mach number:The ratio of the speed of the aircraft to the speed of sound



Aircraft speed regimes are defined approximately as follows:

Subsonic—Mach numbers below 0.75
Transonic—Mach numbers from 0.75 to 1.20
Supersonic—Mach numbers from 1.20 to 5.00
Hypersonic—Mach numbers above 5.00

Wing planform shapes



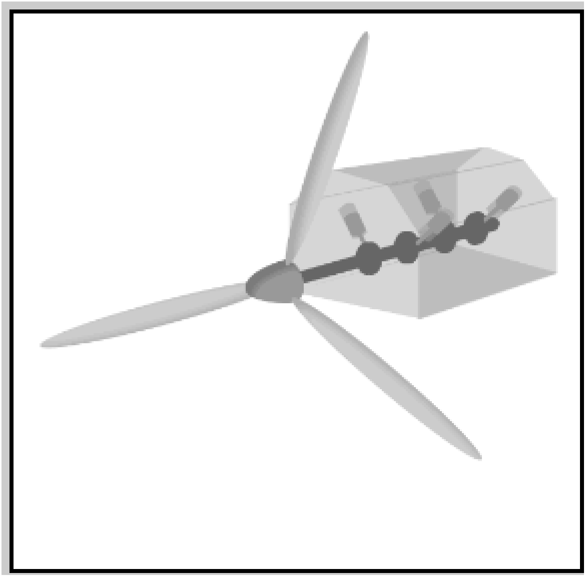
- **Rectangular Wing**: The rectangular wing is the simplest to manufacture. It is a non-tapered, straight wing that is mostly used in small aircrafts. This wing extends out from the aircraft’s fuselage at right angles.One major disadvantage of a rectangular wing is that it isn’t aerodynamically efficient.
- **Elliptical wing:** Elliptical wing is aerodynamically most efficient because elliptical spanwise lift distribution induces the lowest possible drag. However, the manufacturability of this aircraft wing is poor.
- **Tapered Wing:**The tapered wing was designed by modifying the rectangular wing. The chord of the wing is varied across the span for approximate elliptical lift distribution.While it isn’t as efficient as the standard elliptical wing, it does offer a compromise between efficiency and manufacturability.
- **Delta Wing:**This low aspect ratio wing is used in supersonic aircrafts. The main advantage of a delta wing is that it is efficient in all regimes (supersonic, subsonic, and transonic). Moreover, this type of wing offers a large area for the shape thereby improving maneuverability and reducing wing loading.
- **Swept back wings:**Sweeping the wings makes the wing feel like it's flying slower. That, in turn, delays the onset of supersonic airflow over the wing - which delays wave drag.

Aerodynamics of rotary wings

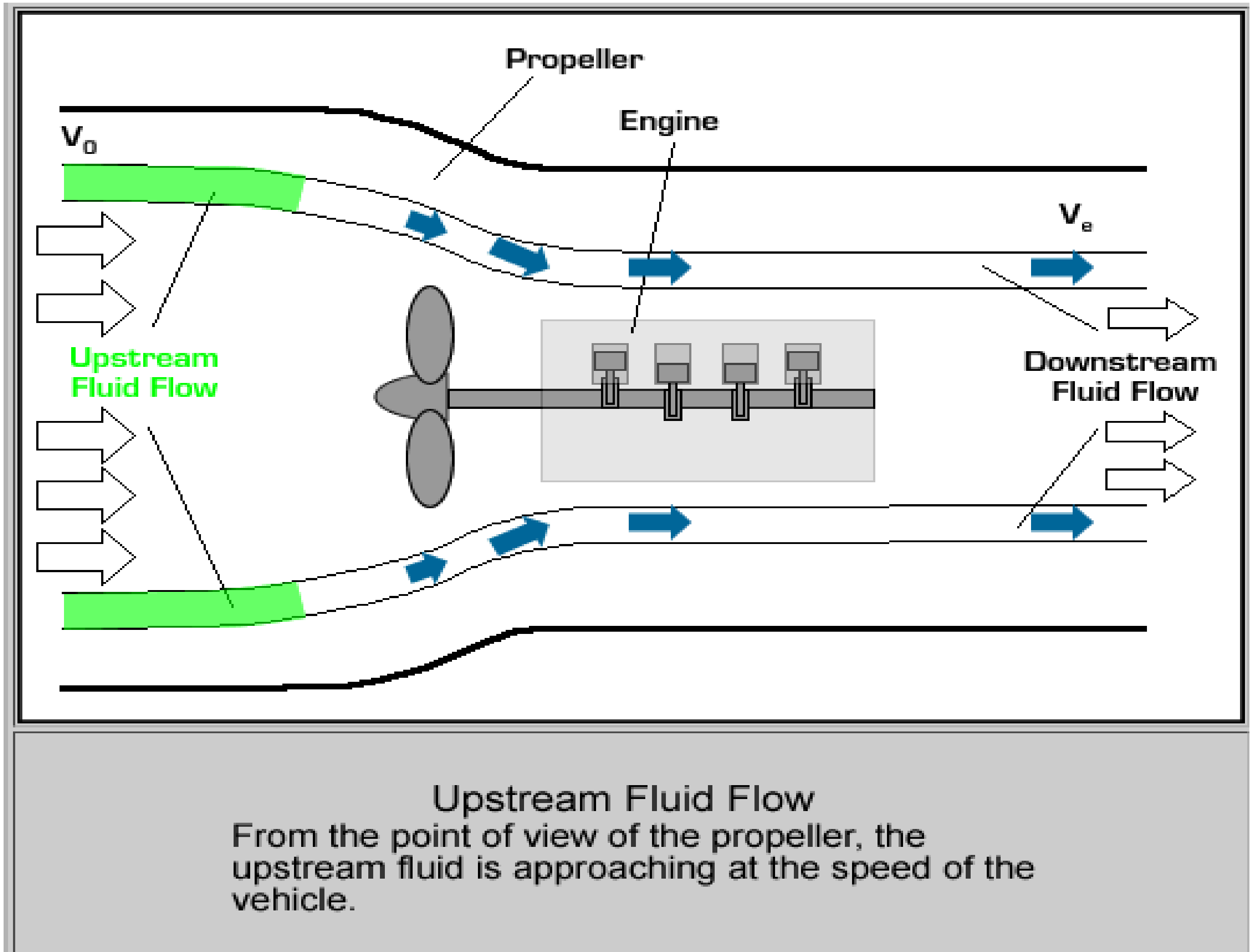
Thrust generation via propellers

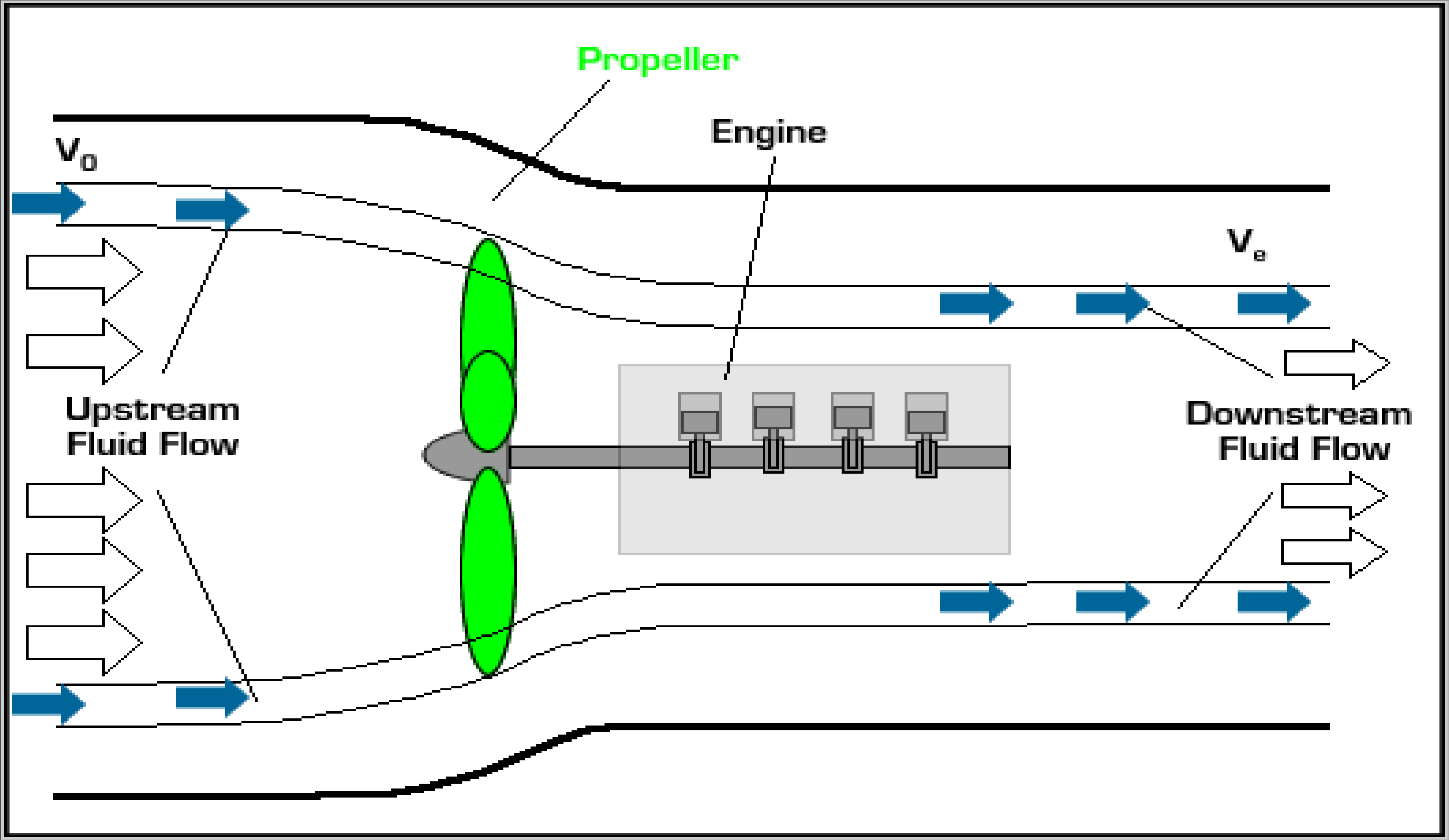
Use the link: https://s2.smu.edu/propulsion/Pages/propeller.htm

- Propellers are used on boats, submarines, and small aircraft. Propellers are simple, revolving hubs with blades placed evenly along the edges (usually 2 to 4 blades on a propeller, but more are possible).
- A mechanical engine attached to the propeller converts fuel or other stored energy into mechanical power which turns the propeller at a high rate of speed.



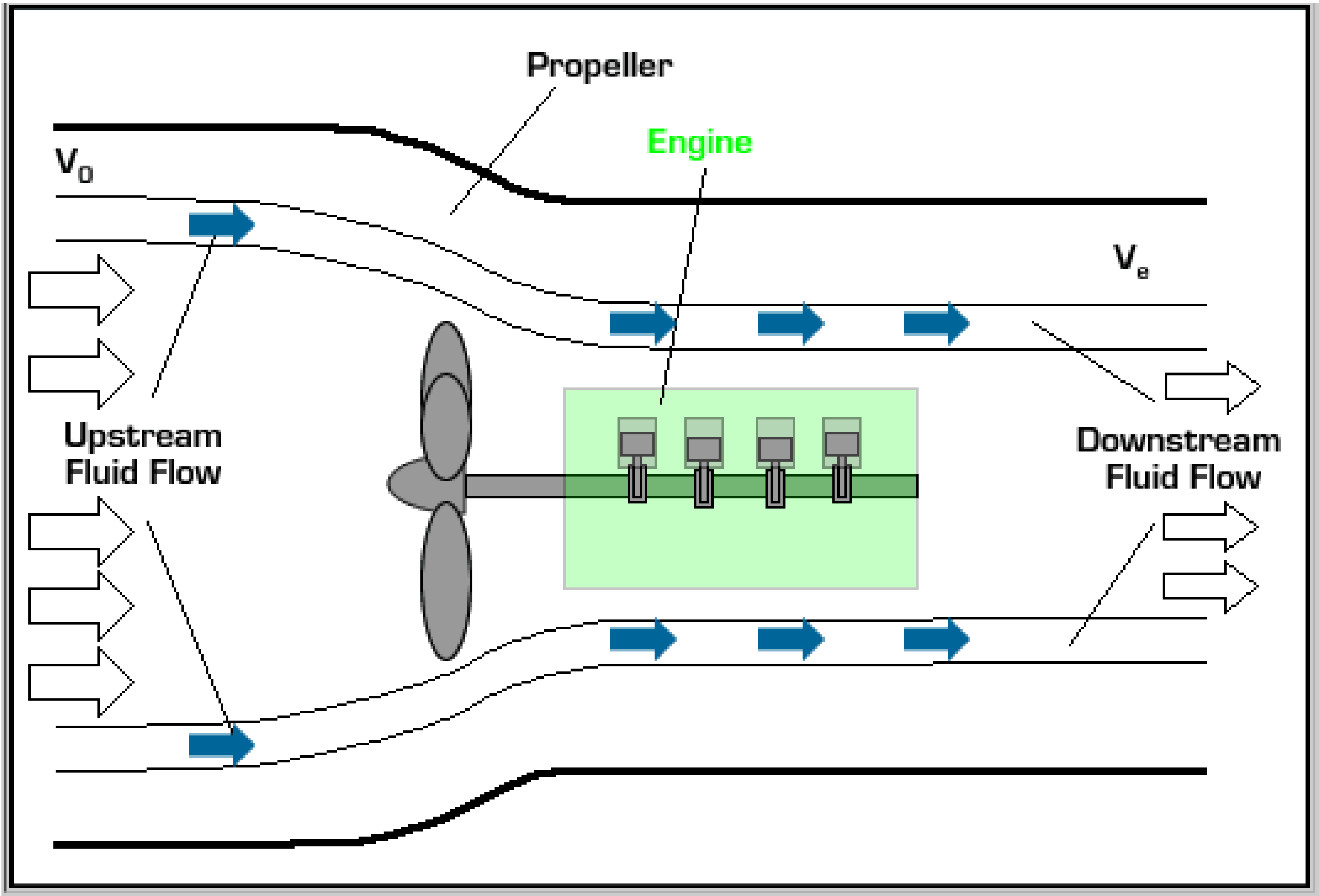
In small aircraft, the propeller is normally powered by a piston engine as shown above. In larger vessels like nuclear submarines, the propeller may be powered by a nuclear power plant. The basic operation of a propeller propulsion system is described in the interactive animation below.





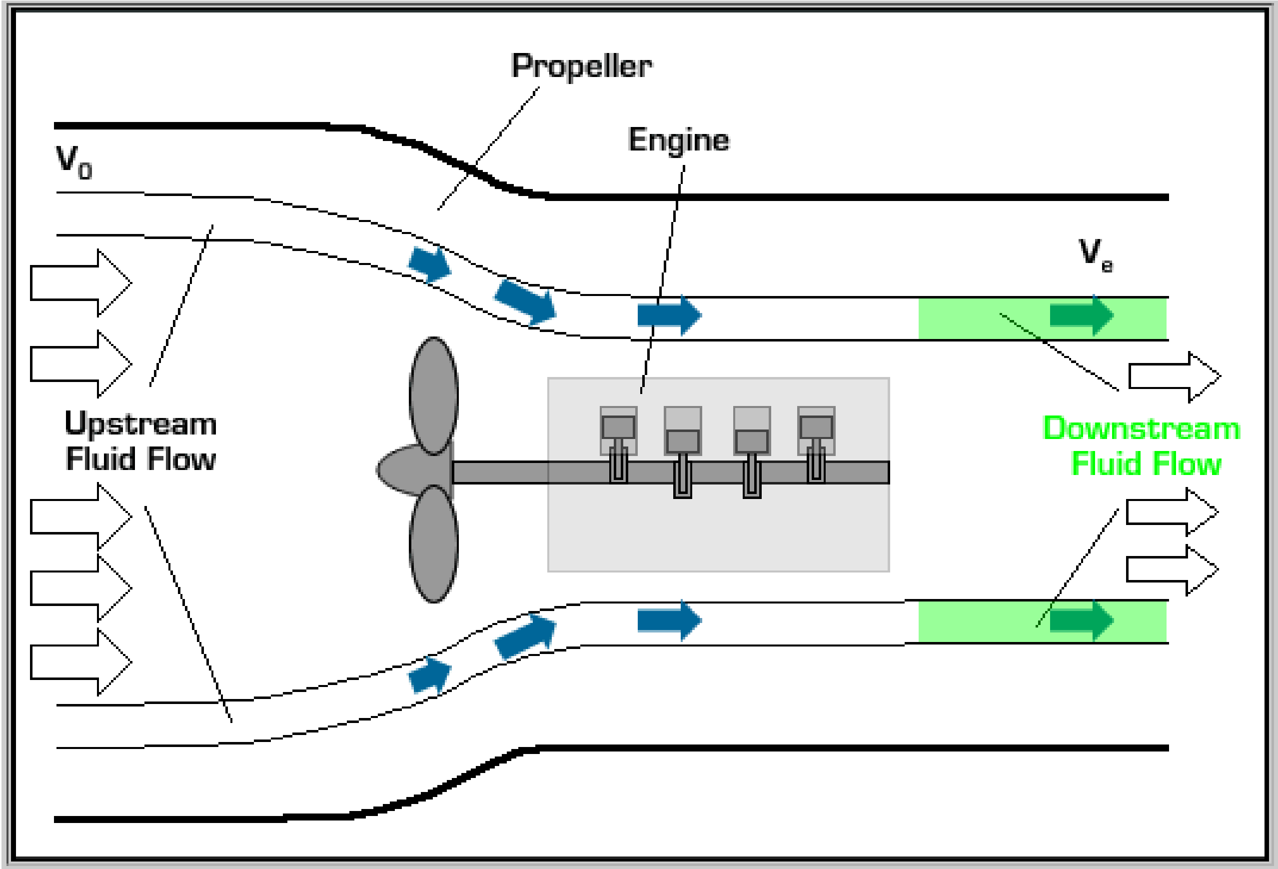
Propeller

The propeller is like a spinning wing. As the upstream fluid approaches, the blades accelerate the fluid creating thrust in the same manner that a wing creates lift as it moves through the air.



Engine

The engine is often an internal combustion engine that converts chemical fuel energy into mechanical power. The mechanical power turns a driveshaft and spins the propeller.



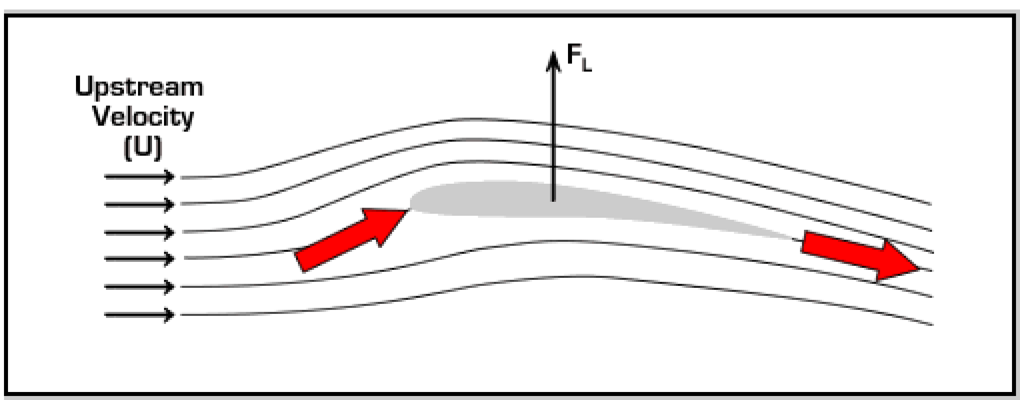
Downstream Fluid Flow

Downstream of the propeller, the air that has already passed through the blades of the propeller, has a much higher velocity than the ambient air. Higher downstream velocity translates into thrust according to the thrust equation.

The design of a propeller is crucial for this system to generate thrust efficiently. A propeller may be thought of as a **spinning wing.** Wings have a very special shape in order to direct the flow around them in a specific way.

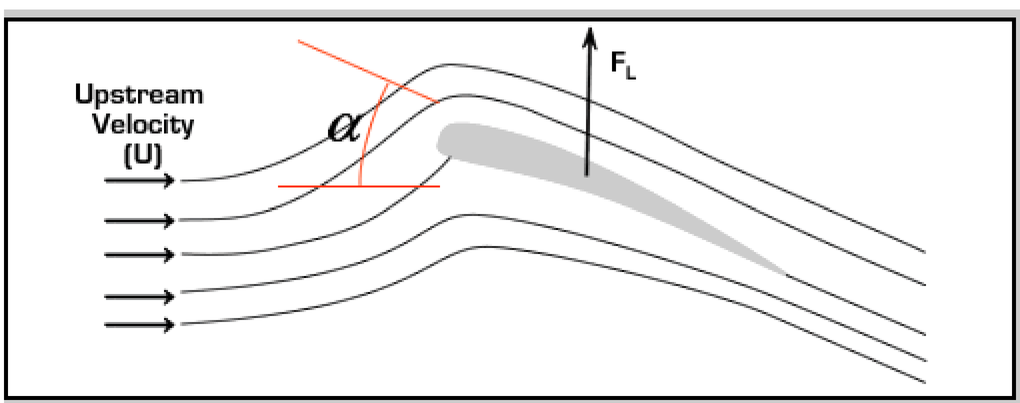
Lift production for an airfoil or wing

- In the figure below, it can be seen that **near the back a wing** has a **slightly steeper slope on the top as compared to the bottom**. As a result, the fluid flowing over the wing tends to flow down and away from the wing as it passes the end or "trailing edge" of the wing. Near the front of the wing, the curvature of the top of the wing adds to this effect because the flow must curve up as it approaches the wing in order to flow smoothly over the hump on the top of the wing. The net effect is a change in flow direction from upward to downward by the wing. **Because the flow is accelerated down** (the direction of the fluid velocity is changed to the downward direction), Newton's Third Law requires there be an upward reaction force on the wing..



Lift @ higher angle of attack

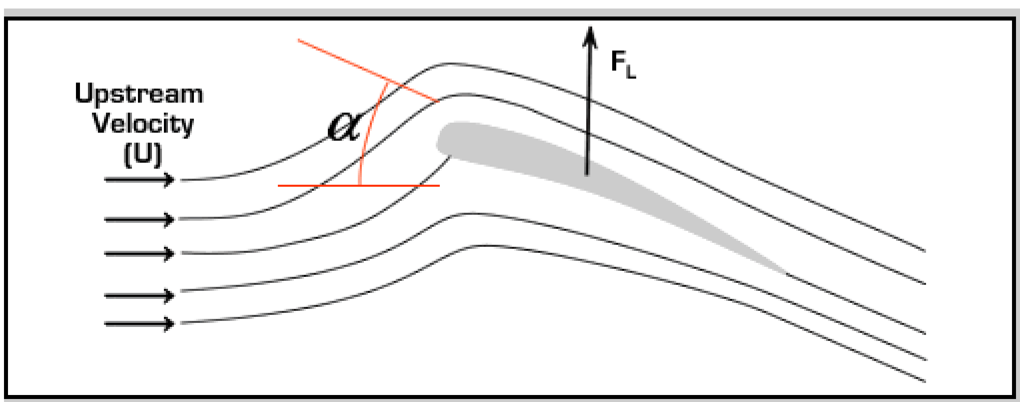
- The vertical force acting on the wing is called lift and it is what keeps airplanes aloft. If the angle of the wing relative to the oncoming flow (angle of attack, α) is increased, **the downward acceleration of the flow is enhanced and lift is increased** (as long as α is not too large).
- In general, the lift force can be computed from the equation where ρ is the fluid density, U is the upstream flow speed, and A is the wing area. C_L is called the lift coefficient and it depends on the wing geometry and α.

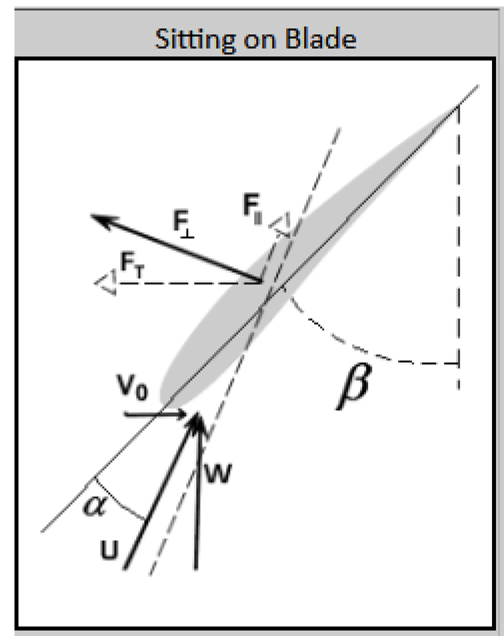


$$\boxed{F_L = \frac{1}{2} C_L \rho A U^2}$$

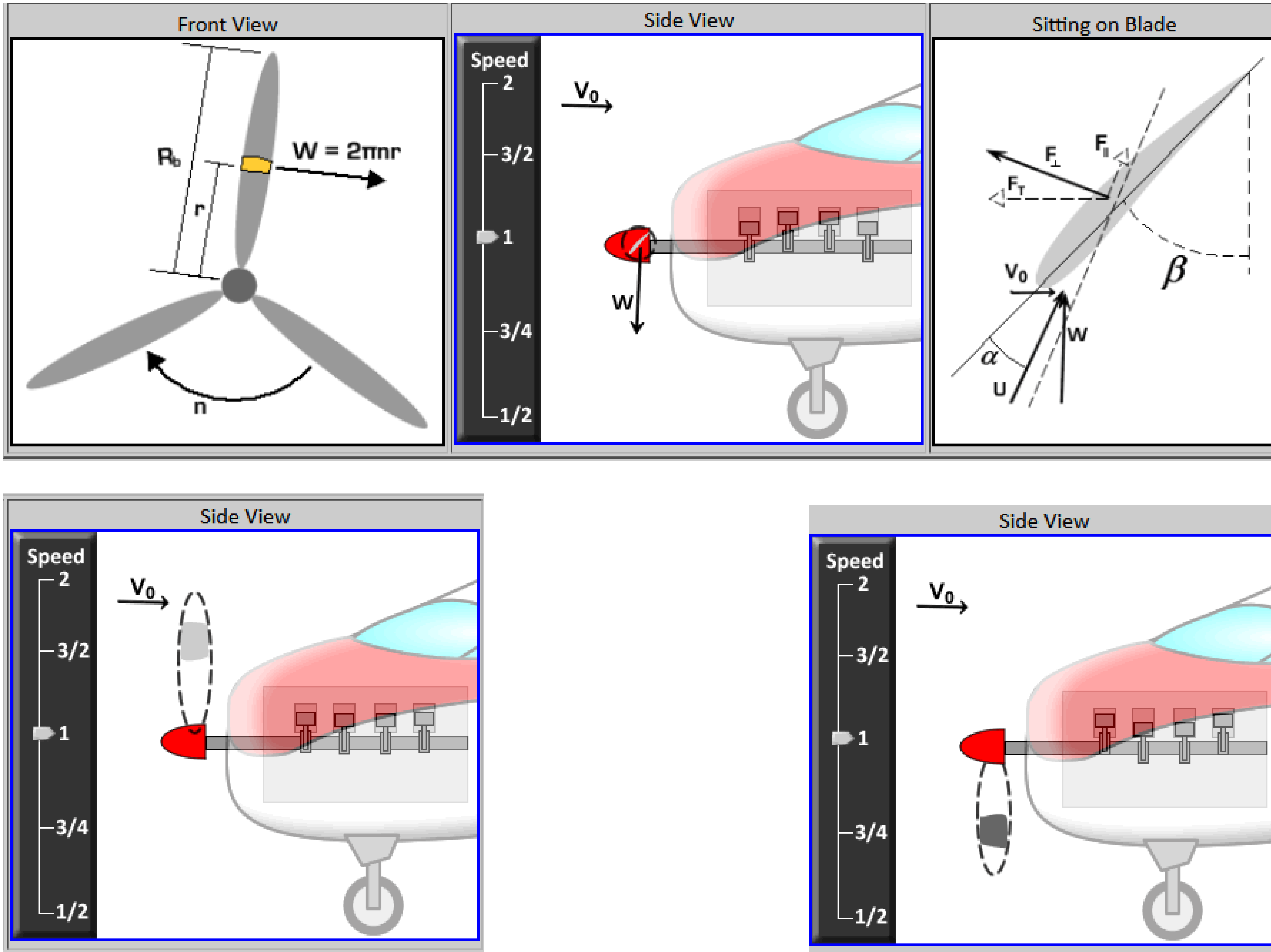
Thrust from propeller blade

- Now, envision the above scenario rotated 90° counter clockwise so that the top of the wing is facing forward. The force on the wing is now pointed forward, creating thrust instead of lift. In this orientation, we call the wing a propeller "blade".



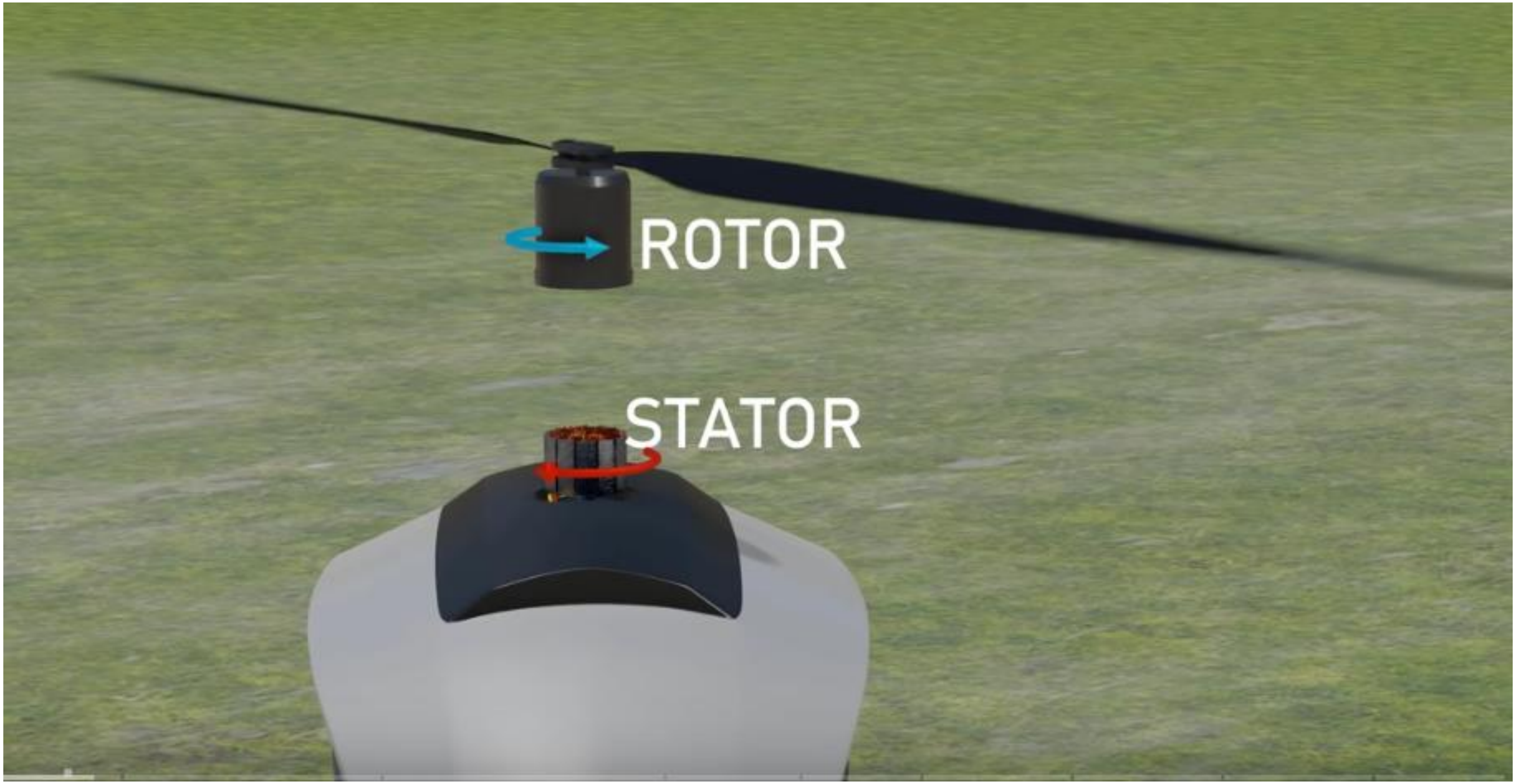


Vo—velocity of the vehicle or flight speed
W- velocity of the spinning wing or linear velocity
U- Velocity of the air as seen from the wing or relative air wing


Front View
Rb
W = 2πnr
r
n
Side View
Speed
2
3/2
1
3/4
1/2
V0
W
Sitting on Blade
F⊥
F∥
FT
V0
W
α
U
β
Side View
Speed
2
3/2
1
3/4
1/2
V0
Side View
Speed
2
3/2
1
3/4
1/2
V0

How do they work?

Discussion of spinning due to counter acting torque

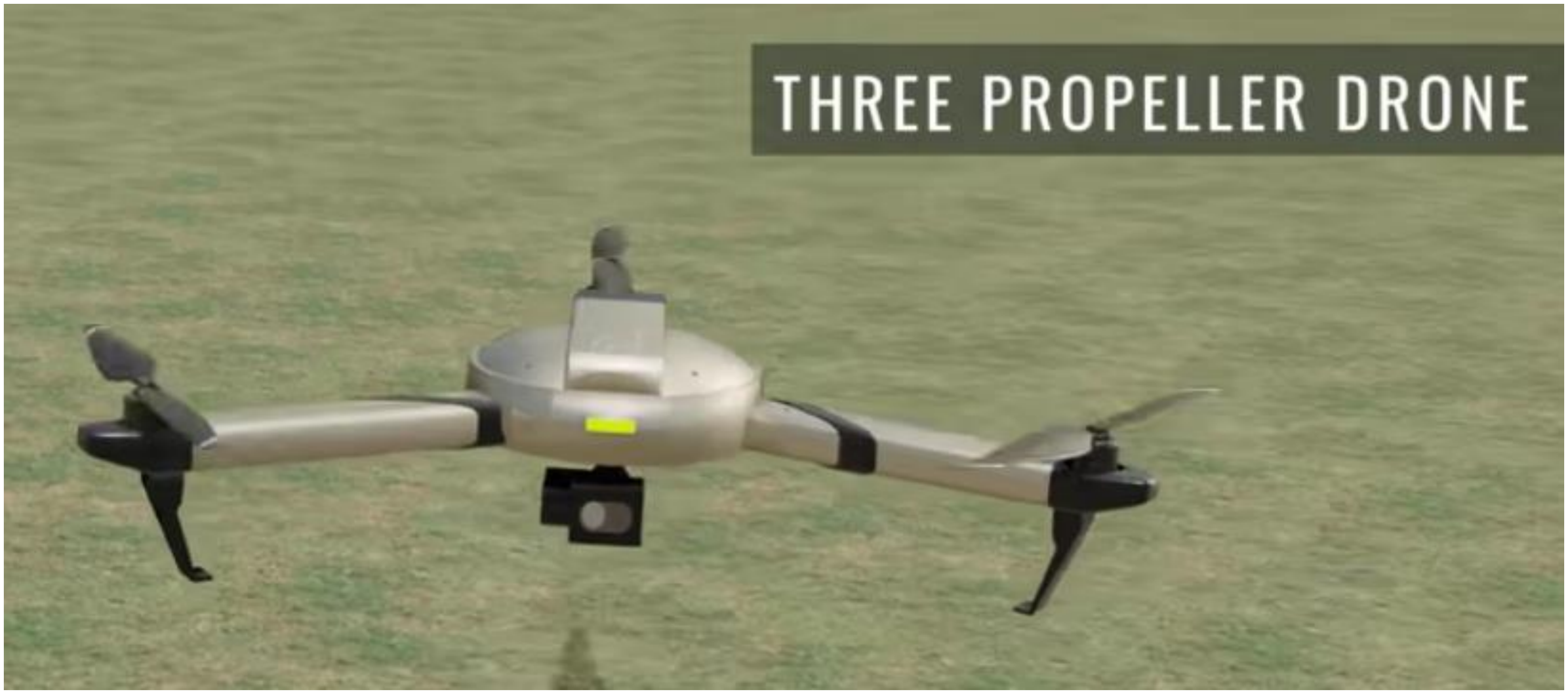


Comparing torque and counter acting torque with rotor and stator


TWO PROPELLER DRONE

Discussion of no spinning due to torque and counter acting torque

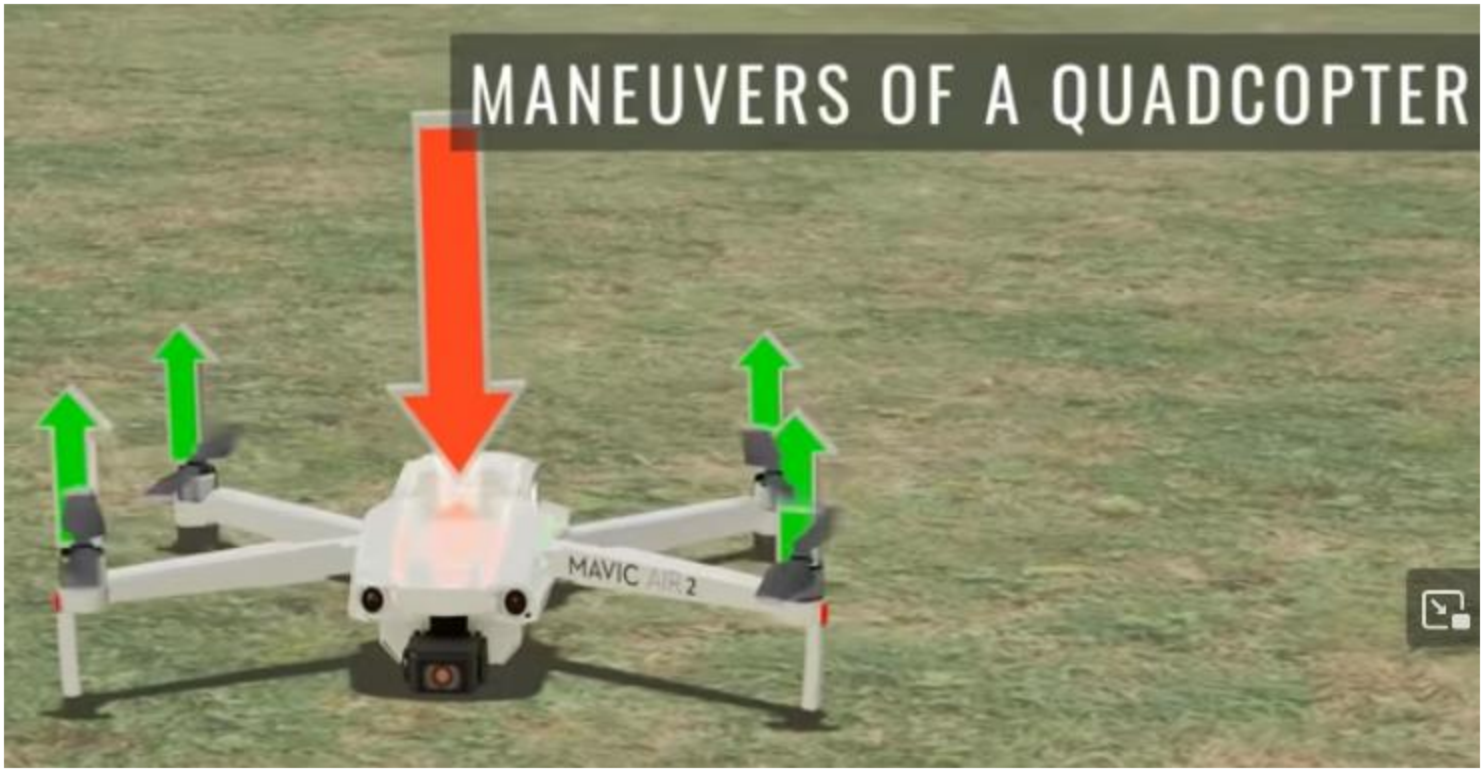
Comparing maneuverability is poor in two prop compared to 4 prop drone and endurance with no of props.


THREE PROPELLER DRONE

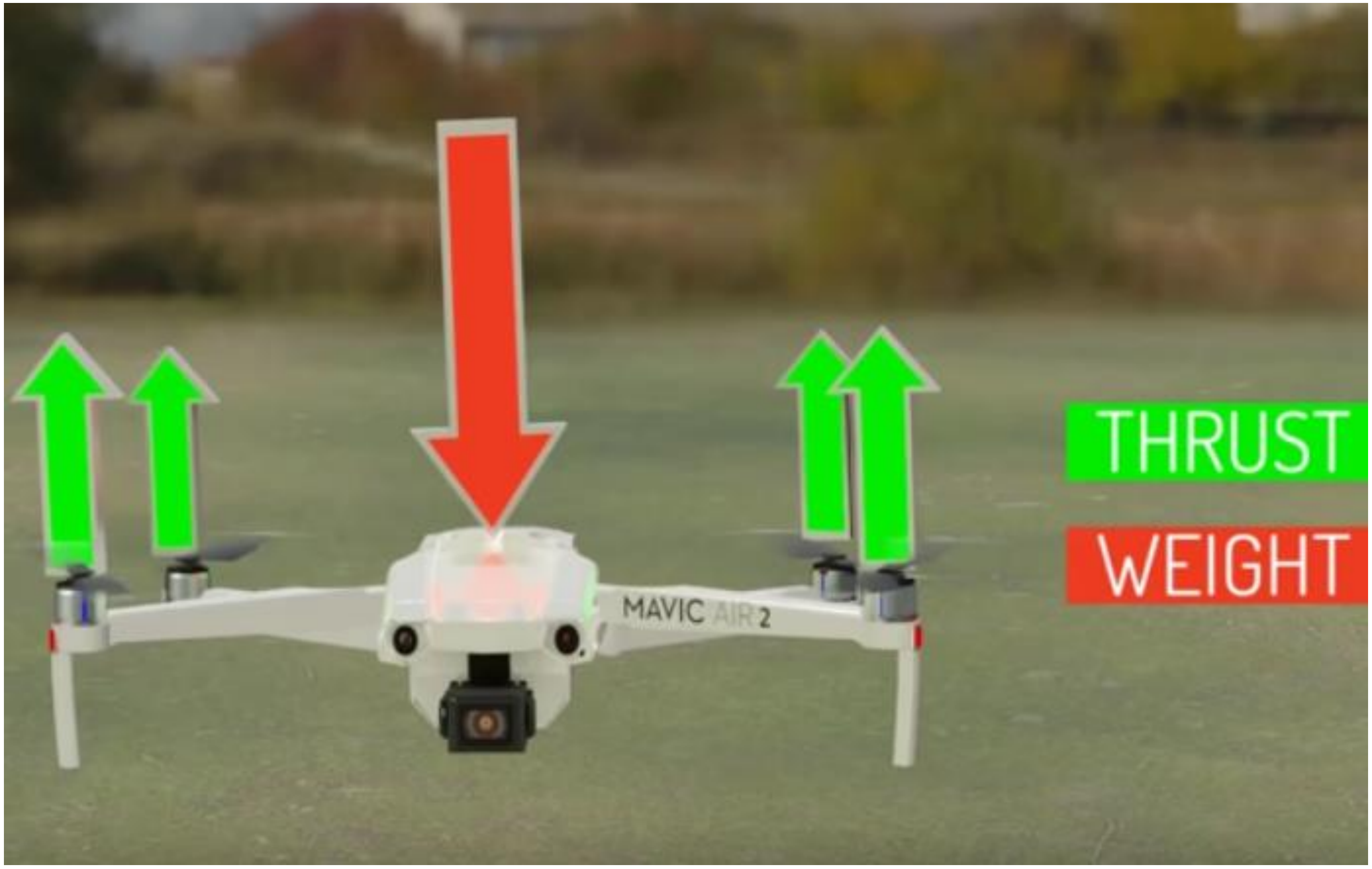
Discussion of counter acting torque of 3 rd propeller leads to spinning of drone

Discussion of X-Type or H- shape: no spinning and good manoeuverability.

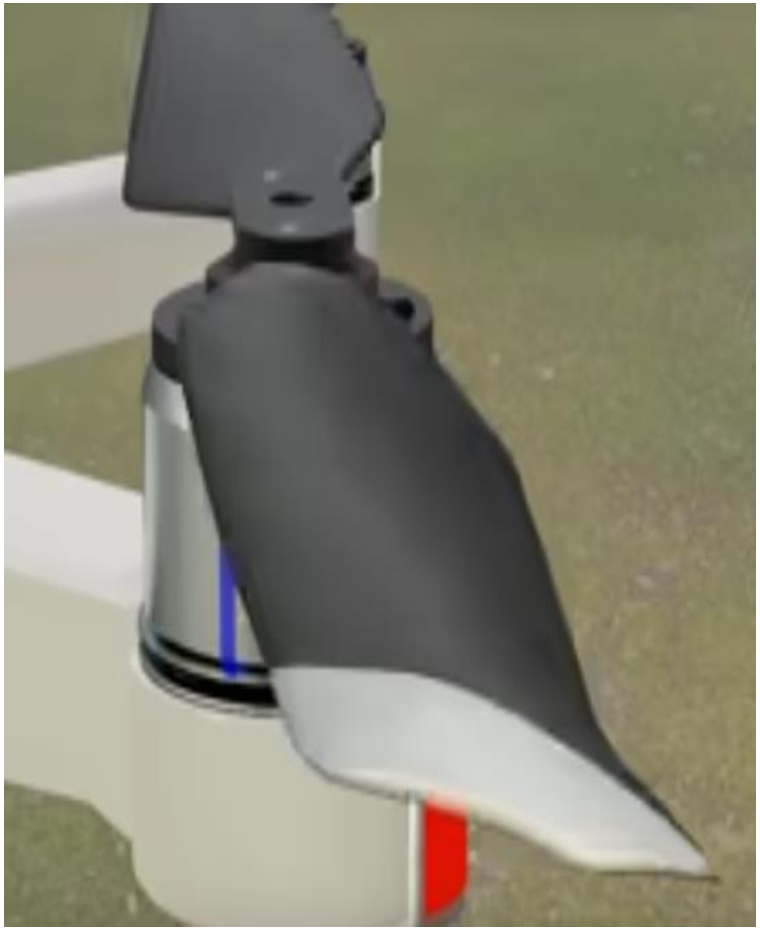
How spinning of drone is avoided? Discussion on counter acting torque

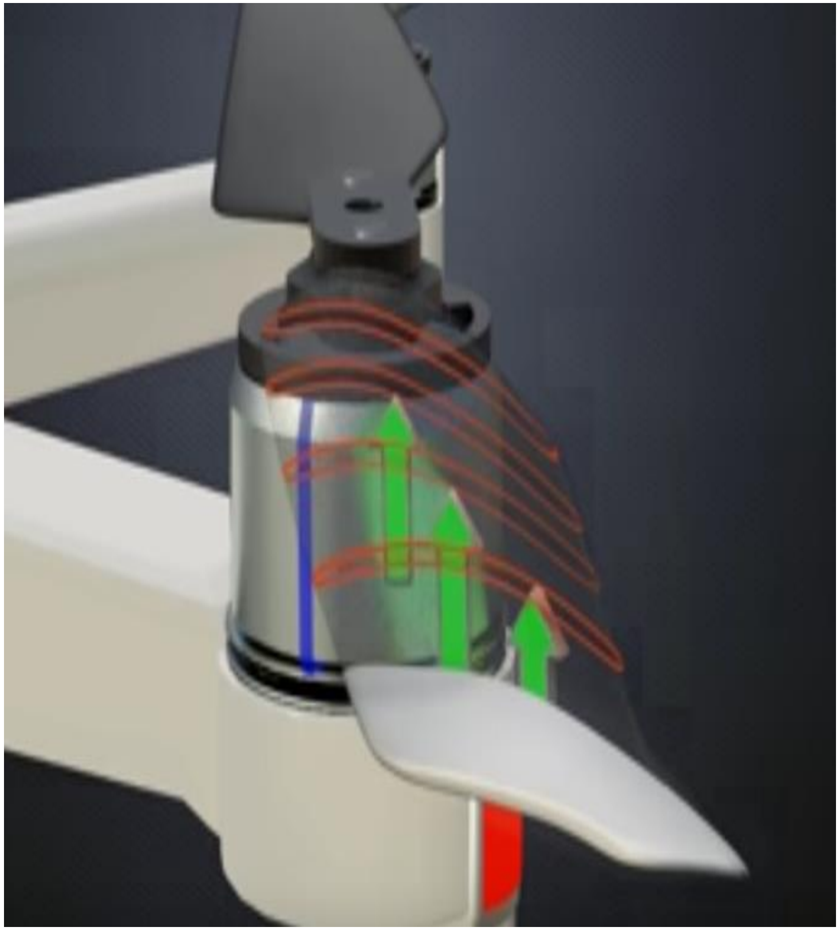

MANEUVERS OF A QUADCOPTER
MAVIC AIR 2

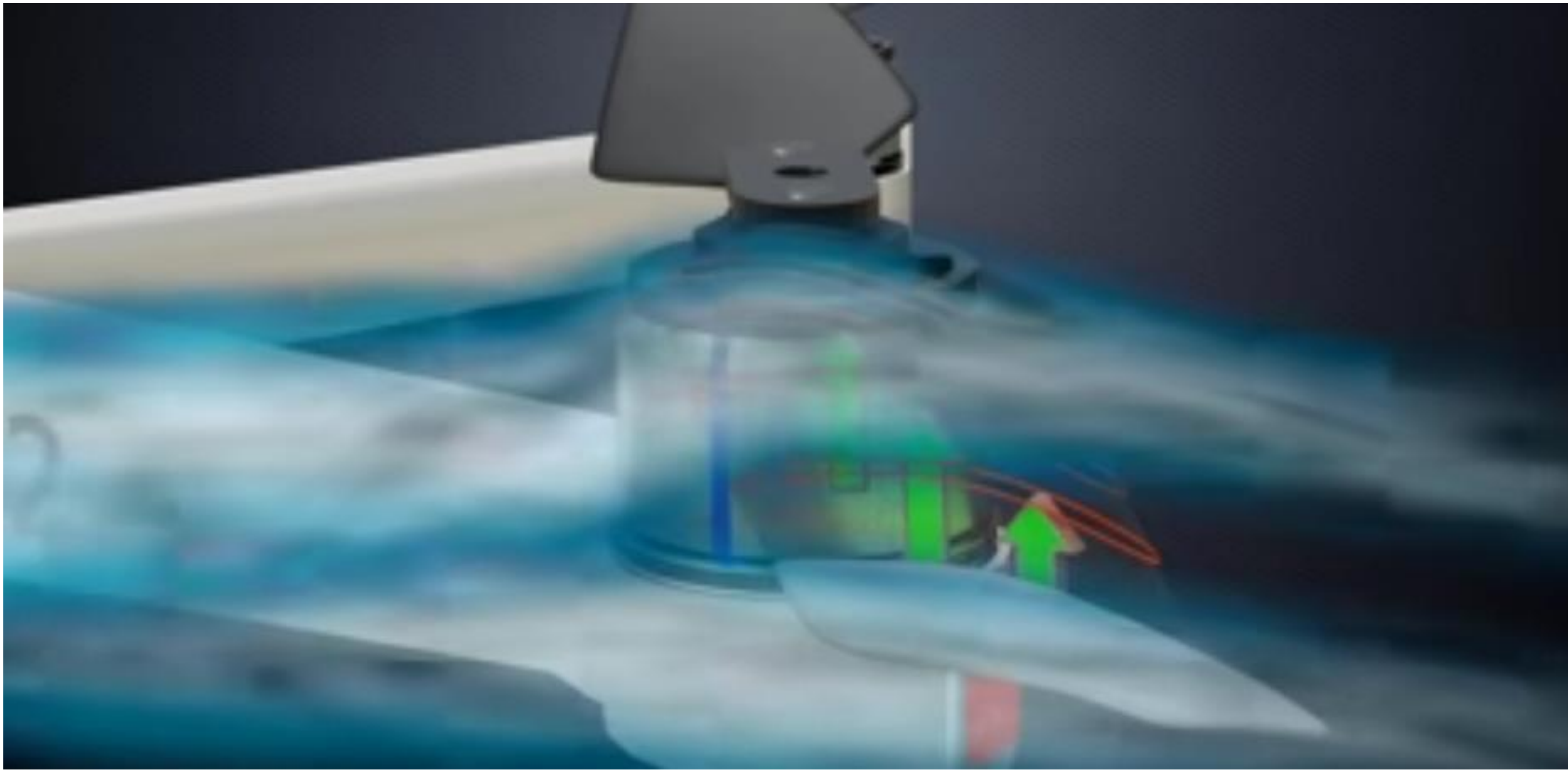
Hovering



Airfoil in lift production

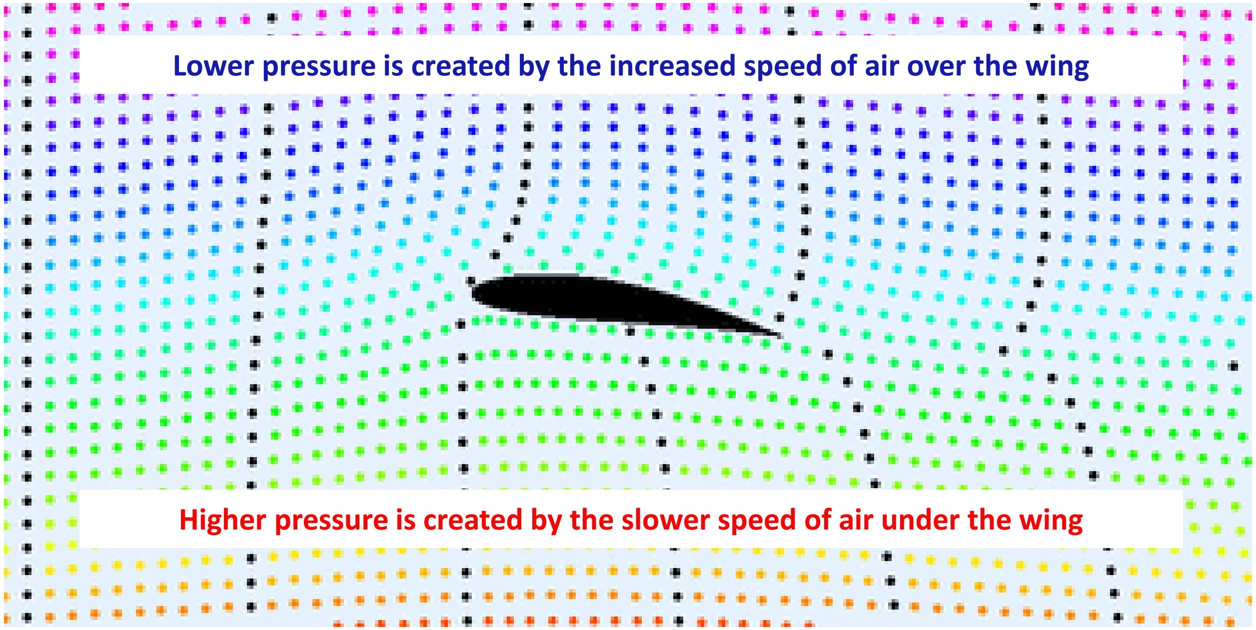




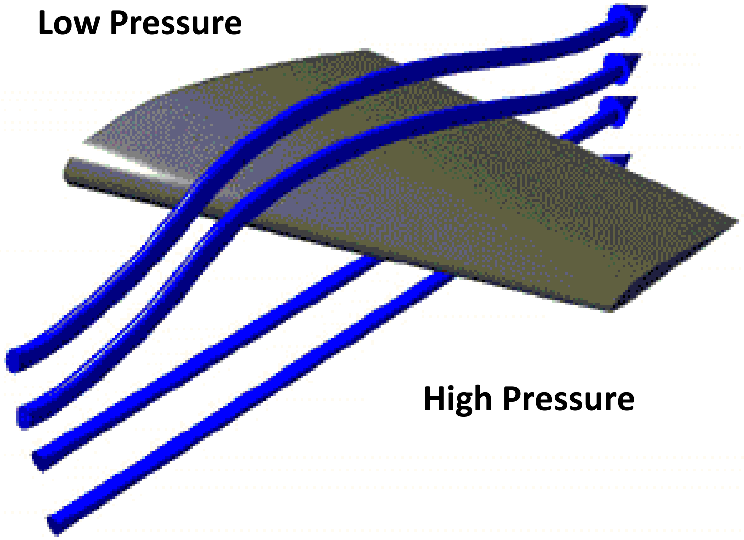


Discussion of bernouli principle for lift production, paper lift , lift production based on Newton 3rd law of motion.

Application of Bernoulli's principle to aircraft wing

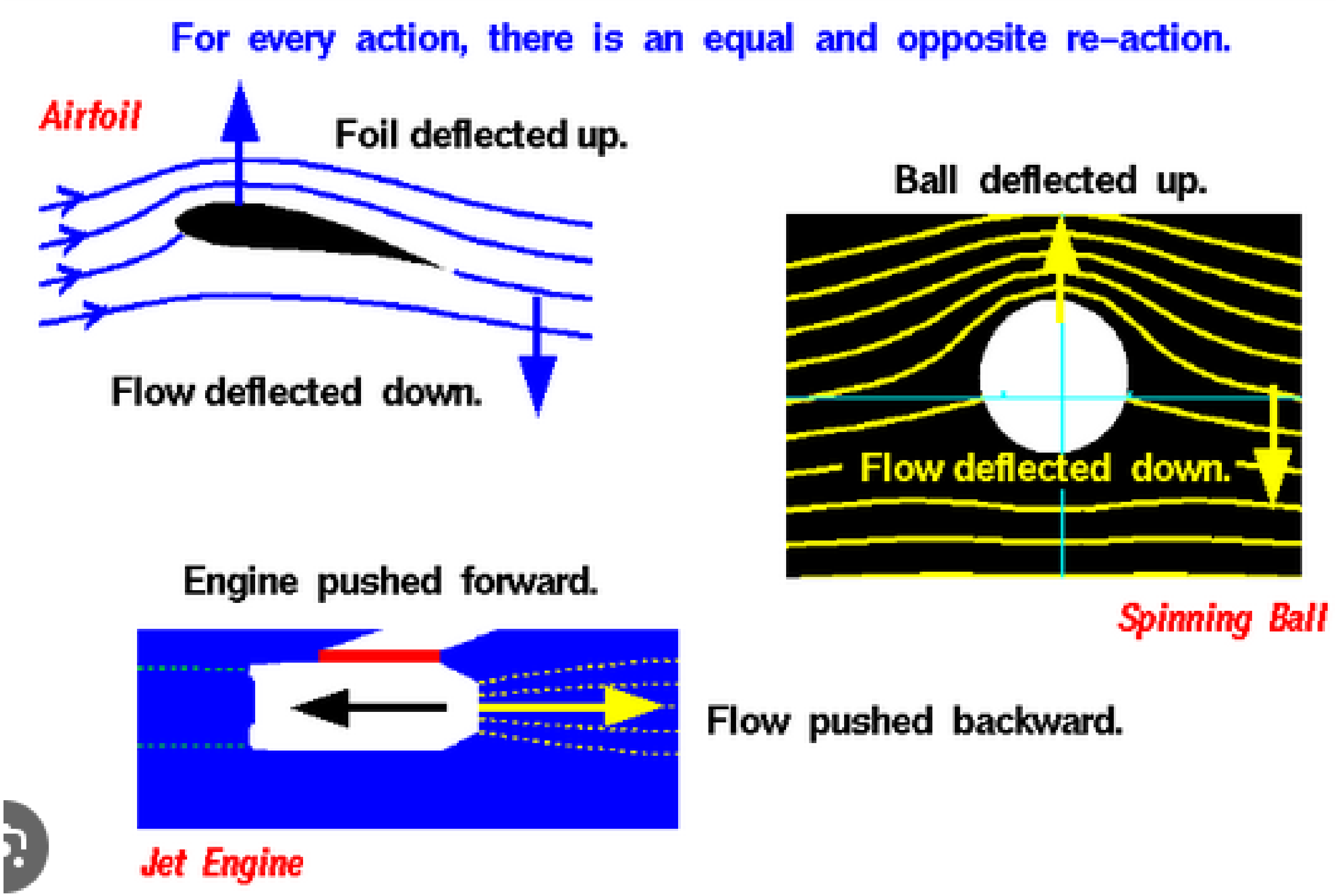


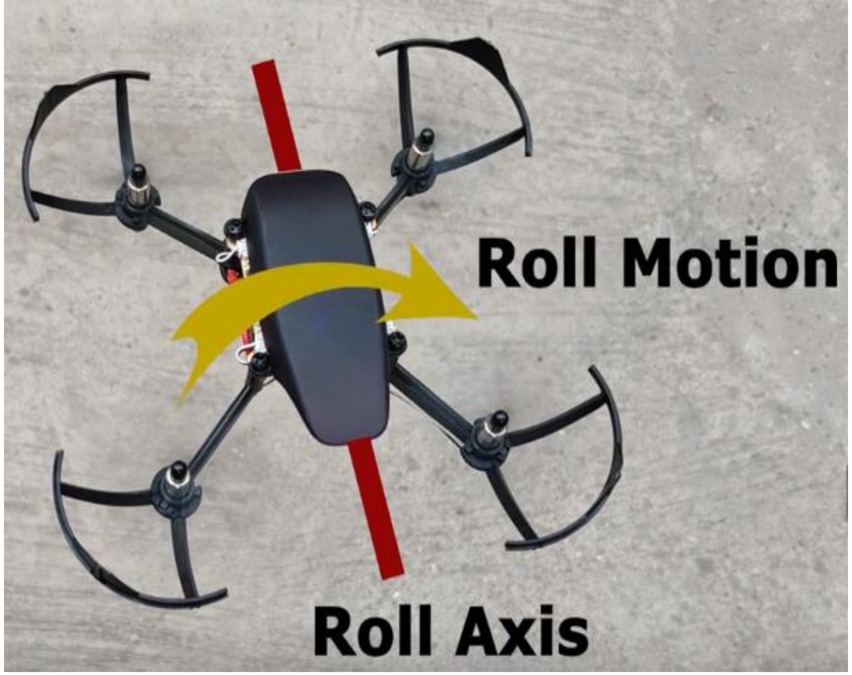
Lift force

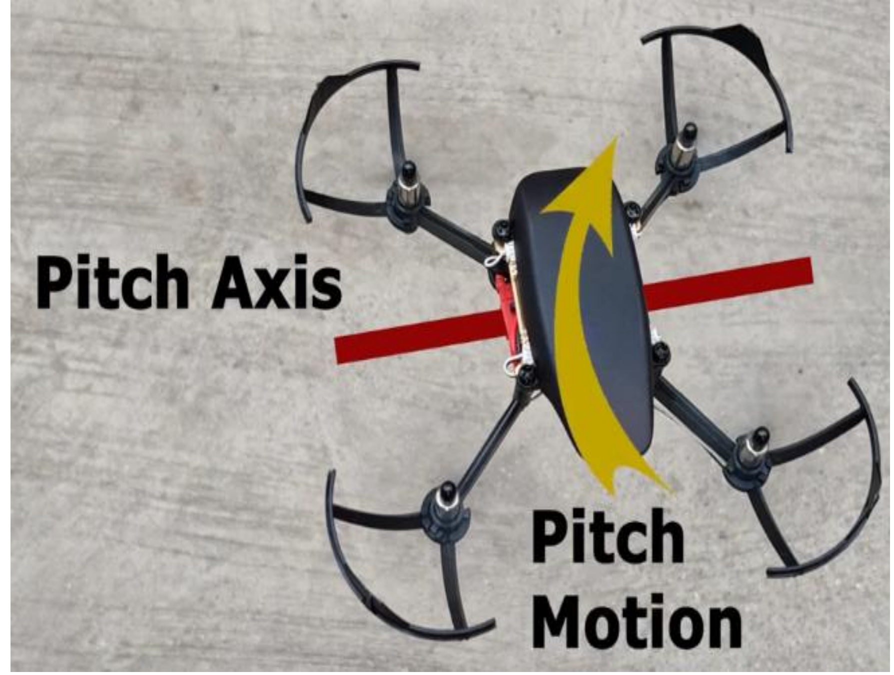


Lift force

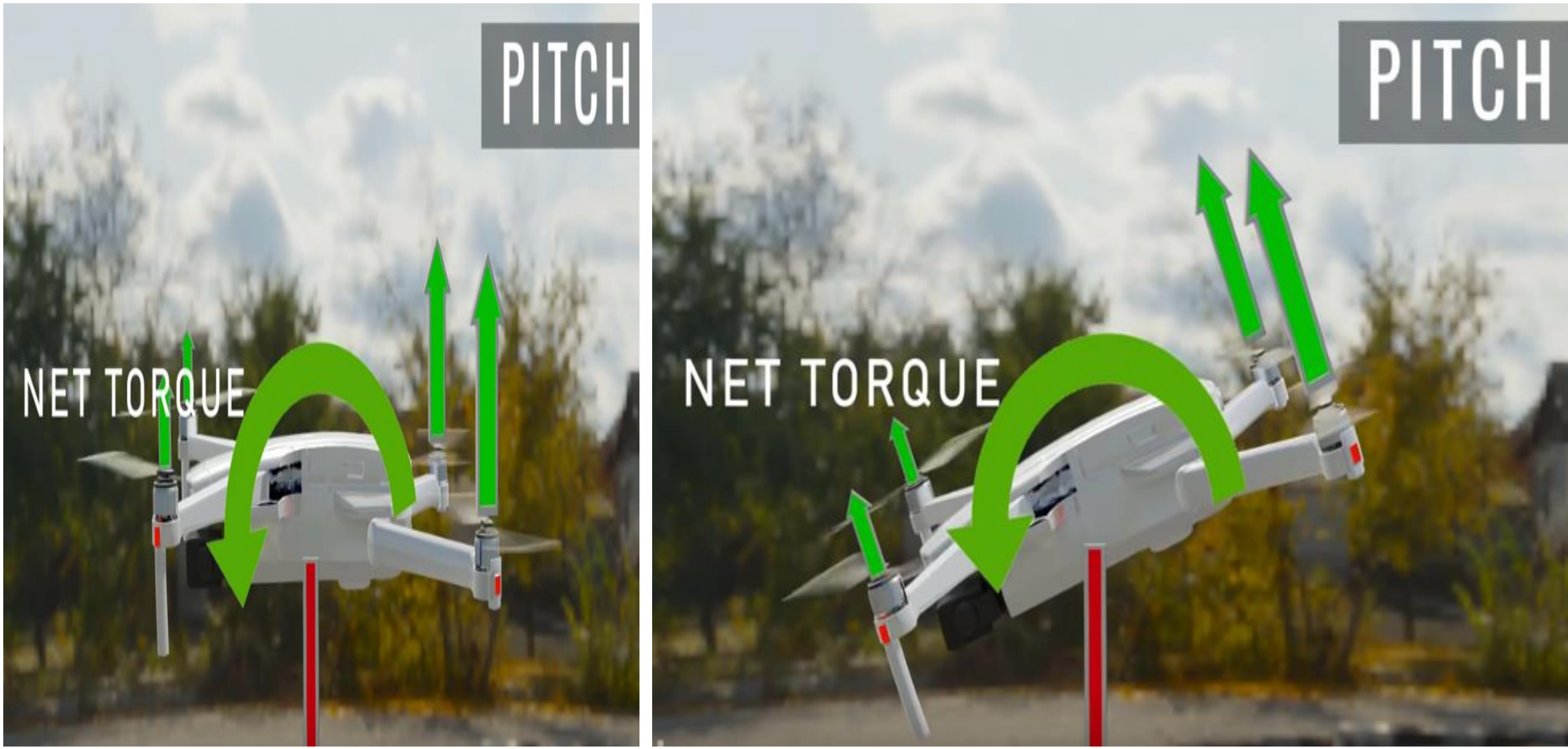
Based on Newton 3rd law of motion: lift production




Roll Motion
Roll Axis

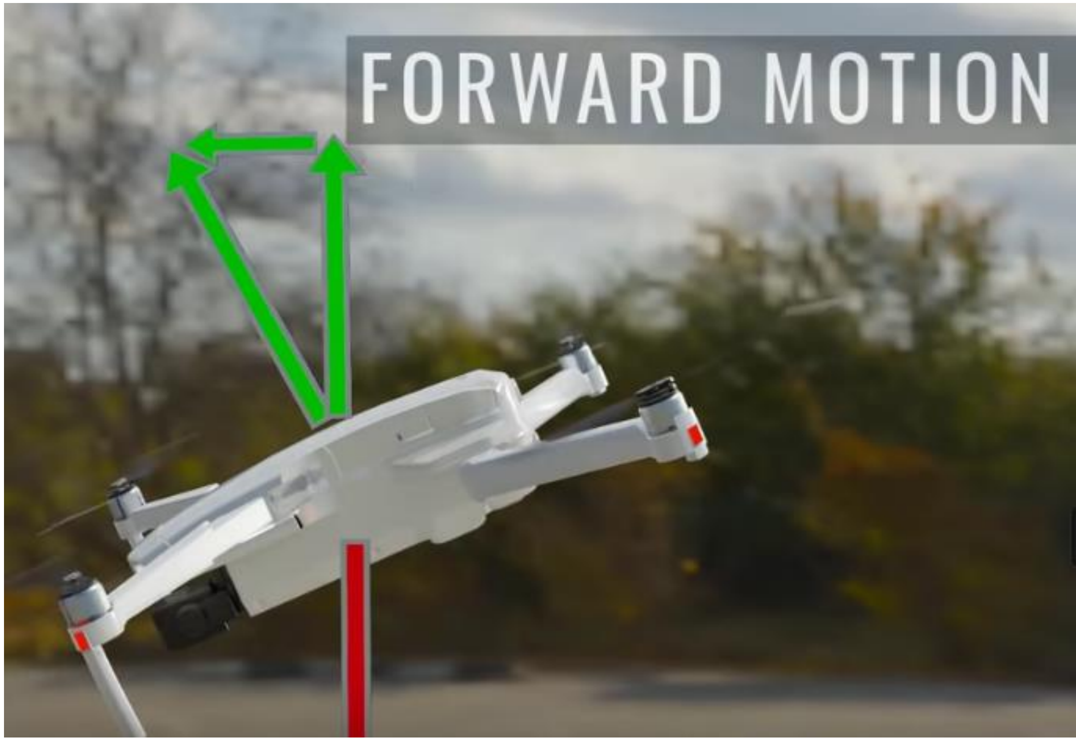

Pitch Axis
Pitch
Motion

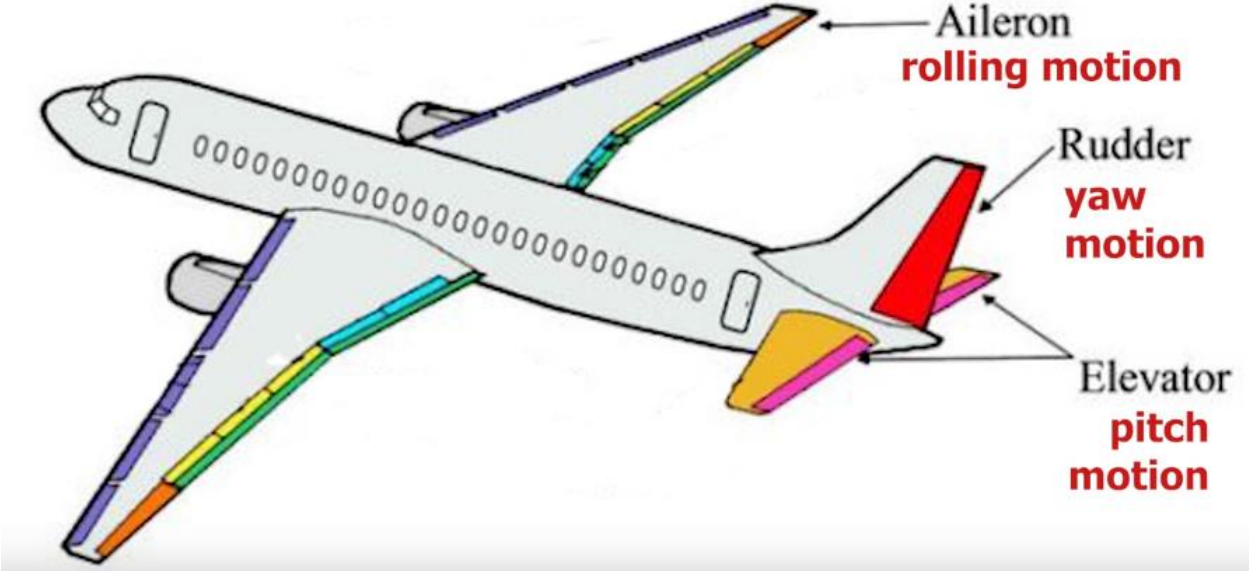

Yaw
Motion
Yaw Axis



Discussion of imbalance of forces due to variation in speeds of prop between front props and rear props leading to net torque creating pitching down motion.
Pitch up/pitch down/ pitching along any direction works on the same principle.

Discussion of rotation of props at same speed after pitching, so that vertical forces are generated inorder to balance the weight of the quad. vertical lift generated exactly balances the weight leading to unbalanced force in the horizontal direction which is responsible for forward motion.





Reminding the pitch, roll and yaw in airplane


ROLL
MAVIC AIR

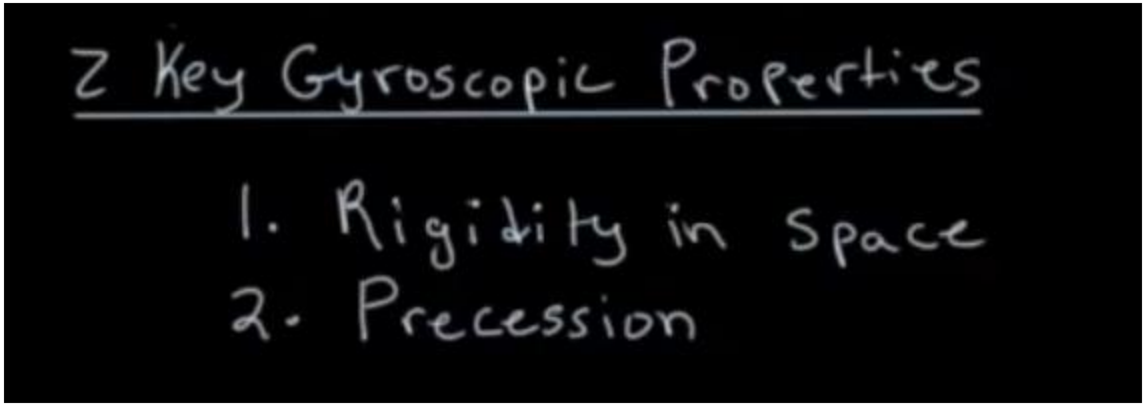
1.Discussion on cancellation of counter acting torque when props are same speed- avoids spinning of drone,

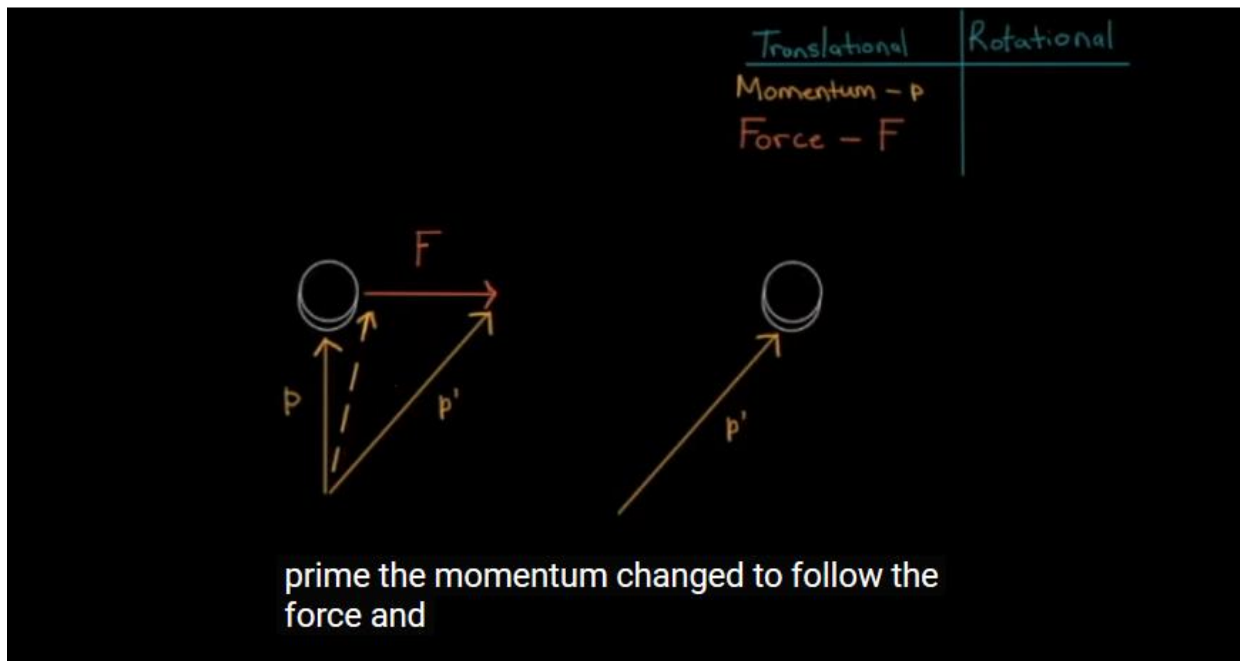
2. Discussion on varying speeds of prop diagonally (any one pair) leading to counter acting torque – causing yawing motion.

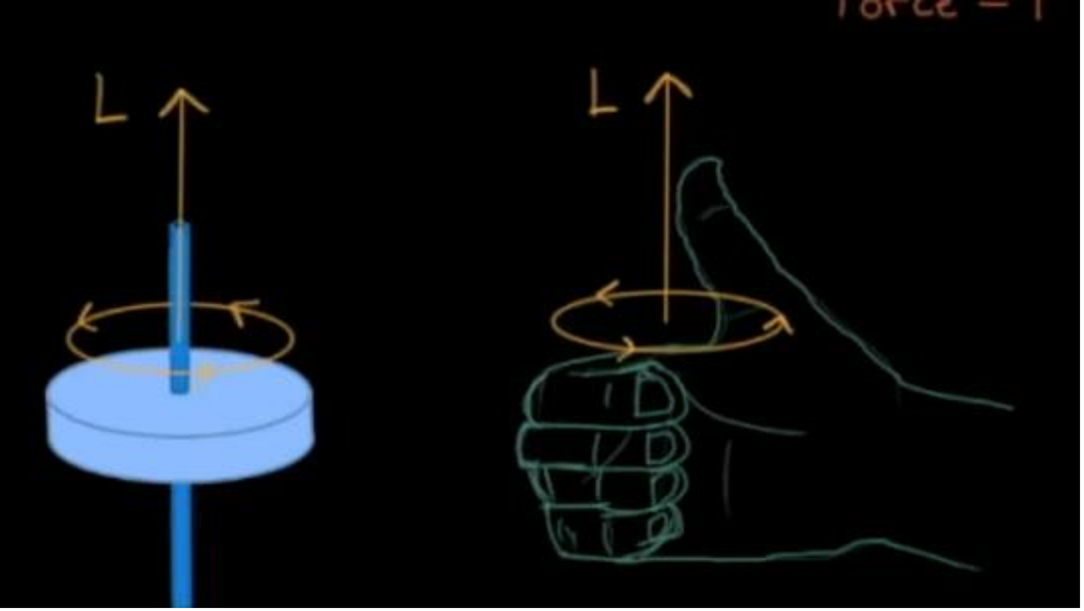
Note: Yawing direction should be on the other side

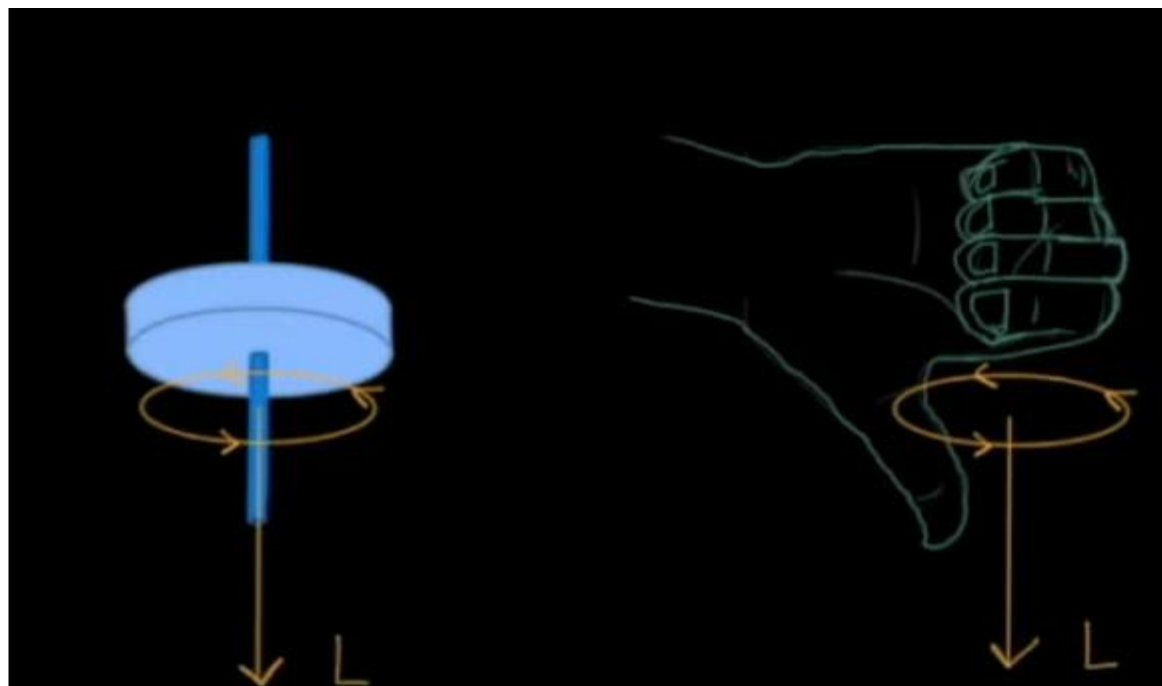
How rotary works?

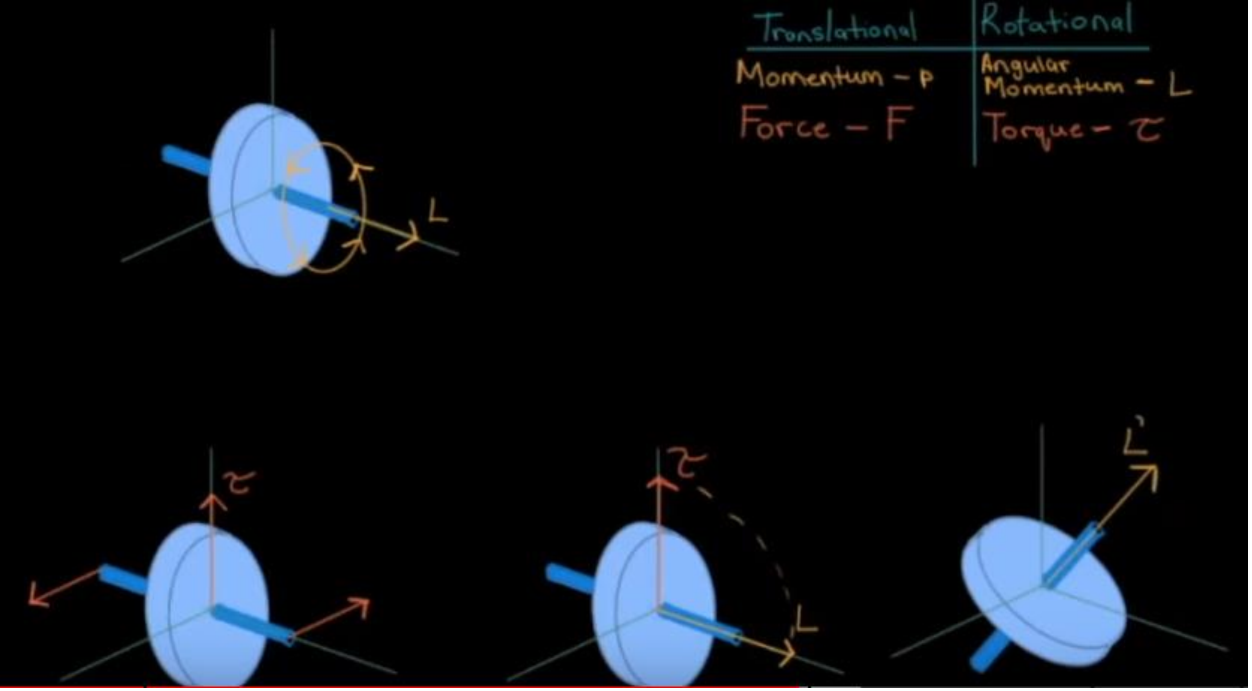
- How rotary wings(helicopter) works: https://www.youtube.com/watch?v=2tdnqZgKa0E
- Torques acted because of front and rear propeller blades will create leftward motion or rightward motion.(Front and rear blades create sideward torque)
- Torques acted because of side propeller blades will create forward motion or backward motion.(Left and right side blades creates forward or backward torque.)
- https://www.youtube.com/watch?v=N_XneaFmOmU How drones work


2 Key Gyroscopic Properties
1. Rigidity in Space
2. Precession

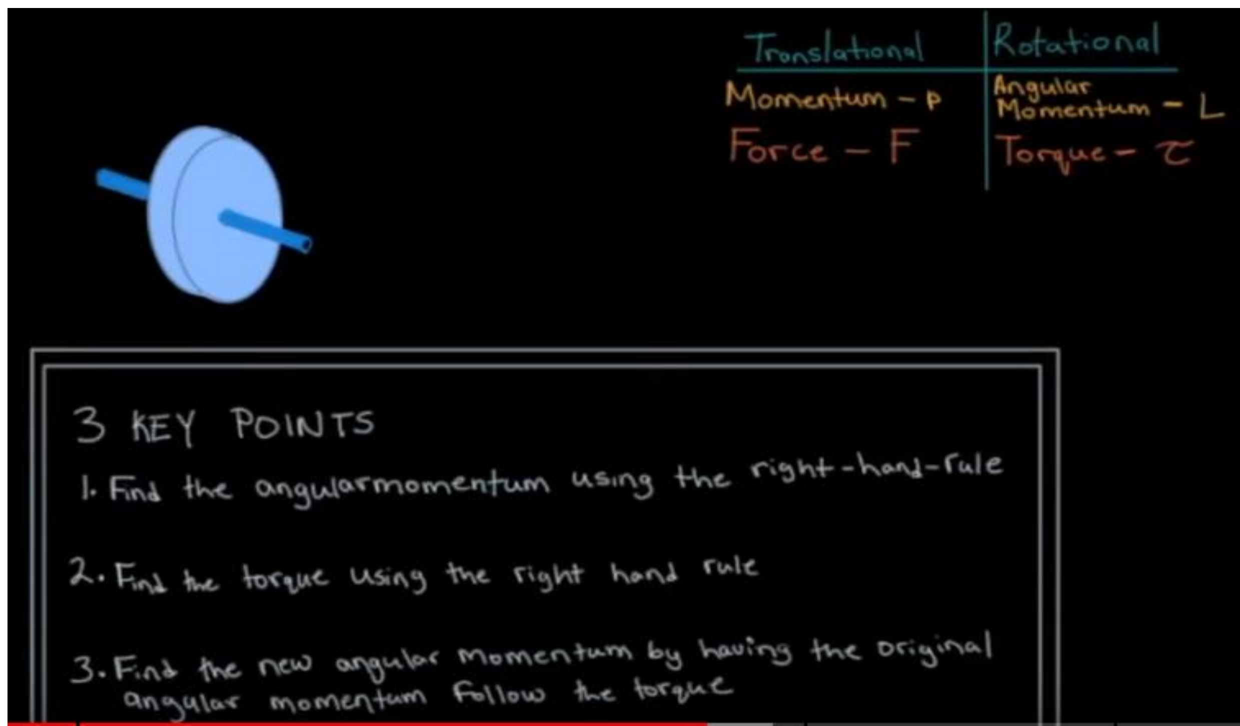

Translational
Rotational
Momentum – p
Force – F
F
p
p'
p'
prime the momentum changed to follow the force and


L
L


L
L



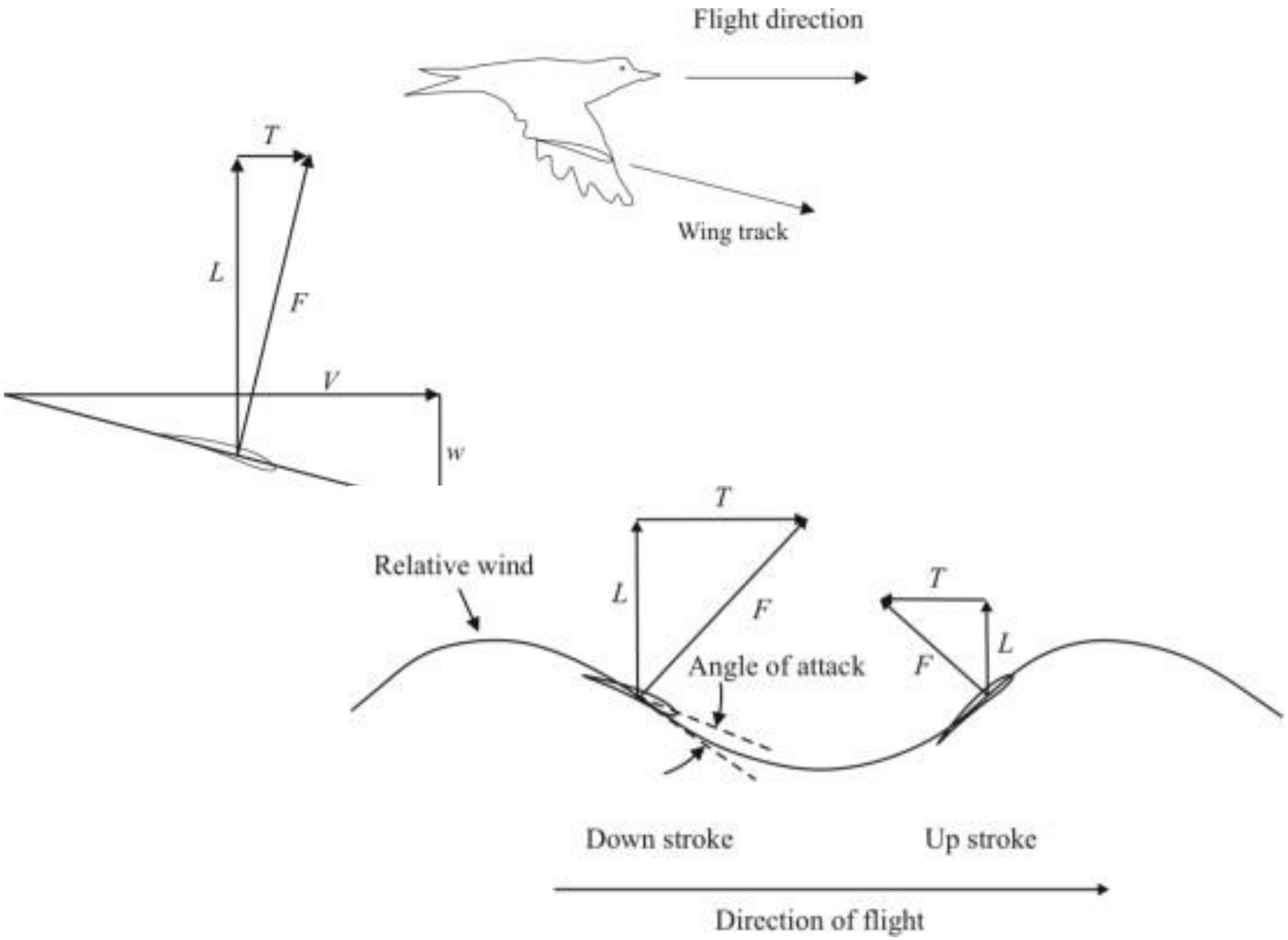
Translational | Rotational
Momentum – p | Angular Momentum – L
Force – F | Torque – τ
L
τ
τ
L
L'



Translational | Rotational
Momentum – p | Angular Momentum – L
Force – F | Torque – τ
3 KEY POINTS
1. Find the angularmomentum using the right-hand-rule
2. Find the torque using the right hand rule
3. Find the new angular momentum by having the original angular momentum follow the torque

Aerodynamics of flapping wings

Flapping Wings

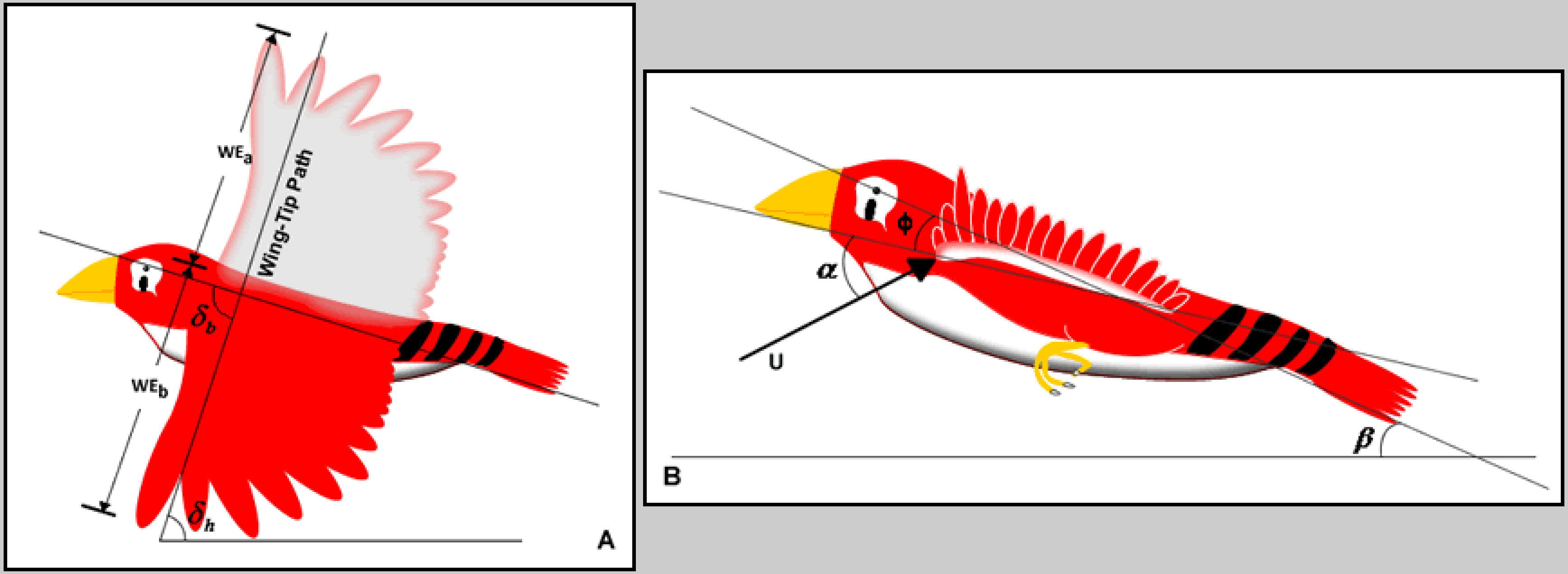


- The flapping of the wings of birds is not a pure up and down or rowing backstroke as commonly thought. The wings of a flying bird move up and down as they are
- flapped, but they also move forward due to the bird's velocity through the air mass. Figure shows the resulting velocity and force triangles when the wing is moving downward. The net velocity of the wing through the air mass is the sum of the forward velocity of the bird's body (V) and the downward velocity of the wing, driven by the muscles of the bird (w), which varies over the length of the wing, being greatest at the wing tip. The resulting total velocity through the air mass is forward and down, which means that the relative wind over the wing is to the rear and up.
- The net aerodynamic force generated by that relative wind (F) is perpendicular to the relative wind and can be resolved into two components, lift (L) upward and thrust (T) forward.
- It is also possible for the bird to introduce a variable twist in the wing over its length, which could maintain the same angle of attack as w increases and the relative wind becomes tilted more upward near the tip. This twist can also be used to create an optimum angle of attack that varies over the length of the wing. This can be used to increase the thrust available from the wing tip.
- The bird can make the negative thrust during the up stroke even smaller by bending its wings during the up stroke.This largely eliminates the forces induced by the outer portions of the wings, which are the most important contributors to thrust, while preserving much of the lift produced near the wing roots

Flapping flight

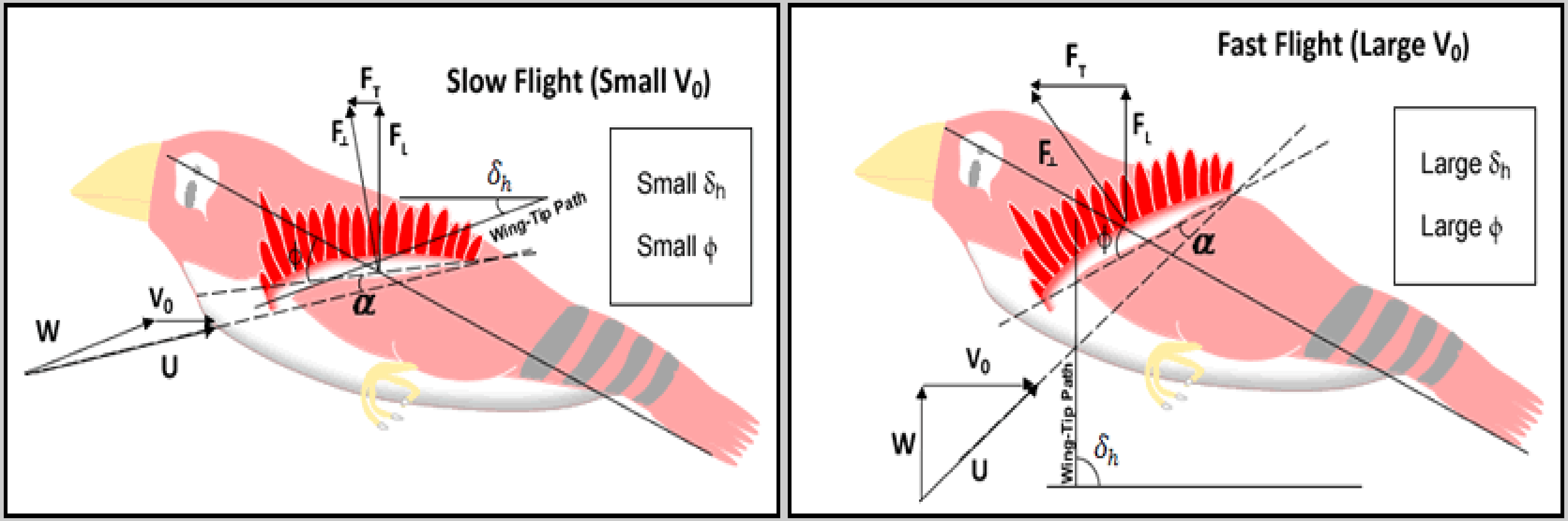
- An additional mode of flapping propulsion is flapping flight utilized by birds. Unlike undulatory swimming, flapping flight involves oscillating (flapping) wings rather than tails. Wings are familiar features from both birds and airplanes, but birds use their wings quite a bit differently than do airplanes. Whereas airplanes use their wings only for generating lift, leaving the job of generating thrust to a separate propulsion system, **birds' wings generate both lift and thrust.**
- As described in the discussion of propellers, wings accelerate fluid away from them to generate a reaction force. If the fluid is accelerated down, lift is the result. If it is accelerated backwards (as in the case of propellers), thrust is the result. To generate both lift and thrust, birds must use their wings as a cross between a wing (lifting surface) and a propeller by accelerating fluid both down and backward. To control the direction of the force on their wings, birds vary two parameters: the stroke-plane angle and the pronation angle (see the figure below).
- The stroke-plane angle can be measured either relative to the horizontal (δ_h) or relative to the axis of the bird body (δ_b). It describes the angle of the wing-tip path during the down stroke**. This is responsible for thrust generation**.
- The pronation angle (ϕ) describes the rotation angle of the wing relative to the axis of the bird body. **This is responsible for lift generation**.

Downstroke



(A) WE$_a$, wingtip elevation at the start of downstroke; WE$_b$, wingtip elevation at the end of downstroke; δ_b, stroke-plane angle relative to the body; δ_h, stroke-plane angle relative to horizontal. (B) ϕ, pronation angle of the wing (negative when above the body axis as shown); α, angle of attack of the wing; β, body angle relative to horizontal.

Adapted from Tobalske, B.W., W.L. Peacock, and K.P. Dial (1999) "Kinematics of flap-bounding flight in the zebra finch over a wide range of speeds," *J. Exp. Biol.* **202**, 1725-1739.



Wing downstroke during slow and fast flight. The wings are shown midway through the downstroke. Flow velocities are shown from the point of view of someone sitting on the wing. V_0 is the flight speed of the bird, *W* is the velocity of the wing, and *U* is the air velocity seen by the wing. Click here for a review of vectors.

To illustrate how birds coordinate δ and ϕ to generate both lift (F_L) and thrust (F_T), **let's focus on a wing downstroke** since this is where most of the action takes place anyway. **For slow speed flight**, the primary force **birds must contend with is gravity since drag is low due to the low forward speed**. For this situation the stroke-plane angle relative to the horizontal (δ_h) is small (< 90°) as shown on the left below. This has two effects. First, it gives the wing forward velocity relative to the bird, so more force can be generated **despite the slow flight speed** (note that *U* is the is the vector sum (addition) of V_0 and *W* and recall that the force on a wing depends on velocity squared). Second, it allows a modest angle of attack (α) to be achieved to be achieved with a smaller pronation angle. A small pronation angle is beneficial because a larger fraction of produces lift (vertical force) and a modest angle of attack is helpful because if α is too large, the "drag" on the wing ($F_{//}$, not shown) can become large, reducing efficiency (see the discussion of thunniform propulsion).

To contend with the **increased drag in high-speed flight**, birds use a larger pronation angle and a larger stroke-plane angle (approaching 90°) during the downstroke. The large pronation angle converts more of to thrust and the large stroke-plane angle allows a positive angle of attack to be achieved at the large pronation angle. The net effect is an increase in the thrust force with sufficient lift to maintain flight.

How bird during downstroke can overcome from low drag(where gravity is major) during low speed flight?

How bird during downstroke can overcome from increased drag during high speed flight.

Contd…

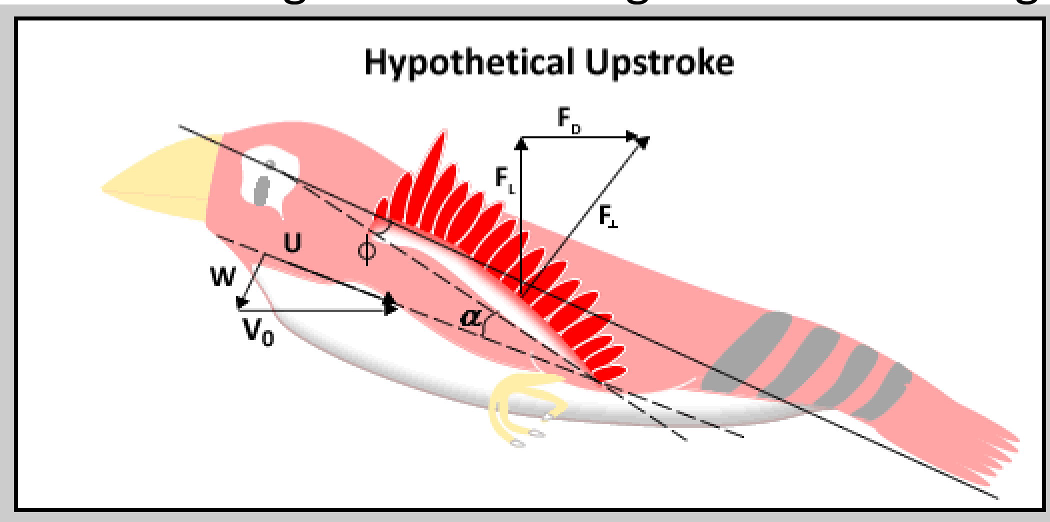
- **How bird during downstroke can overcome from low drag(where gravity is major) during low speed flight?**

-less pronation angle give rise to forward force to overcome drag

- **How bird during downstroke can overcome from increased drag during high speed flight?**

-larger pronation angle give rise to larger forward force.

- **During the upstroke**, birds tend to fold their wings in toward their body (**adduction**). This is especially pronounced at low speed where often no significant lift is generated on the upstroke. The reason for adduction on the upstroke relates to the difficulty in generating beneficial forces during the upstroke in low flight speed.
- To illustrate, a possible upstroke scenario is illustrated below. Notice the large, negative pronation angle required in order to get a positive angle of attack **(required to avoid generating a down force during the upstroke). The result is very little lift generation**, but substantial drag (back force, F_D) generation. To avoid this scenario, birds essentially avoid using their wings during the upstroke **during low-speed flight.**
- In high speed flight, the situation is not quite as bad and many birds do not fold their wings as much on the upstroke. The payoff is lift production on the upstroke with a small drag penalty from the negative pronation angle. The movie below illustrates how this all works together in the flight of a Thrust Nightingale (species *Luscinia luscinia*)



How bird during upstroke avoids downward reaction force?

How bird during upstoke avoids substantial drag in low speed flight?

Contd….

- **How bird during upstroke avoids downward reaction force?**

-larger negative pronation angle for little lift generation

- **How bird during upstroke avoids substantial drag in low speed flight?**

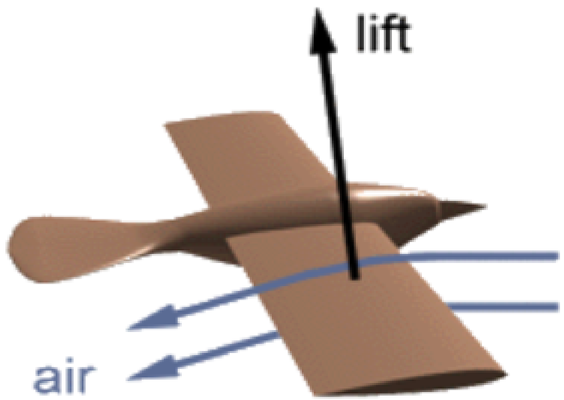
-by folding their wings towards body(adduction).

How Birds & Ornithopters Fly: Gliding flight

- When a bird is just gliding, it moves forward through the air, with its wings held in a fixed position. The wings are at a slight angle, so they deflect the air gently downward. Pushing the air downward causes a reaction force in the opposite direction. You will notice a reaction force, any time you push against anything! The reaction force is called lift. Lift is a force that acts roughly perpendicular to the wing surface and keeps the bird from falling.

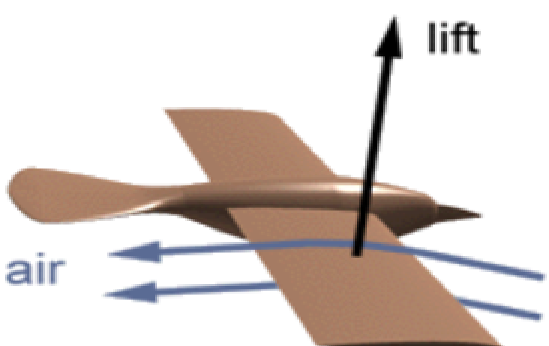
Gliding Flight

When a bird is just gliding, it moves forward through the air, with its wings held in a fixed position. The wings are at a slight angle, so they deflect the air gently downward. Pushing the air downward causes a reaction force in the opposite direction. You will notice a reaction force, any time you push against anything! The reaction force is called lift. Lift is a force that acts roughly perpendicular to the wing surface and keeps the bird from falling.



In gliding flight, a bird's wings deflect air downward, causing a lift force that holds the bird up in the air.

There is also air resistance or drag on the body and wings of the bird. This force would eventually cause the bird to slow down, and then it wouldn't have enough speed to fly. To make up for this, the bird can lean forward a little and go into a shallow dive. That way, the lift force produced by the wings is angled forward slightly and helps the bird speed up. Really what the bird is doing here is giving up some height in exchange for increased speed.The bird must always lose altitude, relative to the surrounding air, if it is to maintain the forward speed that it needs to keep flying.



By tilting forward and going into a slight dive, the bird can maintain forward speed.

References:

- Induced drag: https://www.youtube.com/watch?v=MnB6Lqr91Yc
- Propeller: https://s2.smu.edu/propulsion/Pages/propeller.htm
- Flapping flight: https://s2.smu.edu/propulsion/Pages/flapping.htm
  https://www.ornithopter.org/how.fly.shtml
- swept wings: https://www.youtube.com/watch?v=11nz0YZSNxw
- How rotary wings(helicopter) works: https://www.youtube.com/watch?v=2tdnqZgKa0E
- How drones(quadcopter /rotary wings) work?
  https://www.youtube.com/watch?v=N_XneaFmOmU