Task II.D: Principles of Flight

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Lesson Overview

Objective

The student should develop knowledge of the elements related to primary flight controls, trim control, and wing flaps.

Reference

FAA-H-8083-25B, Pilot's Handbook of Aeronautical Knowledge (Chapter 4, Chapter 5) FAA-H-8083-3B, Airplane Flying Handbook (Chapter 3)

Key Elements

- Pilot control of lift
- Parasite and induced drag

- Ground effect
- Result of a force
- Weight vector
- Centrifugal force
- Stability vs maneuverability
- Left turning tendencies
- Load factors

Elements

- Forces of flight
- Lift
- Airfoils
- Pilot control of lift
- Weight
- Thrust
- Drag
- Ground effect
- Climbs
- Descents
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Equipment

- White board
- Markers
- Model Airplane
- References

Schedule

1. Discuss objectives
2. Review material
3. Development

4. Conclusion

Instructor Actions

1. Discuss lesson objectives
2. Present lecture
3. Questions
4. Homework

Student Actions

- Participate in discussion
- Take notes

Completion Standards

The student can explain the forces of flight and their interactions and effect on flight, and understands the principles of flight.

Instructor Notes

Attention

Everything you ever wanted to know about the science of the airplane which will result in a considerably better understanding of the airplane and make you a considerably better pilot. To know why we do what we do, you need to know why the airplane does what it does.

Overview

Review Objectives and Elements/Key ideas

What

The Principles of Flight are the characteristic forces of flight as well as why and how the airplane performs certain ways.

Why

To become a pilot, a detailed technical course in the science of aerodynamics is not necessary. However, with the responsibilities for the safety of passengers, the competent pilot must have a well-founded concept of the forces which act on the airplane, and the advantageous use of these forces, as well as the operating limitations of the particular airplane.

Lesson Details

Many forces act on an aircraft in flight, and many of these forces work in concert to give desired handling characteristics. A good understanding of how these forces work, and how they combine to give the results desired is crucial to understanding the nuances of flight.

Forces of Flight

- Lift — the upward force created by the effect of airflow as it passes over and under the wing.

- Weight — opposes lift, caused by the downward pull of gravity.
- Thrust — the forward force which propels the airplane through the air.
- Drag — opposes thrust, backward force which limits the speed of an airplane.

Lift

Generated by wing moving through air.

Newton's basic laws of motion

- **First law** — every object persists in its state of rest or uniform motion in a straight line unless it is compelled to change that state by forces impressed on it.
- **Second law** — force is equal to the change in momentum per change in time. For a constant mass, force equals mass times acceleration (F=ma).
- **Third law** — for every action, there is an equal and opposite reaction.

Bernoulli's principle

The pressure of a moving fluid varies with its speed of motion. As the velocity increases, the pressure within the fluid decreases.

Airfoil

Any surface (e.g. wing) that provides aerodynamic force when interacting with a moving stream of air. Chord line: a straight line drawn through the airfoil profile connecting the extremities of the leading and trailing edges.

- **Camber:** distance from chord line to upper and lower wing surfaces.
- **Mean camber line:** line equidistance at all points from upper and lower surfaces.

Lift

Circulation of airstream about the airfoil is an important factor in the generation of lift. The wing's shape is designed to take advantage of both Newton's laws and Bernoulli's principle. Greater curvature on upper portion causes air to accelerate as it passes over the wing, resulting in drop in pressure. Lowered pressure is a component of total lift.

- Positive pressure lifting action from air mass below the wing, negative pressure lifting action from lowered pressure above the wing.
- Top surface of wing generates downward-backward flow of air (downwash) which results in an upward force on the wing (Newton's third law).
- Action/reaction principle—airstream striking the lower surface of the wing when inclined at a small angle to its direction of motion forced downward, causing an upward reaction (positive lift).

Pilot control of lift

- L = ½ρ * V^2 *Cl * S
- CL coefficient of lift—determined by wind tunnel tests and based on airfoil design and angle of attack.

Amount of lift generated controlled by pilot and determined by aircraft design factors—change angle of attack, airspeed, or shape of the wing. AOA establishes CL, and lift is proportional to the square of the airspeed.

- **Angle of attack**
    - Increasing angle of attack increases lift.
    - Change pitch to change AOA of the wings and CL.
- **Airspeed**
    - Increasing speed of wing movement through air increases lift.

Weight

- The force of gravity, acting vertically through the center of gravity of the plane, towards the center of the Earth. Pulls the airplane downward.
- Stabilized level flight when lift=weight, the plane is in equilibrium—doesn’t gain or lose altitude.

Thrust

- The force of gravity, acting vertically through the center of gravity of the plane, towards the center of the Earth. Pulls the airplane downward.
- Stabilized level flight when lift=weight, the plane is in equilibrium—doesn’t gain or lose altitude.

Drag

- Rearward force, caused by disruption of airflow by wing, fuselage, etc.
- Opposes thrust, acts rearward parallel to relative wind.
- Total drag—the sum of parasite and induced drag.

Parasite drag

- Caused by aircraft surfaces deflecting/interfering with the smooth airflow.
- Factors influencing parasite drag: object shape, indicated airspeed.
- Combined effect of parasite drag varies directly proportionally to the square of airspeed.
- Three types
    - Form drag - Results from turbulent wake caused by separation of airflow from surface.

Amount of drag related to size and shape of structure.

  - Interference drag - Varied currents of air over airplane meet and interact—mixing of air.
  - Skin friction drag - Caused by roughness of airplane's surfaces. Thick layer of air clings to surfaces, creating small eddies that add to drag.

Induced Drag

Occurs when a moving object redirects airflow coming at it. The vortices along the trailing edge change the velocity of the airflow behind the trailing edge, producing a downwards deflection and inducing downwash. A higher AOA is therefore required for the same lift, which tilts the total aerodynamic force rearwards.

Ground effect

- Reduction of induced drag when flying close to the ground.
- Earth's surface alters the three-dimensional airflow pattern around the airplane—the vertical component of the airflow around the wing is restricted by the ground surface.
- Aerodynamic Effects:
  - Reduction in wingtip vortices.
  - Decrease in upwash and downwash.
  - Restricted downward airstream deflection.
  - Decreased induced drag

Ground effect on takeoff

Reduced amount of thrust required to produce lift—airplane can lift off at a lower than normal takeoff speed.

During climb out of ground effect, thrust required to sustain flight increases as normal airflow around wing and induced drag increases. Climbing out before reaching normal takeoff speed—may sink back to the surface.

Ground effect on landing

- Decrease in induced drag makes airplane seem to float.
- Power reduction needed during flare to help the airplane land.
- Starts at one wingspan higher than the ground.

Climbs

Steady state, normal climb—wing's lift is the same as in steady level flight at the same airspeed. Flight path changed when climb was established, but AOA reverts to the same value, as does lift. (inclined flight path)

- Raising airplane's nose increases angle of attack and momentarily increases lift. Lift is greater than weight and starts the climb.
- Once flight path is stabilized, AOA and lift revert to level flight values.

If the climb is entered without a change in power settings, airspeed gradually diminishes. Thrust required to maintain airspeed in level flight cannot maintain airspeed in climb.

When inclined upward, a component of weight acts parallel to drag—drag is increased, drag greater than thrust, airspeed will decrease until forces are equalized. Additional power required to maintain the same airspeed.

- Amount of reserve power determines climb performance.

Descents

Forward pressure decreases AOA and reduces lift momentarily. Change to downward flight path dude to lift momentarily becoming less than the weight. When the flight path is in a steady descent, the AOA approaches the original value, weight and lift equalize. Airspeed will gradually increase from the start of the descent until force equalization. Component of weight acts forward along flightpath—thrust is greater than drag.

To descend at the same airspeed, power must be reduced when the descent is entered, depending on the steepness of the descent. Component of weight acting forward increases with an increase in angle of descent.

Turns

Airplane requires a sideward force to make it turn. In a ***normal turn*** force supplied by banking. Lift exerted inward as well as upward.

Lift Component

Lift is divided into two components.

- Vertical component acts vertically, opposite to weight.
- Horizontal component acts horizontally, toward the center of the turn (centripetal force). This is the force that pulls the airplane, making it turn.

Division of lift reduces amount of lift available to oppose gravity/support weight. The airplane will lose altitude if additional lift is not created (by increasing AOA until vertical component of lift equals weight). Vertical component of lift decreases as bank increases—progressively increase AOA as bank is steepened.

Rate of turn

- Rate depends on magnitude of horizontal component of lift, which is proportional to the angle of bank.
- At any given airspeed, the rate of turn can be controlled by adjusting the angle of bank.

Holding altitude

- Increase AOA to provide sufficient vertical component of lift. Induced drag will increase as lift is increased, causing a loss of airspeed in proportion to the angle of bank.
- Apply additional power to prevent airspeed from reducing in level turns. Required additional thrust proportional to angle of bank.

Turning radius

- Increased airspeed results in an increase in turn radius. Centrifugal force is directly related to the radius. Increase in turn radius causes 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.
- To maintain a constant rate of turn with an increased airspeed, the AOA must remain constant and the angle of bank must be increased.

Slipping turns

- Rate of turn is too slow for angle of bank.
- *Plane is yawed to the outside of the turning flight path.*
- Horizontal component of lift is greater than centrifugal force.
- To reestablish horizontal component of lift and centrifugal force equilibrium, decrease bank/increase the rate of turn.

Skidding turns

- Rate of turn too great for angle of bank.
- *Plane is yawed inside the turning flight path.*
- Centrifugal force is greater than the horizontal component of lift.
- Reduce the rate of turn/increase the bank to correct.

Stalls

The plane will fly as long as the wings are creating sufficient lift to counteract the load imposed on them.

Cause of stall—excessive AOA. A given airplane will always stall at the same AOA regardless of speed, weight, load factor, or density altitude. It's the AOA where airflow separates from the upper wing (16°-20°).

> ***Stalling speed is not a fixed value for all flight situations.***

Exceeding AOA

- Low speed flying — as airspeed is decreased, AOA must be increased to retain lift required to hold altitude. At some point the airplane cannot be supported—if airspeed is reduced further, the AOA will exceed the critical angle, and the plane will stall.
- High speed flying — the wing can be brought to an excessive AOA at any speed; low speed is not necessary to stall. E.g. if diving followed by a sudden increase in back elevator pressure: gravity and centrifugal force do not allow the plane to immediately alter its flight path, it merely changes its AOA abruptly from very low to very high, reaching the stalling angle, since the flight path of the airplane in relation to the oncoming air determines the direction of the relative wind.
- Turning flight — stalling speed higher in a level turn than in straight and level flight, because the centrifugal force is added to the plane's weight. Wing must produce sufficient additional lift to counteract the imposed load. Back pressure to acquire necessary additional lift increases AOA and the airplane stalls if the AOA becomes excessive.

Airfoil design characteristics

Planform

- Describes the wing's outline as seen from above.
- Factors affecting shape: purpose, load factors, speeds, construction/maintenance costs, maneuverability/stability, stall/spin characteristics, fuel tanks, high lift devices, gear, etc.

Taper

- The ratio of the root chord to the tip chord.
- Rectangular wings have a taper ratio of 1.
    - Ribs are all the same size—simpler and more economical to produce and repair.
    - Roots stall first, providing more warning and more control during recovery.
- Tapered/ellipse wings—provide the best spanwise load distribution and lowest induced drag.
    - The whole wing stalls at the same time and they are very expensive/complex to build.

Aspect ratio

- Assuming rectangular wing—divide wingspan by chord.
- Greater AR—less induced drag, more lift.
- Increasing the wingspan while keeping the area constant results in smaller wingtips, generating smaller vortices. Reduces drag, increases efficiency.
- Planes that require extreme maneuverability and strength need to have a lower AR.

Sweep

- Line connecting the 25% chord points of all the ribs—not perpendicular to longitudinal axis.
- Usually backward swept, can also be forward.
- Helps in flying near Mach 1; can also contribute to lateral stability in low-speed planes.

Controllability

Capability to respond to pilot's control (especially in regard to flight path and attitude). Quality of response to control application when maneuvering, regardless of stability characteristics.

Maneuverability

Design characteristic-quality that permits a plane to be maneuvered easily and withstand imposed stresses. Governed by weight, inertia, size/location of flight controls, structural strength, and powerplant.

Stability

Inherent quality of airplane to correct for conditions that may disturb its equilibrium and return to or continue on the original flight path. Primarily a design characteristic. Stable plane—tends to return to its original condition if disturbed. Stability and maneuverability must be balanced. More stability = easier to fly. Too stable = significant effort to maneuver.

- Two types: static and dynamic.
- Equilibrium: all opposing forces are balanced. Steady unaccelerated flight conditions.

Static stability

The initial tendency that the airplane displays after its equilibrium is disturbed.

Positive static stability

Initial tendency to return to the original state of equilibrium after being disturbed—most desirable.

Negative static stability

Initial tendency to continue away from the original state of equilibrium after being disturbed.

Neutral static stability

Initial tendency to remain in a new condition after equilibrium has been disturbed.

Dynamic stability

While static stability refers to the initial response to an upset of equilibrium, dynamic stability refers to how the system responds over time. It describes whether the system returns to equilibrium over time, and the degree of stability is described in terms of how quickly it returns to equilibrium (assuming it does).

Dynamic stability can also be divided into oscillatory and non-oscillatory modes. Oscillatory describes the motion of a marble in the bottom of a smooth bowl where if it is disturbed it eventually returns to rest back at the bottom of the bowl. This describes a system that exhibits both positive static stability and oscillatory positive dynamic stability. The longer the oscillations in time, the easier the aircraft is to control Neutral or divergent short oscillation is dangerous as structural failure can result. Non-oscillatory can be described by replacing the marble with a cotton ball, and the system returns to rest with no oscillations.

1. Oscillatory: equilibrium returns after some oscillations.
    a. Longer oscillations (time-wise) = plane easier to control.
    b. Shorter oscillations (period 1-2s) make plane difficult or impossible to control.
2. Neutral/Divergent short oscillation is dangerous—structural failure can result.
3. Non-oscillatory: returns to equilibrium without oscillations.

Longitudinal stability

Quality that makes airplane stable about its lateral axis. Involves the pitching motion. Longitudinally unstable plane tends to dive/climb progressively more steeply, making it difficult/dangerous to fly.

Wing and tail moments must be such that, if the moments are initially balanced and the airplane is suddenly nosed up, the wing moments and tail moments will change so that the sum of their forces will provide an unbalanced but restoring moment, bringing the nose down again. If the plane is nosed down, the resulting change in moments will bring the nose back up.

Static longitudinal stability is dependent on three factors:

Location of the wing in relation to the CG

1. The CG is usually located ahead of the wing's center of lift, which results in a nose-down pitch. Nose heaviness balanced by downward force generated by the horizontal tail (CG-CL-Tail line lever: strong down force at CG, weaker force at Tail, up force at CL).
2. The horizontal stabilizer/elevator are cambered on the bottom to create a tail down force.
3. If pitched up, the negative AOA of the stabilizer is reduced, increasing drag and reducing airspeed, both of which reduce the tail-down force, allowing the plane to pitch down.
4. As the plane pitches down and accelerates, the increasing AOA and airflow at the horizontal tail increase the tail down force, raising the nose, reducing airspeed.
5. Series of progressively smaller oscillations until the plane returns to straight and level.

Location of the horizontal tail surfaces with respect to the CG

1. If the plane is loaded with the CG farther forward, more tail down force is necessary.
2. The nose heaviness makes it more difficult to raise the nose, and the additional tail down forces make it difficult to pitch down. Small disturbances are opposed by larger forces, making them damp out quickly.

3. If the plane is loaded further aft, the plane becomes less stable in pitch. If a gust pitches the nose up, the reduced airflow over the tail will cause the nose to pitch further up.

The area or size of the tail surfaces

1. The area of the tail effects the longitudinal stability of the aircraft.

Lateral stability

Lateral stability describes the stability around the roll axis. Stability around this axis is impacted by dihedral, sweepback angles, keel effect, and weight distribution.

Lateral stability is Affected by:

Dihedral

1. The angle at which the wings are slanted upward from the root to the tip. Involves a balance of lift created by the wing's AOA on each side of the longitudinal axis—the airplane tends to sideslip/slide downward toward the lowered wing.
2. Dihedral causes the air to strike the low wing at a greater AOA than the high wing, increasing the low wing lift and decreasing the high wing lift, restoring the original attitude.

Sweepback angle

1. The angle at which the wings are slanted rearward from the root tip. Increases dihedral to achieve stability, but the effect is not as pronounced.

Keel effect

1. Depends on the action of the relative wind on the side area of the fuselage.
2. The greater portion of the keel area is above/behind the CG in laterally stable planes.
3. When the plane slips to one side, the combination of the plane's weight and the pressure of the airflow against the upper portion of the keel area tends to roll the plane back to wings level.
4. The fuselage is forced by the keel effect to parallel the wind.

Weight distribution

1. If more weight is located on one slide, the airplane will have a tendency to bank that direction.

Directional stability

1. Stability about the vertical axis.
    a. Affected by the area of the vertical fin and the sides of the fuselage aft of the CG, which makes the airplane act like a weathervane, pointing its nose into the relative wind.
        i. Sides: in order for a weathervane to work, a greater surface must be aft of the pivot point. The side surface must be greater aft than ahead of the CG.
        ii. Vertical fin: the fin acts similarly to the feather of an arrow in maintaining straight flight. The farther aft it is placed and the larger its size, the greater the directional stability. Motion is retarded and stopped by the vertical fin—as the plane rotates one way, the air is striking the other side at an angle, causing pressure on one side, resisting

the turn, and slowing the yaw. Acts like the weathervane in turning the airplane into the relative wind.

Turning tendencies

Torque made up of four elements, which produce a twisting motion around at least one of the aircraft's axes.

1. Torque reaction - Newton's 3rd law—for every action, there is an equal and opposite reaction.
   a. The propeller revolves one way, creating an equal force that attempts to rotate the plane the other way.
   b. When airborne, the force acts around the longitudinal axis, which tends to make the airplane roll to the left. It can be corrected by offsetting the engine, or using aileron trim tabs.
   c. On the ground during takeoff, the left side is being forced down resulting in more ground friction, causing a turning moment to the left that can be corrected with rudder.
   d. Magnitude dependent on engine size/hp, prop size/rpm, airplane size, and ground reference.
2. Corkscrew effect of the slipstream
   a. High-speed prop rotation gives a spiraling rotation to the slipstream (corkscrew) — very compact rotation at high prop speeds/low forward speeds, exerts strong sideward force on the vertical tail, causing a left turn around the vertical axis.
3. Gyroscopic action of the propeller - based upon two fundamental principles
   a. Rigidity in space
      i. The resultant action of a spinning rotor when a deflecting force is applied to its rim. If a force is applied, the resulting force takes effect 90° ahead of and in the direction of the turn, causing a pitching/yawing moment or combination of the two, depending on where applied.
      ii. Any yawing around the vertical axis results in a pitching moment.
      iii. Any pitching around the lateral axis results in a yawing moment.
      iv. Correct with the necessary elevator and rudder pressure.
   b. Precession
4. P-factor
   a. When flying with a high AOA, the bite of the down-moving blade is greater than the up-moving blade, moving the center of thrust to the right of the prop disc area. This causes a yaw to the left. Caused by the resultant velocity (generated by the combination of the prop blade velocity in its rotation and the velocity of the air passing horizontally through the prop disc).
   b. At a positive AOA, the right blade is passing through an area of resultant velocity greater than the left.
   c. Increased velocity means increased lift (prop is an airfoil). Down-blade has more lift and tends to yaw the plane to the left

Load factors and airplane design

1. Load factor—force applied to an airplane to deflect its flight from a straight line, producing stress on its structure.
2. Ratio of the total load acting on the airplane to the airplane's gross weight.
3. Pilot can impose dangerous overload on the structure.
4. An increased load factor increases the stall speed, making stalls possible at seemingly safe airspeeds.

Category system

Normal category

limit load factors 3.8 G's to -1.52 G's

Utility category

limit load factors 4.4 G's to -1.76 G's (mild aerobatics including spins)

Acrobatic category

limit load factors 6.0 G's to -3.0 G's

- More severe maneuvers = higher load factors

VG diagram

Shows the flight operating envelope of a plane that is valid for certain weight/altitude operations. Presents the allowable combination of airspeed and load factors for safe operation.

Wingtip vortices

Whenever a wing is producing lift the pressure on the lower surface is higher than the pressure on the upper surface. Air tends to flow from the high pressure area to the lower and during flight this means that air "spills" off the tip of the wing and tries to roll up onto the top. The result is a swirling mass of air trailing the aircraft.

The strength of this vortex is determined by the weight of the aircraft, the speed of the aircraft, and the shape of the wing. AOA directly affects the strength and as weight increases, AOA increases. Also if the wing is "clean" (i.e. has no lift augmentation devices such as flaps and slats deployed) it has a greater AOA. Finally, as speed increases AOA decreases. Therefore the strongest vortex is when the aircraft is heavy, clean, and slow. (i.e. during takeoff and landing).

Vortexes sink at a rate of a few hundred feet per minute, and slowing/diminishing as they get further from the aircraft. When they sink to the ground they tend to move laterally with the wind. This means that winds can bring a vortex into your landing path, so be aware!

The vortexes are the cause of "wake turbulence" and are to be avoided. At a minimum they can make for an uncomfortable ride, and at the worst they can induce unintended aerobatics or structural failure. This is most often a problem when a light aircraft is operating near a heavy jet transport, which can generate very strong vortexes. The vortexes can be avoided by a number of techniques.

During landing stay above the flight path of the aircraft in front of you, and land beyond that aircraft's touchdown point. For parallel runways stay at and above the other aircraft's path, and for crossing runways cross above the other aircraft's path.

During takeoff delay liftoff until after the jet's touchdown point, and takeoff and stay above another departing jet's path. Note that the climb rate for most jets exceed those of light aircraft, so a turn away from the departing aircraft's path may be mandated to avoid wake turbulence.

Vortex behavior

- Remain spaced less than a wingspan apart.
- Drift with the wind.
- Sink at a rate of several hundred fpm, slowing and diminishing the further they are behind the aircraft.
- When larger aircraft vortices sink to the ground (100-200'), they tend to move laterally (2-3 knots). A crosswind will decrease the lateral movement of the upwind, and increase the movement of the downwind. A tailwind can move the vortices of the preceding aircraft forward into the touchdown zone.

Avoidance

Can be a hazard to any aircraft significantly lighter than the generating aircraft. Can incur major structural damage, induced rolling, loss of control.

- When landing—stay above and land beyond the jet's touchdown point and land prior to another jet's takeoff point.
- Parallel runways—stay at or above the jet's path in case there is drift.
- Crossing runways—cross above the jet's flightpath.
- Takeoff—takeoff after the jet's landing point, and takeoff before and stay above the jet's takeoff path.

Conclusion

The competent pilot must have a well-founded concept of the forces which act on the airplane, and the advantageous use of these forces, as well as the operating limitations of the particular airplane.

ACS 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.