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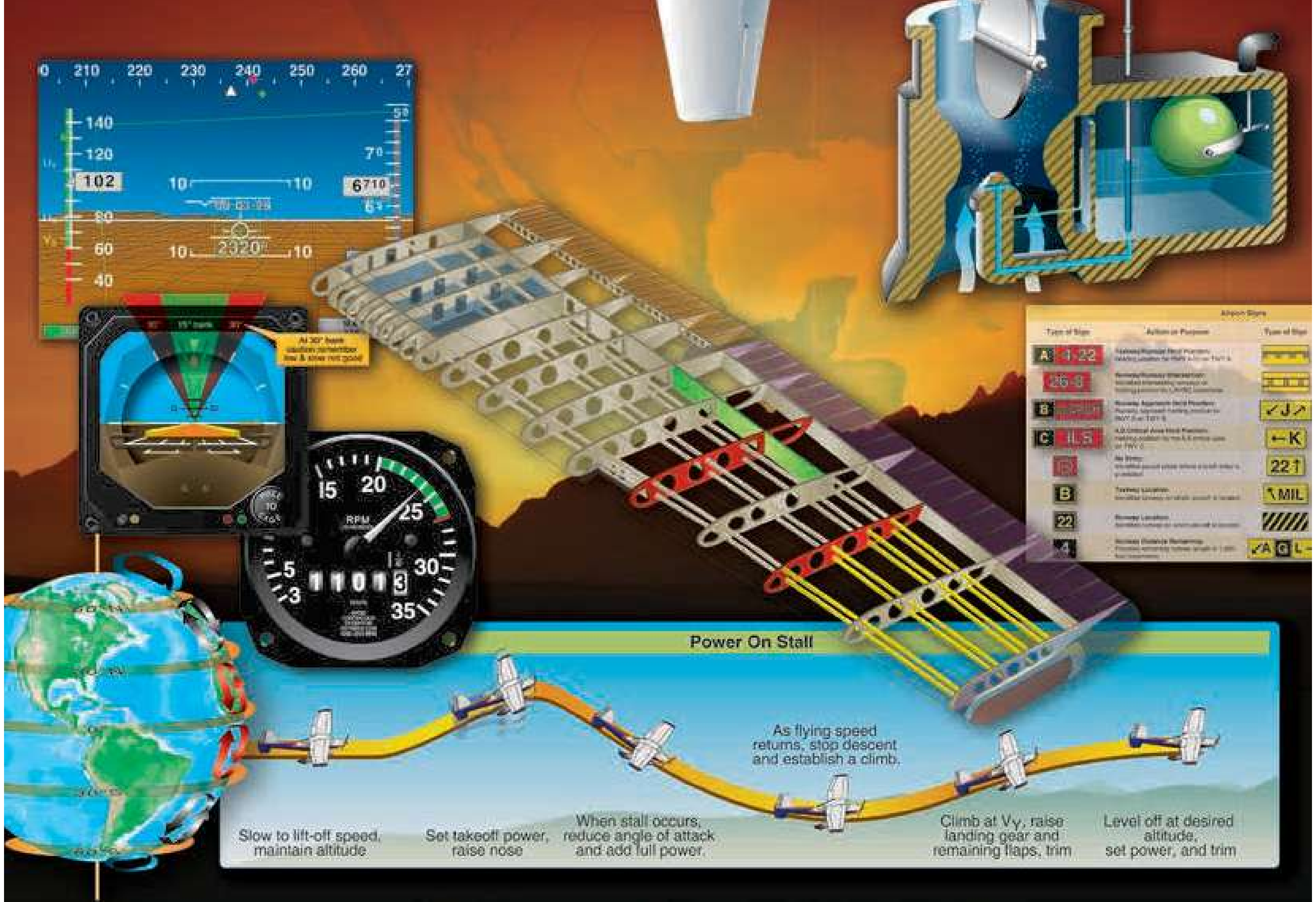
Pilot's Handbook of Aeronautical Knowledge

U.S. Department of Transportation

Federal Aviation Administration



The airflow outside of the boundary layer reacts to the shape of the edge of the boundary layer just as it would to the physical surface of an object. The boundary layer gives any object an "effective" shape that is usually slightly different from the physical shape. The boundary layer may also separate from the body, thus creating an effective shape much different from the physical shape of the object. This change in the physical shape of the boundary layer causes a dramatic decrease in lift and an increase in drag. When this happens, the airfoil has stalled.

In order to reduce the effect of skin friction drag, aircraft designers utilize flush mount rivets and remove any irregularities that may protrude above the wing surface. In addition, a smooth and glossy finish aids in transition of air across the surface of the wing. Since dirt on an aircraft disrupts the free flow of air and increases drag, keep the surfaces of an aircraft clean and waxed.

Induced Drag

The second basic type of drag is induced drag. It is an established physical fact that no system that does work in the mechanical sense can be 100 percent efficient. This means that 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. The more efficient the system, the smaller this loss.

In level flight, the aerodynamic properties of a wing or rotor produce a required lift, but this can be obtained only at the expense of a certain penalty. The name given to this penalty is induced drag. Induced drag is inherent whenever an airfoil is producing lift and, in fact, this type of drag is inseparable from the production of lift. Consequently, it is always present if lift is produced.

An airfoil (wing or rotor blade) produces the lift force by making use of the energy of the free airstream. Whenever an airfoil is producing lift, the pressure on the lower surface of it is greater than that on the upper surface (Bernoulli's Principle). As a result, the air tends to flow from the high pressure area below the tip upward to the low pressure area on the upper surface. In the vicinity of the tips, there is a tendency for these pressures to equalize, resulting in a lateral flow outward from the underside to the upper surface. This lateral flow imparts a rotational velocity to the air at the tips, creating vortices that trail behind the airfoil.

When the aircraft is viewed from the tail, these vortices circulate counterclockwise about the right tip and clockwise about the left tip. *[Figure 5-9]* As the air (and vortices) roll off the back of your wing, they angle down, which is known as downwash. *Figure 5-10* shows the difference in downwash at altitude versus near the ground. Bearing in mind the direction of rotation of these vortices, it can be seen that they induce an upward flow of air beyond the tip and a downwash flow behind the wing's trailing edge. This induced downwash has nothing in common with the downwash that is necessary to produce lift. It is, in fact, the source of induced drag.

Figure 5-9. *Wingtip vortex from a crop duster.*

Downwash points the relative wind downward, so the more downwash you have, the more your relative wind points downward. That's important for one very good reason: lift is always perpendicular to the relative wind. In *Figure 5-11,* you can see that when you have less downwash, your lift vector is more vertical, opposing gravity. And when you have more downwash, your lift vector points back more, causing induced drag. On top of that, it takes energy for your wings to create downwash and vortices, and that energy creates drag.

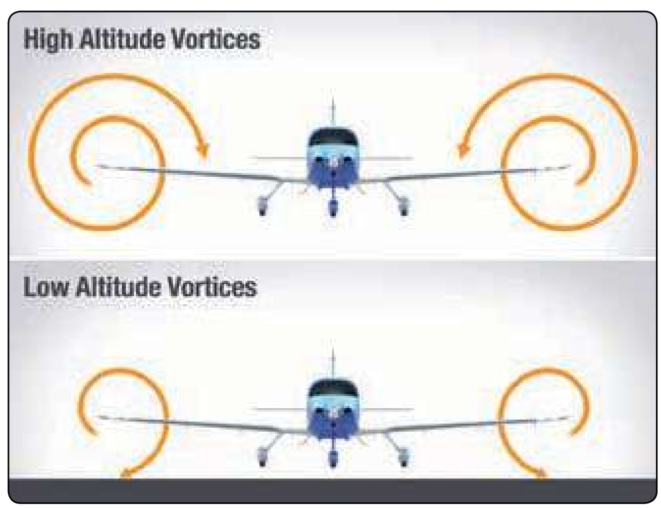


Figure 5-10. *The difference in wingtip vortex size at altitude versus near the ground.*

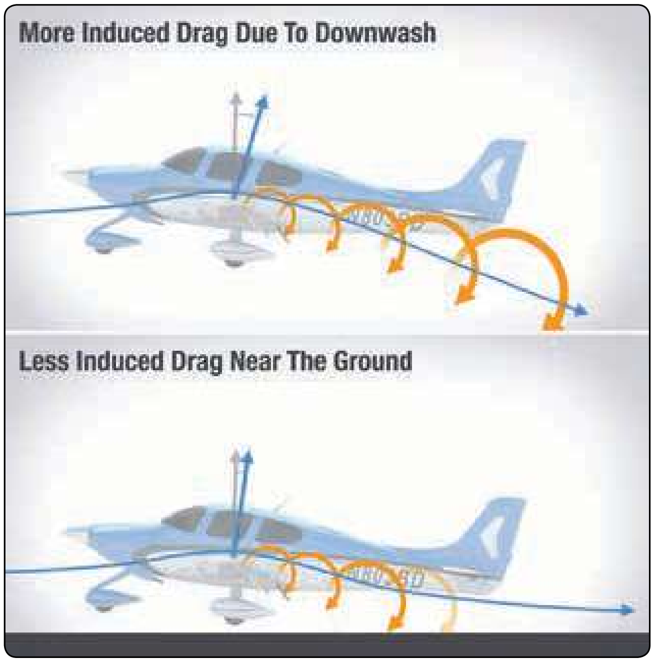


Figure 5-11. *The difference in downwash at altitude versus near the ground.*

The greater the size and strength of the vortices and consequent downwash component on the net airflow over the airfoil, the greater the induced drag effect becomes. This downwash over the top of the airfoil at the tip has the same effect as bending the lift vector rearward; therefore, the lift is slightly aft of perpendicular to the relative wind, creating a rearward lift component. This is induced drag.

In order to create a greater negative pressure on the top of an airfoil, the airfoil can be inclined to a higher AOA. If the AOA of a symmetrical airfoil were zero, there would be no pressure differential, and consequently, no downwash component and no induced drag. In any case, as AOA increases, induced drag increases proportionally. To state this another way—the lower the airspeed, the greater the AOA required to produce lift equal to the aircraft's weight and, therefore, the greater induced drag. The amount of induced drag varies inversely with the square of the airspeed.

Conversely, parasite drag increases as the square of the airspeed. Thus, in steady state, as airspeed decreases to near the stalling speed, the total drag becomes greater, due mainly to the sharp rise in induced drag. Similarly, as the aircraft reaches its never-exceed speed (V_{NE}), the total drag increases rapidly due to the sharp increase of parasite drag. As seen in *Figure 5-6,* at some given airspeed, total drag is at its minimum amount. In figuring the maximum range of aircraft, the thrust required to overcome drag is at a minimum if drag is at a minimum. The minimum power and maximum endurance occur at a different point.

Weight

Gravity is the pulling force that tends to draw all bodies to the center of the earth. The CG may be considered as a point at which all the weight of the aircraft is concentrated. If the aircraft were supported at its exact CG, it would balance in any attitude. It will be noted that CG is of major importance in an aircraft, for its position has a great bearing upon stability. The allowable location of the CG is determined by the general design of each particular aircraft. The designers determine how far the center of pressure (CP) will travel. It is important to understand that an aircraft's weight is concentrated at the CG and the aerodynamic forces of lift occur at the CP. When the CG is forward of the CP, there is a natural tendency for the aircraft to want to pitch nose down. If the CP is forward of the CG, a nose up pitching moment is created. Therefore, designers fix the aft limit of the CG forward of the CP for the corresponding flight speed in order to retain flight equilibrium.

Weight has a definite relationship to lift. This relationship is simple, but important in understanding the aerodynamics of flying. Lift is the upward force on the wing acting perpendicular to the relative wind and perpendicular to the aircraft's lateral axis. Lift is required to counteract the aircraft's weight. In stabilized level flight, when the lift force is equal to the weight force, the aircraft is in a state of equilibrium and neither accelerates upward or downward. If lift becomes less than weight, the vertical speed will decrease. When lift is greater than weight, the vertical speed will increase.

Wingtip Vortices

Formation of Vortices

The action of the airfoil that gives an aircraft lift also causes induced drag. When an airfoil is flown at a positive AOA, a pressure differential exists between the upper and lower surfaces of the airfoil. The pressure above the wing is less than atmospheric pressure and the pressure below the wing is equal to or greater than atmospheric pressure. Since air always moves from high pressure toward low pressure, and the path of least resistance is toward the airfoil's tips, there is a spanwise movement of air from the bottom of the airfoil outward from the fuselage around the tips. This flow of air results in "spillage" over the tips, thereby setting up a whirlpool of air called a vortex. *[Figure 5-12]*

At the same time, the air on the upper surface has a tendency to flow in toward the fuselage and off the trailing edge. This air current forms a similar vortex at the inboard portion of the trailing edge of the airfoil, but because the fuselage limits the inward flow, the vortex is insignificant. Consequently, the deviation in flow direction is greatest at the outer tips where the unrestricted lateral flow is the strongest.

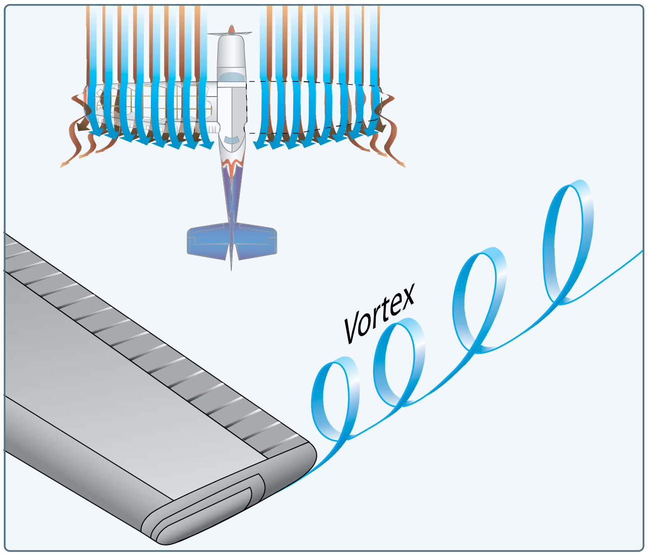


Figure 5-12. *Wingtip vortices.*

As the air curls upward around the tip, it combines with the downwash to form a fast-spinning trailing vortex. These vortices increase drag because of energy spent in producing the turbulence. Whenever an airfoil is producing lift, induced drag occurs and wingtip vortices are created.

Just as lift increases with an increase in AOA, induced drag also increases. This occurs because as the AOA is increased, there is a greater pressure difference between the top and bottom of the airfoil, and a greater lateral flow of air; consequently, this causes more violent vortices to be set up, resulting in more turbulence and more induced drag.

In *Figure 5-12,* it is easy to see the formation of wingtip vortices. The intensity or strength of the vortices is directly proportional to the weight of the aircraft and inversely proportional to the wingspan and speed of the aircraft. The heavier and slower the aircraft, the greater the AOA and the stronger the wingtip vortices. Thus, an aircraft will create wingtip vortices with maximum strength occurring during the takeoff, climb, and landing phases of flight. These vortices lead to a particularly dangerous hazard to flight, wake turbulence.

Avoiding Wake Turbulence

Wingtip vortices are greatest when the generating aircraft is "heavy, clean, and slow." This condition is most commonly encountered during approaches or departures because an aircraft's AOA is at the highest to produce the lift necessary to land or take off. To minimize the chances of flying through an aircraft's wake turbulence:

- Avoid flying through another aircraft's flight path.
- Rotate prior to the point at which the preceding aircraft rotated when taking off behind another aircraft.
- Avoid following another aircraft on a similar flight path at an altitude within 1,000 feet. *[Figure 5-13]*
- Approach the runway above a preceding aircraft's path when landing behind another aircraft and touch down after the point at which the other aircraft wheels contacted the runway. *[Figure 5-14]*

A hovering helicopter generates a down wash from its main rotor(s) similar to the vortices of an airplane. Pilots of small aircraft should avoid a hovering helicopter by at least three rotor disc diameters to avoid the effects of this down wash. In forward flight, this energy is transformed into a pair of strong, high-speed trailing vortices similar to wing-tip vortices of larger fixed-wing aircraft. Helicopter vortices should be avoided because helicopter forward flight airspeeds are often very slow and can generate exceptionally strong wake turbulence.

Wind is an important factor in avoiding wake turbulence because wingtip vortices drift with the wind at the speed of the wind. For example, a wind speed of 10 knots causes the vortices to drift at about 1,000 feet in a minute in the wind direction. When following another aircraft, a pilot should consider wind speed and direction when selecting an intended takeoff or landing point. If a pilot is unsure of the other aircraft's takeoff or landing point, approximately 3 minutes provides a margin of

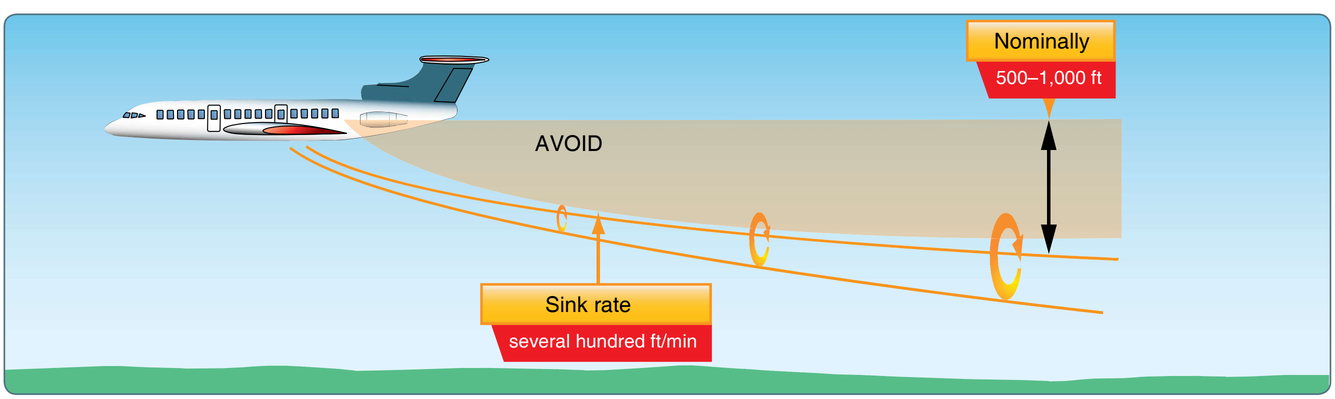


Figure 5-13. *Avoid following another aircraft at an altitude within 1,000 feet.*

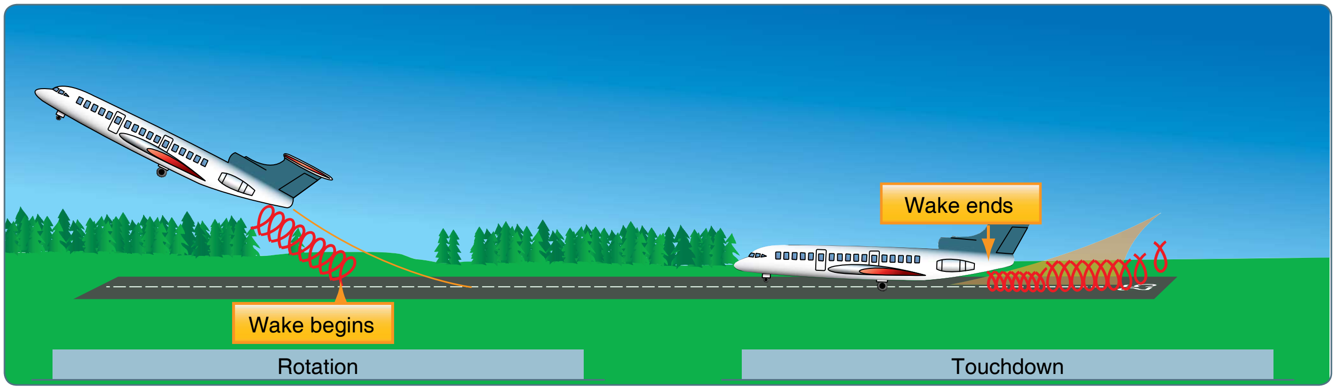


Figure 5-14. *Avoid turbulence from another aircraft.*

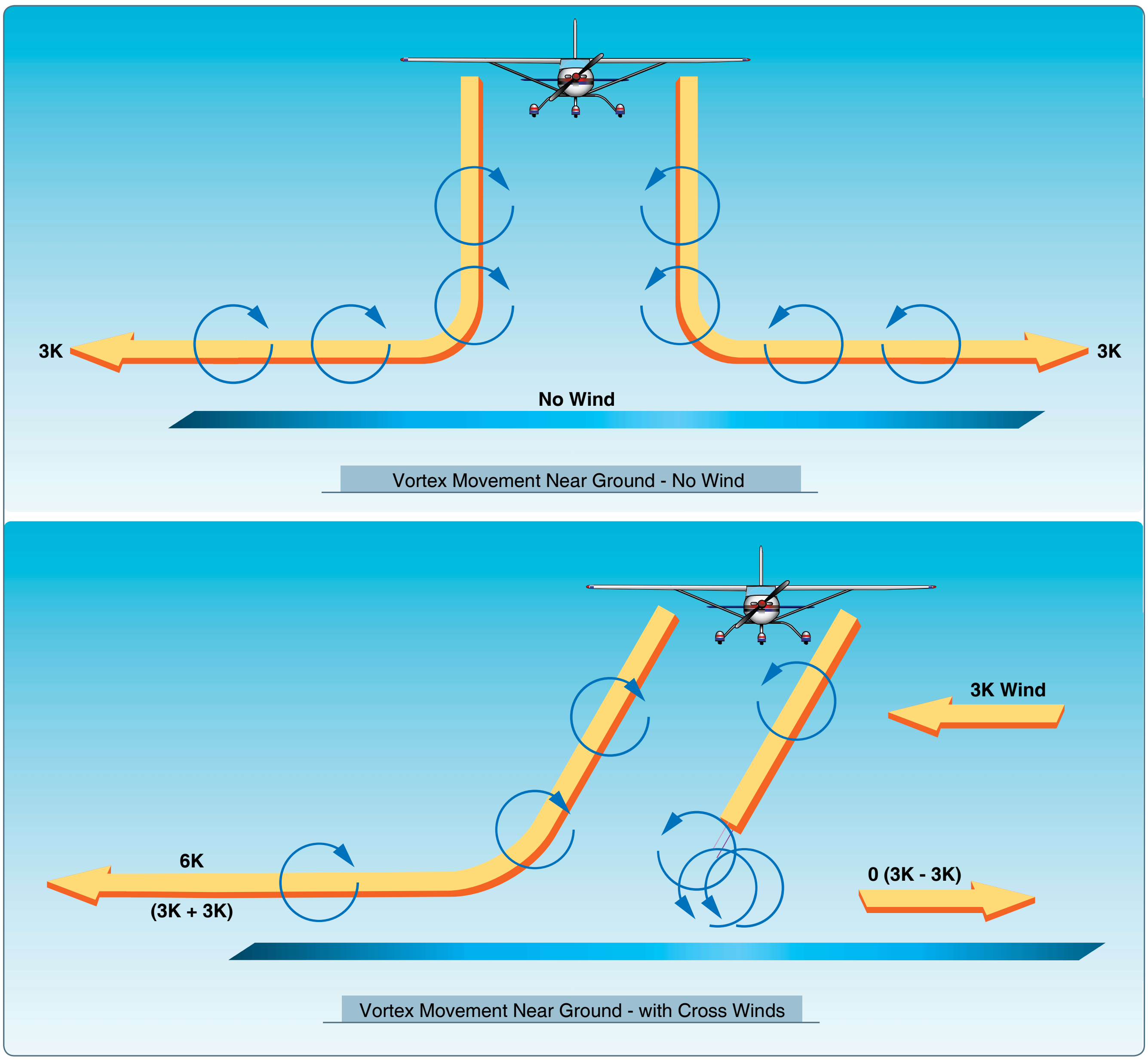


Figure 5-15. *When the vortices of larger aircraft sink close to the ground (within 100 to 200 feet), they tend to move laterally over the ground at a speed of 2 or 3 knots (top). A crosswind will decrease the lateral movement of the upwind vortex and increase the movement of the downwind vortex. Thus a light wind with a cross runway component of 1 to 5 knots could result in the upwind vortex remaining in the touchdown zone for a period of time and hasten the drift of the downwind vortex toward another runway (bottom).*

safety that allows wake turbulence dissipation. *[Figure 5-15]* For more information on wake turbulence, see Advisory Circular (AC) 90-23, Aircraft Wake Turbulence.

Ground Effect

Ever since the beginning of manned flight, pilots realized that just before touchdown it would suddenly feel like the aircraft did not want to go lower, and it would just want to go on and on. This is due to the air that is trapped between the wing and the landing surface, as if there were an air cushion. This phenomenon is called ground effect.

When an aircraft in flight comes within several feet of the surface, ground or water, a change occurs in the three-dimensional flow pattern around the aircraft because the vertical component of the airflow around the wing is restricted by the surface. This alters the wing's upwash, downwash, and wingtip vortices. *[Figure 5-16]* Ground effect, then, is due to the interference of the ground (or water) surface with the airflow patterns about the aircraft in flight. While the aerodynamic characteristics of the tail surfaces and the fuselage are altered by ground effect, the principal effects due to proximity of the ground are the changes in the aerodynamic characteristics of the wing. As the wing encounters ground effect and is maintained at a constant AOA, there is consequent reduction in the upwash, downwash, and wingtip vortices.

Induced drag is a result of the airfoil's work of sustaining the aircraft, and a wing or rotor lifts the aircraft simply by accelerating a mass of air downward. It is true that reduced pressure on top of an airfoil is essential to lift, but that is only one of the things contributing to the overall effect of pushing an air mass downward. The more downwash there is, the harder the wing pushes the mass of air down. At high angles of attack, the amount of induced drag is high; since this corresponds to lower airspeeds in actual flight, it can be said that induced drag predominates at low speed. However, the reduction of the wingtip vortices due to ground effect alters

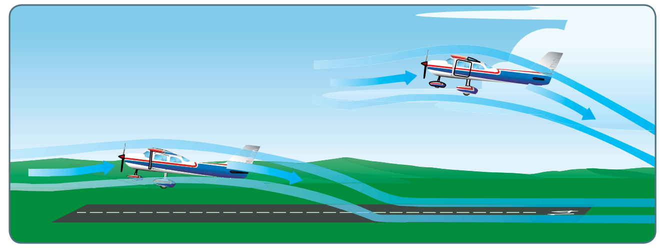


Figure 5-16. *Ground effect changes airflow.*

the spanwise lift distribution and reduces the induced AOA and induced drag. Therefore, the wing will require a lower AOA in ground effect to produce the same C_L. If a constant AOA is maintained, an increase in C_L results. *[Figure 5-17]*

Ground effect also alters the thrust required versus velocity. Since induced drag predominates at low speeds, the reduction of induced drag due to ground effect will cause a significant reduction of thrust required (parasite plus induced drag) at low speeds. Due to the change in upwash, downwash, and wingtip vortices, there may be a change in position (installation) error of the airspeed system associated with ground effect. In the majority of cases, ground effect causes an increase in the local pressure at the static source and produces a lower indication of airspeed and altitude. Thus, an aircraft may be airborne at an indicated airspeed less than that normally required.

In order for ground effect to be of significant magnitude, the wing must be quite close to the ground. One of the direct results of ground effect is the variation of induced drag with wing height above the ground at a constant C_L. When the wing is at a height equal to its span, the reduction in induced drag is only 1.4 percent. However, when the wing is at a height equal to one-fourth its span, the reduction in induced drag is 23.5 percent and, when the wing is at a height equal to one-tenth its span, the reduction in induced drag is 47.6 percent. Thus, a large reduction in induced drag takes place only when the wing is very close to the ground. Because of this variation, ground effect is most usually recognized during the liftoff for takeoff or just prior to touchdown when landing.

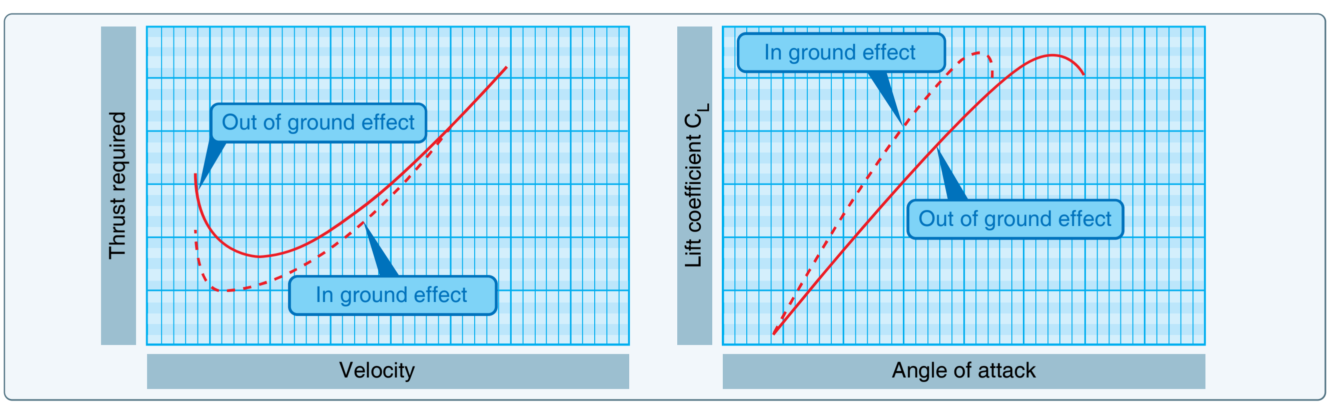


Figure 5-17. *Ground effect changes drag and lift.*

Automatic Dependent Surveillance–Broadcast (ADS-B)

Automatic Dependent Surveillance–Broadcast (ADS–B) is a surveillance technology being deployed throughout the NAS to facilitate improvements needed to increase the capacity and efficiency of the NAS, while maintaining safety. ADS-B supports these improvements by providing a higher update rate and enhanced accuracy of surveillance information over the current radar-based surveillance system. In addition, ADS-B enables the expansion of air traffic control (ATC) surveillance services into areas where none existed previously. The ADS-B ground system also provides Traffic Information Services-Broadcast (TIS-B) and Flight Information Services-Broadcast (FIS-B) for use on appropriately equipped aircraft, enhancing the user's situational awareness (SA) and improving the overall safety of the NAS.

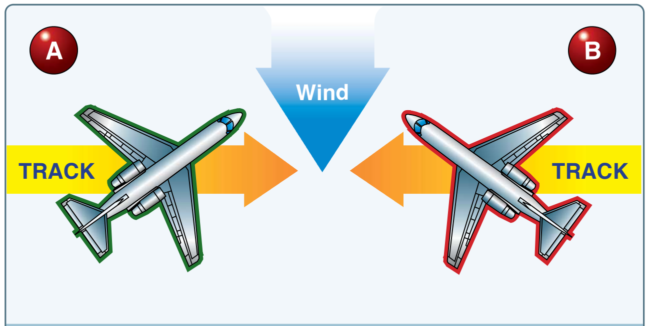
The ADS–B system is composed of aircraft avionics and a ground infrastructure. Onboard avionics determine the position of the aircraft by using the GPS and transmit its position, along with additional information about the aircraft, to ground stations for use by ATC and nearby ADS-B equipped aircraft.

In the United States, ADS–B equipped aircraft exchange information on one of two frequencies: 978 or 1090 MHz. The 1090 MHz frequency is associated with Mode A, C, and S transponder operations. 1090 MHz transponders with integrated ADS–B functionality extend the transponder message sets with additional ADS–B information. This additional information is known as an "extended squitter" message and referred to as 1090ES. ADS–B equipment operating on 978 MHz is known as the Universal Access Transceiver (UAT).

Radar Traffic Advisories

Radar equipped ATC facilities provide radar assistance to aircraft on instrument flight plans and VFR aircraft provided the aircraft can communicate with the facility and are within radar coverage. This basic service includes safety alerts, traffic advisories, limited vectoring when requested, and sequencing at locations where this procedure has been established. ATC issues traffic advisories based on observed radar targets. The traffic is referenced by azimuth from the aircraft in terms of the 12-hour clock. Also, distance in nautical miles, direction in which the target is moving, and type and altitude of the aircraft, if known, are given.

An example would be: "Traffic 10 o'clock 5 miles east bound, Cessna 152, 3,000 feet." The pilot should note that traffic position is based on the aircraft track and that wind correction can affect the clock position at which a pilot locates traffic. This service is not intended to relieve the pilot of the responsibility to see and avoid other aircraft. *[Figure 14-44]* In addition to basic radar service, terminal radar service area (TRSA) has been implemented at certain terminal locations. TRSAs are depicted on sectional aeronautical charts and listed in the Chart Supplement U.S. (formerly Airport/Facility Directory). The purpose of this service is to provide separation between all participating VFR aircraft and all IFR aircraft operating within the TRSA. Class C service provides approved separation between IFR and VFR aircraft and sequencing of VFR aircraft to the primary airport. Class B service provides approved separation of aircraft based on IFR, VFR, and/or weight and sequencing of VFR arrivals to the primary airport(s).



Traffic information would be issued to the pilot of aircraft "A" as 12 o'clock. The actual position of the traffic as seen by the pilot of aircraft "A" would be 1 o'clock. Traffic information issued to aircraft "B" would also be given as 12 o'clock, but in this case, the pilot of "B" would see traffic at 10 o'clock.

Figure 14-44. *Traffic advisories.*

Wake Turbulence

All aircraft generate wake turbulence during flight. This disturbance is caused by a pair of counter-rotating vortices trailing from the wingtips. The vortices from larger aircraft pose problems to encountering aircraft. The wake of these aircraft can impose rolling moments exceeding the roll-control authority of the encountering aircraft. Also, the turbulence generated within the vortices can damage aircraft components and equipment if encountered at close range. For this reason, a pilot must envision the location of the vortex wake and adjust the flight path accordingly.

Vortex Generation

Lift is generated by the creation of a pressure differential over the wing surface. The lowest pressure occurs over the upper wing surface and the highest pressure under the wing. This pressure differential triggers the rollup of the airflow aft of the wing resulting in swirling air masses trailing downstream of the wingtips. After the rollup is completed, the wake consists of two counter rotating cylindrical vortices. Most of the energy lies within a few feet of the center of each vortex. *[Figure 14-45]*

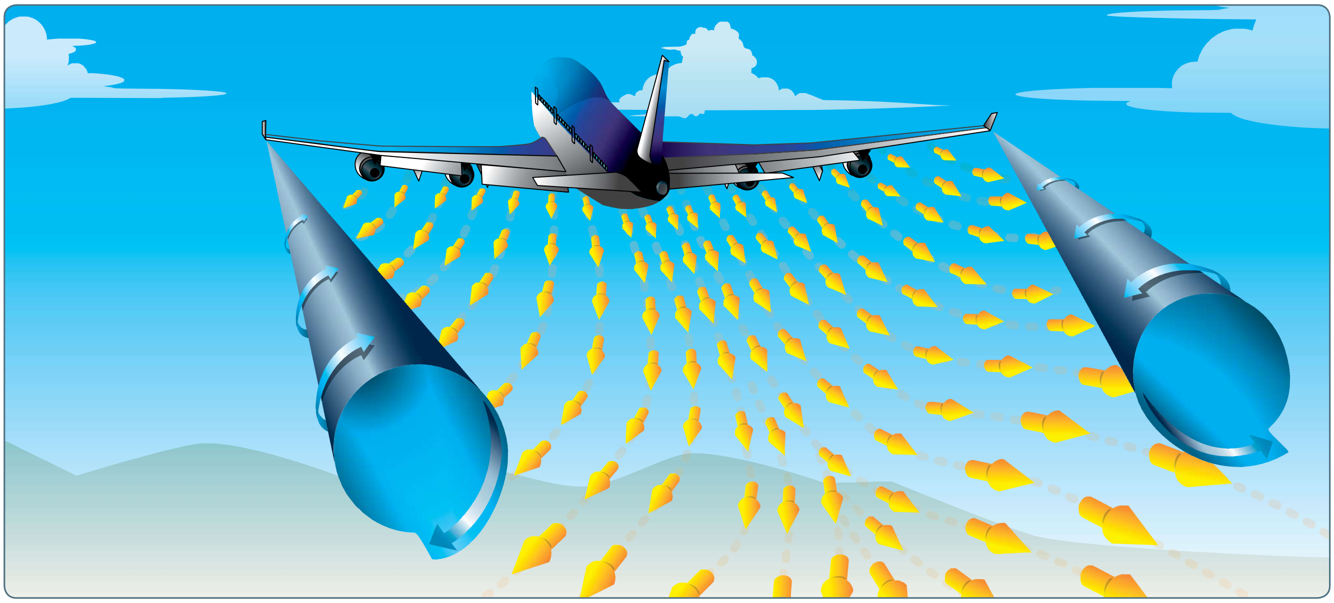


Figure 14-45. *Vortex generation.*

Vortex Strength

Terminal Area

Wake turbulence has historically been thought of as only a function of aircraft weight, but recent research considers additional parameters, such as speed, aspects of the wing, wake decay rates, and aircraft resistance to wake, just to name a few. The vortex characteristics of any aircraft will be changed with the extension of flaps or other wing configuration devices, as well as changing speed. However, as the basic factors are weight and speed, the vortex strength increases proportionately with an increase in aircraft operating weight or decrease in aircraft speed. The greatest vortex strength occurs when the generating aircraft is heavy, slow, and clean, since the turbulence from a "dirty" aircraft configuration hastens wake decay.

En Route

En route wake turbulence events have been influenced by changes to the aircraft fleet mix that have more "Super" (A380) and "Heavy" (B-747, B-777, A340, etc.) aircraft operating in the NAS. There have been wake turbulence events in excess of 30NM and 2000 feet lower than the wake generating aircraft. Air density is also a factor in wake strength. Even though the speeds are higher in cruise at high altitude, the reduced air density may result in wake strength comparable to that in the terminal area. In addition, for a given separation distance, the higher speeds in cruise result in less time for the wake to decay before being encountered by a trailing aircraft.

Vortex Behavior

Trailing vortices have certain behavioral characteristics that can help a pilot visualize the wake location and take avoidance precautions.

Vortices are generated from the moment an aircraft leaves the ground (until it touches down), since trailing vortices are the byproduct of wing lift. *[Figure 14-46]* The vortex circulation is outward, upward, and around the wingtips when viewed from either ahead or behind the aircraft. Tests with large

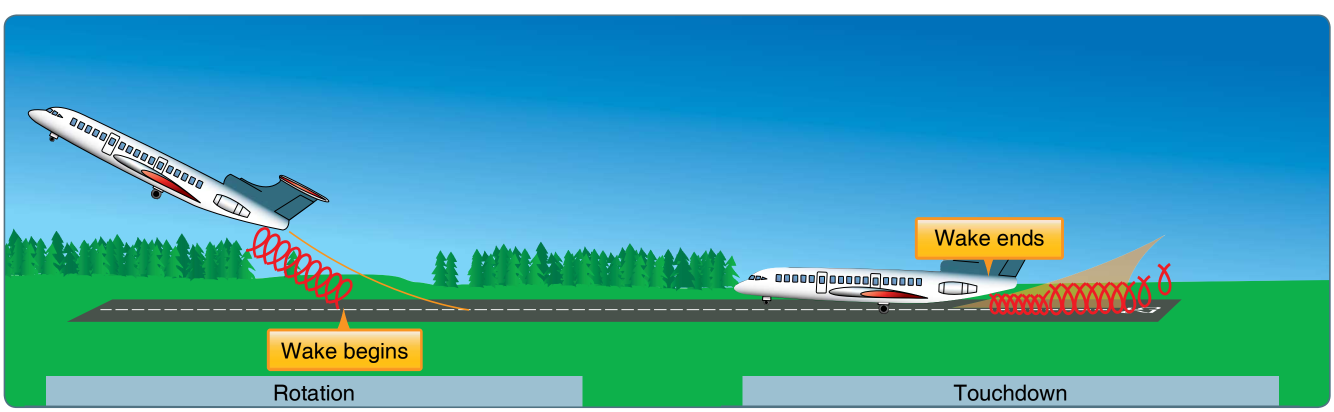


Figure 14-46. *Vortex behavior.*

aircraft have shown that vortices remain spaced a bit less than a wingspan apart, drifting with the wind, at altitudes greater than a wingspan from the ground. Tests have also shown that the vortices sink at a rate of several hundred feet per minute, slowing their descent and diminishing in strength with time and distance behind the generating aircraft.

When the vortices of larger aircraft sink close to the ground (within 100 to 200 feet), they tend to move laterally over the ground at a speed of 2–3 knots. A crosswind decreases the lateral movement of the upwind vortex and increases the movement of the downwind vortex. A light quartering tailwind presents the worst case scenario as the wake vortices could be all present along a significant portion of the final approach and extended centerline and not just in the touchdown zone as typically expected.

Vortex Avoidance Procedures

The following procedures are in place to assist pilots in vortex avoidance in the given scenario.

- Landing behind a larger aircraft on the same runway—stay at or above the larger aircraft's approach flight path and land beyond its touchdown point. *[Figure 14-47A]*
- Landing behind a larger aircraft on a parallel runway closer than 2,500 feet—consider the possibility of drift and stay at or above the larger aircraft's final approach flight path and note its touchdown point. *[Figure 14-47B]*
- Landing behind a larger aircraft on crossing runway—cross above the larger aircraft's flight path.
- Landing behind a departing aircraft on the same runway—land prior to the departing aircraft's rotating point.
- Landing behind a larger aircraft on a crossing runway—note the aircraft's rotation point and, if that point is past the intersection, continue and land prior to the intersection. If the larger aircraft rotates prior to the intersection, avoid flight below its flight path. Abandon the approach unless a landing is ensured well before reaching the intersection. *[Figure 14-47C]*
- Departing behind a large aircraft—rotate prior to the large aircraft's rotation point and climb above its climb path until turning clear of the wake.
- For intersection takeoffs on the same runway—be alert to adjacent larger aircraft operations, particularly upwind of the runway of intended use. If an intersection takeoff clearance is received, avoid headings that cross below the larger aircraft's path.
- If departing or landing after a large aircraft executing a low approach, missed approach, or touch-and-go landing (since vortices settle and move laterally near the ground, the vortex hazard may exist along the runway and in the flight path, particularly in a quartering tailwind), it is prudent to wait at least 2 minutes prior to a takeoff or landing.
- En route, it is advisable to avoid a path below and behind a large aircraft, and if a large aircraft is observed above on the same track, change the aircraft position laterally and preferably upwind.

Collision Avoidance

Title 14 of the CFR part 91 has established right-of-way rules, minimum safe altitudes, and VFR cruising altitudes to enhance flight safety. The pilot can contribute to collision avoidance by being alert and scanning for other aircraft. This is particularly important in the vicinity of an airport.

Effective scanning is accomplished with a series of short, regularly spaced eye movements that bring successive areas of the sky into the central visual field. Each movement should not exceed 10°, and each should be observed for at least 1 second to enable detection. Although back and forth eye movements seem preferred by most pilots, each pilot should develop a scanning pattern that is most comfortable and then adhere to it to assure optimum scanning. Even if entitled to the right-of-way, a pilot should yield if another aircraft seems too close.

Clearing Procedures

The following procedures and considerations are in place to assist pilots in collision avoidance under various situations:

- Before takeoff—prior to taxiing onto a runway or landing area in preparation for takeoff, pilots should scan the approach area for possible landing traffic, executing appropriate maneuvers to provide a clear view of the approach areas.
- Climbs and descents—during climbs and descents in flight conditions that permit visual detection of other traffic, pilots should execute gentle banks left and right at a frequency that permits continuous visual scanning of the airspace.
- Straight and level—during sustained periods of straight-and-level flight, a pilot should execute appropriate clearing procedures at periodic intervals.
- Traffic patterns—entries into traffic patterns while descending should be avoided.
- Traffic at VOR sites—due to converging traffic, sustained vigilance should be maintained in the vicinity of VORs and intersections.
- Training operations—vigilance should be maintained and clearing turns should be made prior to a practice

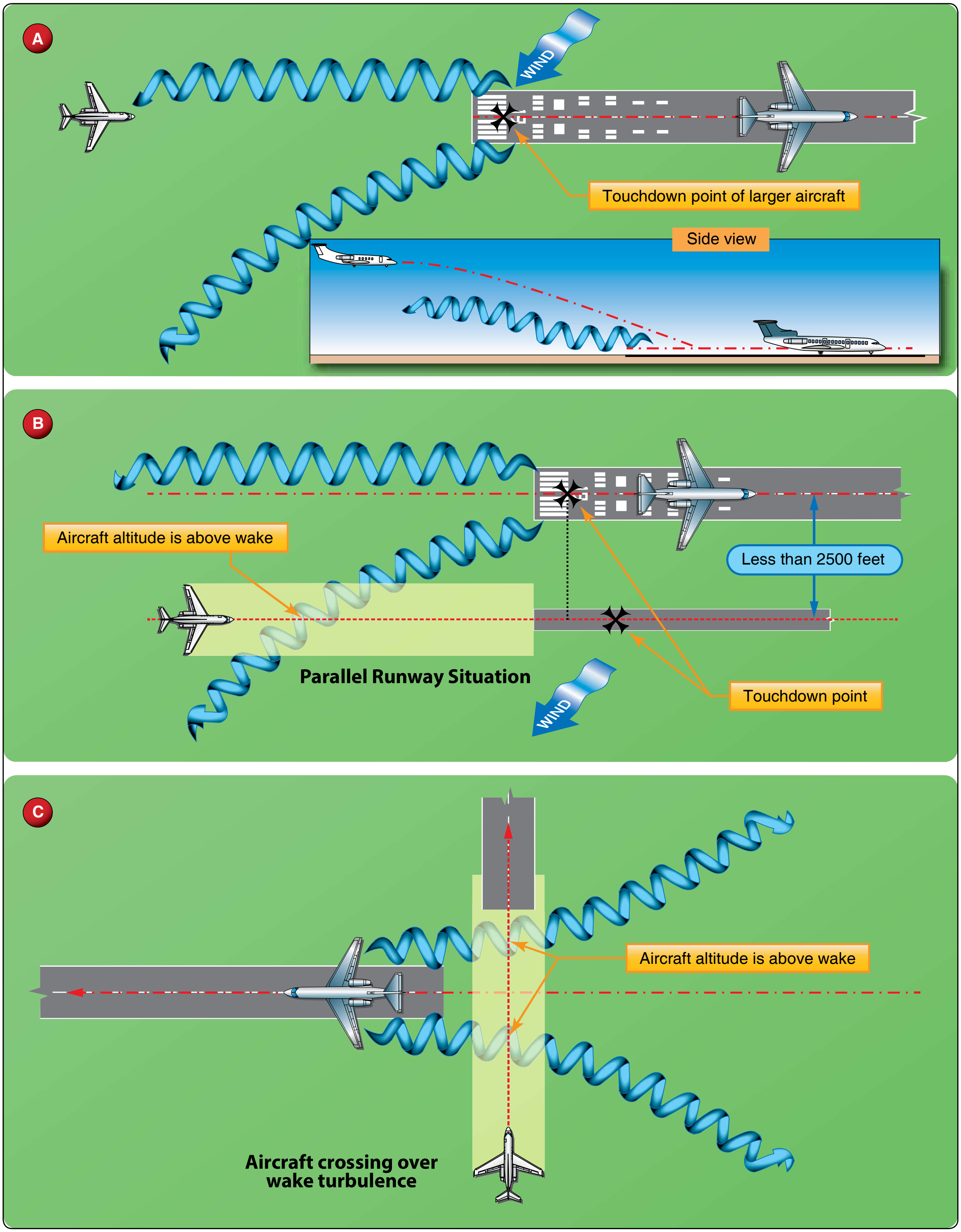


Figure 14-47. *Vortex avoidance procedures.*