

## **II.D. Forces of Flight and Maneuvers (Additional Info no longer included in the PTS)**

---

References: FAA-H-8083-3, FAA-H-8083-25

Objectives	The student should become familiar with the four forces of flight and the forces of flight maneuvers.
Key Elements	<ol style="list-style-type: none"><li>1. Pilot Control of Lift</li><li>2. Parasite vs. Induced Drag</li><li>3. Ground Effect</li></ol>
Elements	<ol style="list-style-type: none"><li>1. Intro</li><li>2. Lift</li><li>3. Airfoils</li><li>4. Pilot Control of Lift</li><li>5. Weight</li><li>6. Thrust</li><li>7. Drag</li><li>8. Ground Effect</li><li>9. Climbs</li><li>10. Descents</li><li>11. Turns</li><li>12. Stalls</li></ol>
Schedule	<ol style="list-style-type: none"><li>1. Discuss Objectives</li><li>2. Review material</li><li>3. Development</li><li>4. Conclusion</li></ol>
Equipment	<ol style="list-style-type: none"><li>1. White board and markers</li><li>2. References</li><li>3. Model Airplane</li></ol>
IP's Actions	<ol style="list-style-type: none"><li>1. Discuss lesson objectives</li><li>2. Present Lecture</li><li>3. Ask and Answer Questions</li><li>4. Assign homework</li></ol>
SP's Actions	<ol style="list-style-type: none"><li>1. Participate in discussion</li><li>2. Take notes</li><li>3. Ask and respond to questions</li></ol>
Completion Standards	The student displays the ability to explain the forces of flight and their interaction and affect on flight.

**Instructors Notes:**

---

**Introduction:**

**Attention**

Interesting fact or attention grabbing story

Everything you ever wanted to know about the science of the airplane which will result in a considerably better understanding of the airplane and hopefully make you a considerably better pilot.

**Overview**

Review Objectives and Elements/Key ideas

**What:**

The four forces of flight are in essence the fundamental principles that govern flight; they are what make an airplane fly.

**Why:**

How well a pilot performs in flight depends on the ability to plan and coordinate the use of power and flight controls to change the forces of thrust, drag, lift, and weight. It is the balance between these forces that the pilot must always control. The better the understanding of the forces, and means of controlling of them, the greater pilot's skill.

**How:**

**1. Intro - Forces of Flight**

- A. Lift – The upward force created by the effect of airflow as it passes over and under the wing
- B. Weight – Opposes lift, and is caused by the downward pull of gravity
- C. Thrust – The forward force which propels the airplane through the air
- D. Drag – Opposes thrust, and is the backward, or retarding force, which limits the speed of the airplane
- E. Terminology:
  - i. Chord Line: The imaginary straight line joining the leading and trailing edges of an airfoil
  - ii. Relative Wind: The direction of movement of the wind relative to the aircraft's flight path. It is opposite the aircraft's flight path, and irrespective of the angle of attack
    - a. EX: Straight and level slow flight and high speed flight have the same relative wind
  - iii. Angle of Attack: The angle between the chord line and the relative wind

**2. Lift**

- A. The force that opposes weight
- B. Principles of Lift
  - i. Newton's three laws of motion:
    - a. Newton's 1<sup>st</sup> Law: A body at rest tends to remain at rest, and a body in motion tends to remain moving at the same speed and in the same direction
    - b. Newton's 2<sup>nd</sup> Law: When a body is acted upon by a constant force, its resulting acceleration is inversely proportional to the mass of the body and is directly proportional to the applied force
      - The law may be expressed by the following formula: Force = Mass x Acceleration ( $F=ma$ )
    - c. Newton's 3<sup>rd</sup> Law: For every action, there is an equal and opposite reaction
  - ii. Bernoulli's Principle
    - a. As the velocity of a fluid (air) increases, its internal pressure decreases

**3. Airfoils**

- A. Definition

## II.D. Forces of Flight and Maneuvers

- i. An airfoil is any surface, such as a wing, which provides aerodynamic force when it interacts with a moving stream of air

### B. Airfoils and Lift

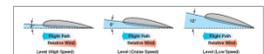
- i. Circulation of the airstream about the airfoil is an important factor in the generation of lift
- ii. The wing's shape is designed to take advantage of both Newton's Laws and Bernoulli's Principle
  - a. The greater curvature on the upper portion causes air to accelerate as it passes over the wing
    - According to Bernoulli, the increase in the speed of the air on the top of an airfoil produces a drop in pressure and this lowered pressure results in lift
      - a. Molecules moving over the upper surface are forced to move faster
        1. Since the upper molecules travel a greater distance, pressure is reduced above
  - b. A downward-backward flow of air also is generated from the top surface of the wing
    - The reaction to this downwash results in an upward force on the wing (Newton's 3<sup>rd</sup> Law)
  - c. The action/reaction principle is also apparent as the airstream strikes the lower surface of the wing when inclined at a small angle (the angle of attack) to its direction of motion
    - The air is forced downward and therefore causes an upward force resulting in positive lift

## 4. Pilot Control of Lift

- A.  $Lift = \frac{1}{2} \rho C_L V^2 S$  (Memory Aid:  $\frac{1}{2}$  Pint, Chug a liter, Vomit twice, Sleep it off)
  - i.  $P = \rho$  or a pressure constant
  - ii.  $C_L =$  Coefficient of Lift – A way to measure lift as it relates to the angle of attack
    - a. Determined by wind tunnel tests and based on airfoil design and angle of attack
  - iii.  $V =$  Velocity
  - iv.  $S =$  Surface Area (Constant)
- B. The amount of lift generated is controlled by the pilot as well as determined by aircraft design factors
  - i. The pilot can change the Angle of Attack (AOA), the airspeed (AS) or you can change the shape of the wing by lowering the flaps
- C. Changing the Angle of Attack
  - i. AOA - The angle between the chord line of the airfoil and the direction of the relative wind
  - ii. Increasing the AOA increases lift
    - a. By changing pitch, you change the AOA of the wings, and at the same time the coefficient of lift ( $C_L$ ) is changing
- D. Changing Airspeed
  - i. The faster the wing moves through the air, the more lift is produced
    - a. Lift is proportional to the square of the AS
      - EX: At 200 knots, an airplane has 4 times the lift as if it was traveling at 100 knot (if other factors remain constant)
        - a. But, if the speed is reduced by  $\frac{1}{2}$ , lift is decreased to  $\frac{1}{4}$  of the previous value
- E. Angle of Attack and Airspeed
  - i. The AOA establishes the  $C_L$  for the airfoil and lift is proportional to the square of the AS
    - a. Since you can control both the AOA and the AS, you can control lift

## 5. Weight

- A. Definition
  - i. The force of gravity which acts vertically through the center of the plane toward the center of earth
  - ii. The combined load of the airplane itself, the crew, the fuel, and the cargo or baggage (everything)
- B. Weight pulls the airplane downward because of the force of gravity
- C. In stabilized level flight, when the lift = weight, the plane is in equilibrium and doesn't gain/lose altitude
  - i. If lift becomes less than weight, the airplane loses altitude and the other way around



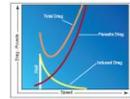
## 6. Thrust

## II.D. Forces of Flight and Maneuvers

- A. Thrust is the forward-acting force which opposes drag and propels the airplane
  - i. This force is provided when the engine turns the prop and acts parallel to the longitudinal axis
  - ii.  $F=MA$ 
    - a. Force is provided by the expansion of burning gases in the engine which turns the propeller
    - b. A mass of air is accelerated opposite to the direction of the flight path (Newton's 3<sup>rd</sup> Law)
      - The equal/opposite reaction is thrust, a force on the plane in the direction of flight
- B. Thrust begins the airplane moving, it continues to move and gain speed until thrust and drag are equal
  - i. In order to maintain a constant AS, thrust and drag must be equal
  - ii. If thrust (power) is reduced the plane will decelerate as long as thrust is less than drag
    - a. Likewise, if AS is increased, thrust becomes greater than drag and AS increases until equal

### 7. Drag

- A. Definition
  - i. Rearward, retarding force, caused by disruption of airflow by the wing, fuselage, or other objects
  - ii. Drag opposes thrust, and acts rearward and parallel to the relative wind
    - a. Acts in opposition to the direction of flight, opposing the forward-acting force of thrust, and limits the forward speed of the airplane
- B. Two types of drag
  - i. Parasite Drag
    - a. Caused by an aircraft surface which deflects/interferes with the smooth airflow of the airplane
    - b. Three Types of Parasite Drag
      - Form Drag: Results from the turbulent wake caused by the separation of airflow from the surface of a structure (The amount is related to the size and shape of the structure)
        - a. Basically, how aerodynamic is the aircraft?
      - Interference Drag: Occurs when varied currents or air over an airplane meet and interact
        - a. EX: Mixing of air over structures like wing and tail surface brace struts and gear struts
      - Skin Friction Drag: Caused by the roughness of the airplane's surfaces
        - a. A thin layer of air clings to these surfaces and creates small eddies which add to drag
    - c. Parasite Drag and Airplane Speed
      - The combined effect of all parasite drag varies proportionately to the square of the airspeed
        - a. EX: Plane, at a constant altitude has 4x as the parasite drag at 160 knots than at 80 knots
    - d. Main Point: As airspeed increases, Parasite drag increases
  - ii. Induced Drag
    - a. Systems in General
      - Physical fact that no system, doing work in the mechanical sense, can be 100% efficient
        - a. Whatever the nature of the system, the required work is obtained at the expense of certain additional work that is dissipated or lost in the system
        - b. The more efficient the system, the smaller the loss
    - b. The Wing as a System



- In level flight, the aerodynamic properties of the wing produce lift, but this is obtained at the expense of a penalty, Drag
  - a. Induced drag is inherent *whenever* lift is produced

#### How it Works

- When lift is produced, the pressure on the lower surface is greater than the upper surface
  - a. The air flows from the high pressure area below the wingtip upward to the low pressure
- The high pressure air beneath the wing joins the low pressure air above the wing at the trailing edge and wingtips causing a spiral or vortex which trails behind each wingtip

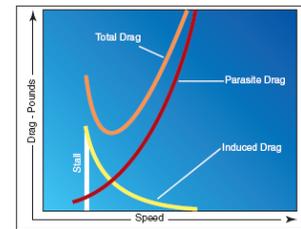
## II.D. Forces of Flight and Maneuvers

- a The spiral is a lateral flow outward from the underside to the upper surface of the wing
- b Basically, induced drag is made by the air circulation around the wing as it creates lift
- There is an upward flow of air beyond the wingtip and a downwash behind the trailing edge
  - a The downwash has nothing to do with the downwash necessary to produce lift
    - 1. It is the source of induced drag
      - a. Vortices increase drag because of the energy spent in producing the turbulence
- Downwash – The Source
  - a The vortices deflect the airstream downward, creating an increase in downwash
    - 1. The wing operates in an average relative wind which is inclined downward and rearward near the wing
  - b Because the lift produced by the wing is perpendicular to the relative wind, the lift is inclined aft by the same amount, reducing it
  - c The greater the size and strength of the vortices, and therefore the downwash component, the greater the induced drag becomes
- The lower the AS, the greater the AOA required to produce lift equal to the airplane's weight and, the greater the induced drag
  - a Induced drag varies inversely as the square of the airspeed

d. Main Point: As lift increases, induced drag increases

### iii. Total Drag

- a. Total drag is the sum of induced and parasite drag



## 8. Ground Effect

A. Associated with the reduction of induced drag

B. Explanation

- i. During takeoff/landing when you are flying very close to the ground, the earth's surface actually alters the three-dimensional airflow pattern around the airplane because the vertical component of the airflow around the wing is restricted by the ground surface
  - a. This causes a reduction in wingtip vortices and a decrease in upwash and downwash
  - b. Since the ground effect restricts downward deflection of the airstream, induced drag decreases

C. Effects on Flight

i. Takeoff

- a. With the reduction of induced drag, the amount of thrust required to produce lift is reduced
  - Therefore, the airplane is capable of lifting off at lower than normal takeoff speed
- b. As you climb out of ground effect, the power (thrust) required to sustain flight increases significantly as the normal airflow around the wing returns and induced drag is increased
  - If you climb out before reaching the normal takeoff speed you might sink back to the surface

ii. Landing

- a. The decrease in induced drag makes the airplane seem to float
  - Power reduction is usually required during the flare to help the airplane land

## 9. Climbs

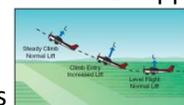
A. In a steady state, normal climb the wing's lift is the same as it is in steady level flight at the same airspeed (AS)

- i. Though the flight path has changed when the climb has been established, the Angle of Attack (AOA) of the wing with respect to the inclined flight path reverts to practically the same values, as does lift

B. During the change from straight and level to a climb, a change in lift occurs when elevator is 1<sup>st</sup> applied

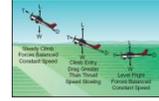
- i. Raising the airplane's nose increases the AOA and momentarily increases lift
- ii. Lift at this moment is now greater than weight and starts the airplane climbing

C. Once the flight path is stabilized, the AOA and lift revert to approx level flight values



## II.D. Forces of Flight and Maneuvers

- D. If the climb is entered with no change in power settings, the AS gradually diminishes
  - i. This is because thrust required to maintain an AS in level flight cannot maintain the AS in a climb
  - ii. When inclined upward, a component of weight acts in the same direction as, and parallel to drag
    - a. This increases drag (drag is greater than thrust and therefore AS will decrease until equal)
- E. Since, in a climb, weight is not only acting downward but rearward along with drag, additional power is needed to maintain the same AS as in level flight
  - i. The amount of reserve power determines the climb performance



### 10. Descents

- A. When forward pressure is applied, the AOA is decreased and, as a result, the lift of the airfoil is reduced
  - i. Reduction in lift/AOA is momentary and occurs during the time the flight path changes downward
  - ii. The change to a downward flight path is due to the lift momentarily becoming less than weight
- B. When the flight path is in a steady descent, the airfoil's AOA again approaches the original value and lift and weight become stabilized
- C. From the time the descent is started until it is stabilized, the AS will gradually increase
  - i. This is due to a component of weight acting forward along the flight path (like rearward in a climb)
    - a. Thrust is greater than drag
- D. To descend at the same AS, power must be reduced when the descent is entered
  - i. The amount of power is dependent on the steepness of the descent
    - a. The component of weight acting forward will increase with an increase in angle of descent

### 11. Turns

- A. Like any moving object, an airplane requires, a sideward force to make it turn
  - i. In a normal turn, this force is supplied by banking so that lift is exerted inward as well as upward
- B. When the airplane banks, lift acts inward toward the center of the turn, as well as upward
  - i. Lift is divided into two components, the horizontal component and the vertical component
    - a. Vertical Component – Acts vertically and opposite to weight
    - b. Horizontal Component – Acts horizontally toward the center of the turn (Centripetal Force)
      - This is what makes the airplane turn
  - ii. The division of lift reduces the amount of lift opposing gravity and supporting weight
    - a. Consequently, the airplane will lose altitude unless additional lift is created
      - This is done by increasing the AOA until the vertical component of lift again equals weight
    - b. Since the vertical component of lift decreases as bank increases, AOA must be increased as the bank angle is steepened
- C. Holding Altitude
  - i. To provide a vertical component of lift sufficient to hold altitude, an increase in the AOA is required
  - ii. Since drag is directly proportional to AOA, induced drag will increase as lift is increased
    - a. This in turn, causes a loss of AS in proportion to the angle of bank
  - iii. Additional power must be applied to prevent airspeed from reducing in level turns
    - a. The required amount of additional thrust is proportional to the angle of bank
- D. Rate of Turn
  - i. The rate at which an airplane turns depends on the magnitude of the horizontal component of lift
    - a. The horizontal component of lift is proportional to the angle of bank
  - ii. Therefore, at any given AS, the rate of turn can be controlled by adjusting the angle of bank
- E. Turning Radius
  - i. Increased AS results in an increase in turn radius and centrifugal force is directly related to radius
    - a. The increase in the radius of the turn causes an increase in centrifugal force which must be balanced by an increase in the horizontal component of lift
      - The horizontal component of lift can only be increased by increasing bank angle

## II.D. Forces of Flight and Maneuvers

- ii. To maintain a constant rate of turn with an increased AS, the angle of bank must be increased
- F. Slipping Turns
  - i. In a slipping turn, the rate of turn is too slow for the angle of bank, and the plane is yawed to the outside of the turning flight path
    - a. The horizontal component ( $H_{CL}$ ) of lift is greater than Centrifugal Force (CF)
  - ii.  $H_{CL}$  and CF equilibrium is reestablished by decreasing bank/increasing the rate of turn
    - a. Increase or decrease rudder pressure to center the ball or adjust bank
- G. Skidding Turns
  - i. In a skidding turn, the rate of turn is too great for the angle of bank and the plane is yawed inside the turn
    - a. There is excess centrifugal force compared to the  $H_{CL}$
  - ii. Correction involves reducing the rate of turn/increasing the bank
    - a. Increase or decrease rudder pressure as necessary or adjust bank

### 12. Stalls

- A. As long as the wing is creating sufficient lift to counteract the load imposed on it, the plane will fly
  - i. When the lift is completely lost, the airplane will stall
- B. The direct cause of every stall is an excessive angle of attack
- C. The stalling speed of a particular airplane is not a fixed value for all flight situations
  - i. However, a given airplane will always stall at the same AOA regardless of speed, weight, load factor, or density altitude
  - ii. Each plane has a particular AOA where airflow separates from the upper wing and it stalls ( $16^\circ$ - $20^\circ$ )
- D. 3 situations where the critical AOA can be exceeded:
  - i. Low Speed Flying
    - a. As AS is decreased, the AOA must be increased to retain the lift required to hold altitude
    - b. The slower the AS, the more AOA must increase. At the critical AOA, lift cannot increase further
      - If AS is reduced, the airplane will stall, since the AOA has exceeded the critical AOA
  - ii. High Speed Flying
    - a. Low speed is not necessary to produce a stall
    - b. The wing can be brought to an excessive angle of attack at any speed
    - c. EX: diving at 200 knots with a sudden increase in back elevator pressure
      - Because of gravity and centrifugal force, the plane can not immediately alter its flight path
        - a It would merely change its AOA abruptly from very low to very high
      - Since the flight path of the airplane in relation to the oncoming air determines the direction of the relative wind, the AOA is increased, and the stalling angle would be reached
  - iii. Turning Flight
    - a. The stalling speed of an aircraft is higher in a level turn than in straight and level flight
      - This is because the centrifugal force is added to the plane's weight
        - a The wing must produce sufficient additional lift to counteract the load imposed
    - b. In a turn, the necessary additional lift is acquired by applying back pressure
      - This increases the wings AOA (AOA increases with the bank angle to maintain level flight)
    - c. If at any time during a turn the AOA becomes excessive, the airplane will stall

### Conclusion:

Brief review of each main point

## II.D. Forces of Flight and Maneuvers

### **PTS Requirements:**

To determine that the applicant exhibits instructional knowledge of the elements of principles of flight by describing:

1. Airfoil design characteristics.
2. Airplane stability and controllability.
3. Turning tendency (torque effect).
4. Load factors in airplane design.
5. Wingtip vortices and precautions to be taken.

II.D. Forces of Flight and Maneuvers

