Chapter 2

Aerodynamics of Flight

Introduction

This chapter presents aerodynamic fundamentals and principles as they apply to helicopters. The content relates to flight operations and performance of normal flight tasks. It covers theory and application of aerodynamics for the pilot, whether in flight training or general flight operations.

Gravity acting on the mass (the amount of matter) of an object creates a force called weight. The rotor blade below weighs 100 lbs. It is 20 feet long (span) and is 1 foot wide (chord). Accordingly, its surface area is 20 square feet. *[Figure 2-1]*

The blade is perfectly balanced on a pinpoint stand, as you can see in *Figure 2-2* from looking at it from the end (the airfoil view). The goal is for the blade to defy gravity and stay exactly where it is when we remove the stand. If we do nothing before removing the stand, the blade will simply fall to the ground. Can we exert a force (a push or pull) opposite gravity that equals the 100 lb. weight of the blade? Yes, for example, electromagnetic force could be used. In helicopters, however, we use aerodynamic force to oppose weight and to maneuver.

Every object in the atmosphere is surrounded by a gas that exerts a static force of 2,116 lb per square foot (a force times a unit area, called pressure) at sea level. However, that pressure is exerted equally all over the blade (top and bottom) and therefore does not create any useful force on the blade. We need only create a difference of a single pound of static pressure differential per square foot of blade surface to have a force equal to the blade's weight (100 lb of upward pressure opposite 100 lb downward weight).

Total pressure consists of static pressure and, if the air is moving, dynamic pressure (a pressure in the direction of the air movement). As shown in *Figure 2-3*, if dynamic pressure is increased the static pressure will decrease. Due to the design of the airfoil, the velocity of the air passing over the upper surface will be greater than that of the lower surface, leading to higher dynamic pressure on the upper surface than on the lower surface. The higher dynamic pressure on the upper surface lowers the static pressure on the upper surface. The static pressure on the bottom will now be greater than the static pressure on the top. The blade will experience an upward force. With just the right amount of air passing over the blade the upward force will equal one pound per square foot. This upward force is equal to, and acts opposite the blade's weight of 100 lb. So, if we now remove the stand, the blade will defy gravity and remain in its position (ignoring rearward drag for the moment).

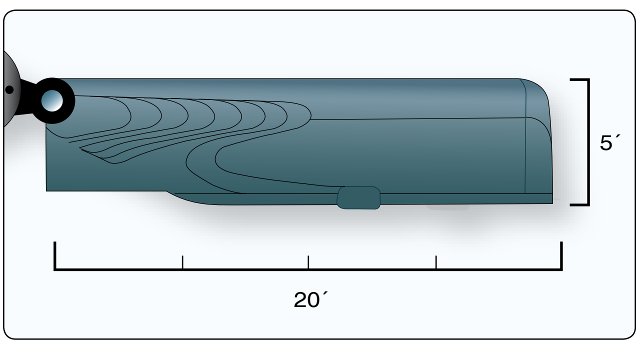

Figure 2-1. *Area of a blade.*

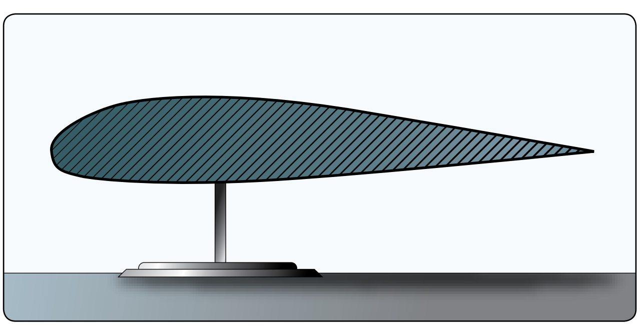

Figure 2-2. *Profile of an airfoil.*

The force created by air moving over an object (or moving an object through the air) is called aerodynamic force. Aero means air. Dynamic means moving or motion. Accordingly, by moving the air over an airfoil we can change the static pressures on the top and bottom thereby generating a useful force (an aerodynamic force). The portion of the aerodynamic force that is usually measured perpendicular to the air flowing around the airfoil is called lift and is used to oppose weight. Drag is the portion of aerodynamic force that is measured as the resistance created by an object passing through the air (or having the air passed over it). Drag acts in a streamwise direction with the wind passing over the airfoil and retards forward movement.

Forces Acting on the Aircraft

Once a helicopter leaves the ground, it is acted upon by four aerodynamic forces; thrust, drag, lift, and weight. Understanding how these forces work and knowing how to control them with the use of power and flight controls are essential to flight. *[Figure 2-3]* They are defined as follows:

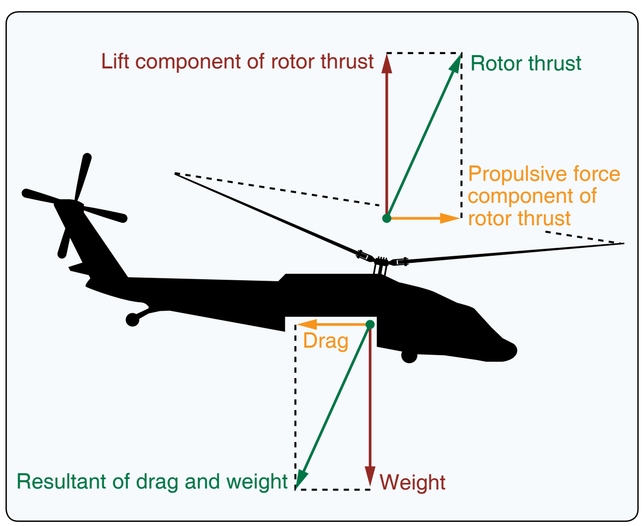

Figure 2-3. *Four forces acting on a helicopter in forward flight.*

- Lift—opposes the downward force of weight, is produced by the dynamic effect of the air acting on the airfoil and acts perpendicular to the flightpath through the center of lift.
- Weight—the combined load of the aircraft itself, the crew, the fuel, and the cargo or baggage. Weight pulls the aircraft downward because of the force of gravity. It opposes lift and acts vertically downward through the aircraft's center of gravity (CG).
- Thrust—the force produced by the power plant/ propeller or rotor. It opposes or overcomes the force of drag. As a general rule, it acts parallel to the longitudinal axis. However, this is not always the case, as explained later.
- Drag—a rearward, retarding force caused by disruption of airflow by the wing, rotor, fuselage, and other protruding objects. Drag opposes thrust and acts rearward parallel to the relative wind.

For a more in-depth explanation of general aerodynamics, refer to the Pilot's Handbook of Aeronautical Knowledge.

Lift

Lift is generated when an object changes the direction of flow of a fluid or when the fluid is forced to move by the object passing through it. When the object and fluid move relative to each other and the object turns the fluid flow in a direction perpendicular to that flow, the force required to do this work creates an equal and opposite force that is lift. The object may be moving through a stationary fluid, or the fluid may be flowing past a stationary object—these two are effectively identical as, in principle, it is only the frame of reference of the viewer which differs. The lift generated by an airfoil depends on such factors as:

- Speed of the airflow
- Density of the air
- Total area of the segment or airfoil
- Angle of attack (AOA) between the air and the airfoil

The AOA is the angle at which the airfoil meets the oncoming airflow (or vice versa). In the case of a helicopter, the object is the rotor blade (airfoil) and the fluid is the air. Lift is produced when a mass of air is deflected, and it always acts perpendicular to the resultant relative wind. A symmetric airfoil must have a positive AOA to generate positive lift. At a zero AOA, no lift is generated. At a negative AOA, negative lift is generated. A cambered or nonsymmetrical airfoil may produce positive lift at zero, or even small negative AOA.

The basic concept of lift is simple. However, the details of how the relative movement of air and airfoil interact to produce the turning action that generates lift are complex. In any case causing lift, an angled flat plate, revolving cylinder, airfoil, etc., the flow meeting the leading edge of the object is forced to split over and under the object. The sudden change in direction over the object causes an area of low pressure to form behind the leading edge on the upper surface of the object. In turn, due to this pressure gradient and the viscosity of the fluid, the flow over the object is accelerated down along the upper surface of the object. At the same time, the flow forced under the object is rapidly slowed or stagnated causing an area of high pressure. This also causes the flow to accelerate along the upper surface of the object. The two sections of the fluid each leave the trailing edge of the object with a downward component of momentum, producing lift. *[Figure 2-4]*

Bernoulli's Principle

Bernoulli's principle describes the relationship between internal fluid pressure and fluid velocity. It is a statement of the law of conservation of energy and helps explain why an airfoil develops an aerodynamic force. The concept of conservation of energy states energy cannot be created or destroyed and the amount of energy entering a system must also exit. Specifically, in this case the "energy" referred to is the dynamic pressure (the kinetic energy of the air—more velocity, more kinetic energy) and static air pressure (potential energy). These will change among themselves, but the total pressure energy remains constant inside the tube.

A simple tube with a constricted portion near the center of its length illustrates this principle. An example is running water through a garden hose. The mass of flow per unit area (cross-sectional area of tube) is the mass flow rate. In *Figure 2-5,* the flow into the tube is constant, neither accelerating nor decelerating; thus, the mass flow rate through the tube must be the same at stations 1, 2, and 3. If the cross-sectional area at any one of these stations—or any given point—in the tube is reduced, the fluid velocity must increase to maintain a constant mass flow rate to move the same amount of fluid through a smaller area. The continuity of mass flow causes the air to move faster through the venturi. In other words, fluid speeds up in direct proportion to the reduction in area.

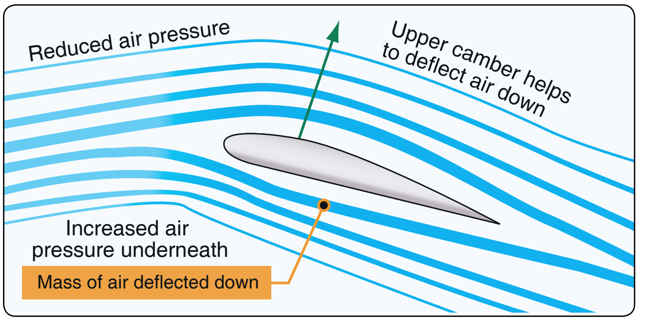

Figure 2-4. *Production of lift.*

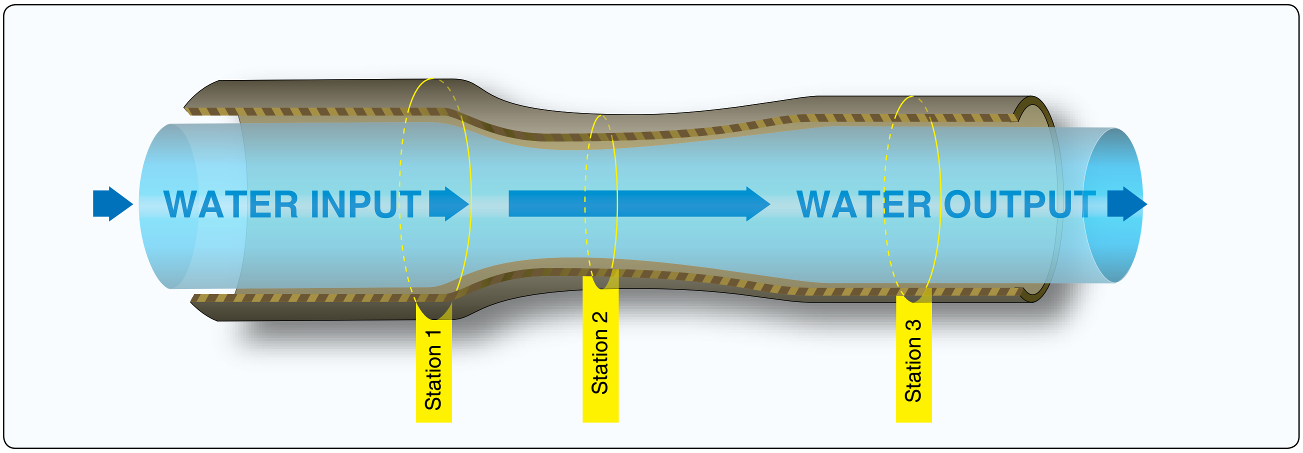

Figure 2-5. *Water flow through a tube.*

Bernoulli ($P_{total} = P_{dynamic} + P_{static}$) states that the increase in velocity will increase the streamwise dynamic pressure. Since the total pressure in the tube must remain constant, the static pressure on the sides of the venturi will decrease. Venturi effect is the term used to describe this phenomenon.

Figure 2-6 illustrates plates of one square foot in the dynamic flow and on the sides of the tube indicating static pressure, with corresponding pressure. At point 2, it is easier to visualize the static pressure reduction on the top of the airfoil as compared to the bottom of the airfoil, which is depicted as outside of the tube and therefore at ambient static pressure. Keep in mind with actual blades it is not a simple as this example because the bottom static pressure is influenced by blade design and blade angle, among other things. However, the basic idea is that it is the static pressure differential between the top and bottom multiplied by the surface area of the blade that generates the aerodynamic force.

Venturi Flow

While the amount of total energy within a closed system (the tube) does not change, the form of the energy may be altered. Pressure of flowing air may be compared to energy in that the total pressure of flowing air always remains constant unless energy is added or removed. Fluid flow pressure has two components—static and dynamic pressure. Static pressure is the pressure component measured in the flow but not moving with the flow as pressure is measured. Static pressure is also known as the force per unit area acting on a surface. Dynamic pressure of flow is that component existing as a result of movement of the air. The sum of these two pressures is total pressure. As air flows through the constriction, static pressure decreases as velocity increases. This increases dynamic pressure. *Figure 2-7* depicts the bottom half of the constricted area of the tube, which resembles the top half of an airfoil. Even with the top half of the tube removed, the air

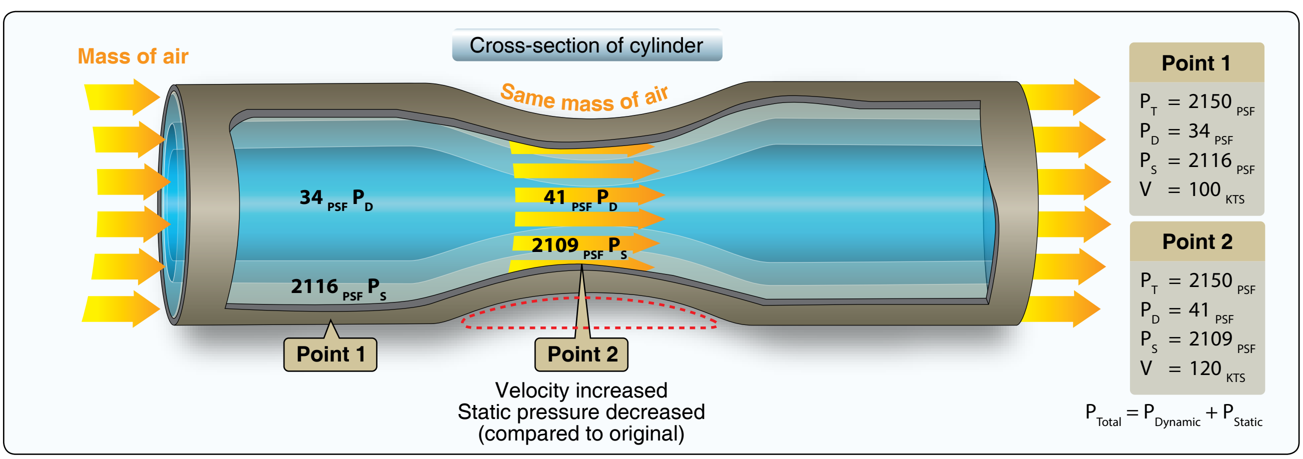

Figure 2-6. *Venturi effect.*

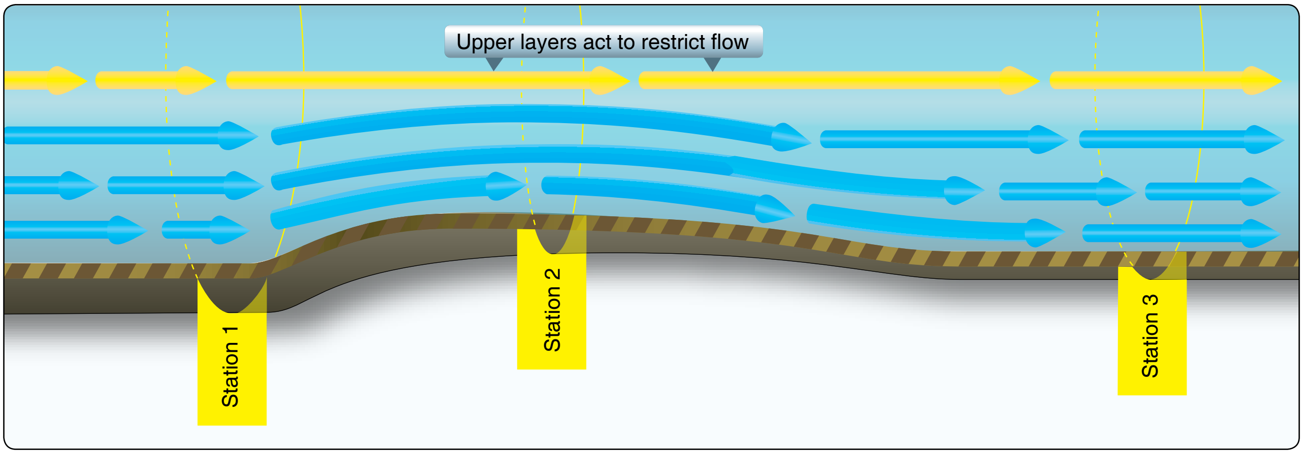

Figure 2-7. *Venturi flow.*

still accelerates over the curved area because the upper air layers restrict the flow—just as the top half of the constricted tube did. This acceleration causes decreased static pressure above the curved portion and creates a pressure differential caused by the variation of static and dynamic pressures.

Newton's Third Law of Motion

Additional lift is provided by the rotor blade's lower surface as air striking the underside is deflected downward. According to Newton's Third Law of Motion, "for every action there is an equal and opposite reaction," the air that is deflected downward also produces an upward (lifting) reaction.

Since air is much like water, the explanation for this source of lift may be compared to the planing effect of skis on water. The lift that supports the water skis (and the skier) is the force caused by the impact pressure and the deflection of water from the lower surfaces of the skis.

Under most flying conditions, the impact pressure and the deflection of air from the lower surface of the rotor blade provides a comparatively small percentage of the total lift. The majority of lift is the result of decreased pressure above the blade, rather than the increased pressure below it.

Weight

Normally, weight is thought of as being a known, fixed value, such as the weight of the helicopter, fuel, and occupants. To lift the helicopter off the ground vertically, the rotor disk must generate enough lift to overcome or offset the total weight of the helicopter and its occupants. Newton's First Law states: "Every object in a state of uniform motion tends to remain in that state of motion unless an external force is applied to it." In this case, the object is the helicopter whether at a hover or on the ground and the external force applied to it is lift, which is accomplished by increasing the pitch angle of the main rotor blades. This action forces the helicopter into a state of motion, without it the helicopter would either remain on the ground or at a hover.

The weight of the helicopter can also be influenced by aerodynamic loads. When you bank a helicopter while maintaining a constant altitude, the "G" load or load factor increases. The load factor is the actual load on the rotor blades at any time, divided by the normal load or gross weight (weight of the helicopter and its contents). Any time a helicopter flies in a constant altitude curved flightpath, the load supported by the rotor blades is greater than the total weight of the helicopter. The tighter the curved flightpath is, the steeper the bank is; the more rapid the flare or pullout from a dive is, the greater the load supported by the rotor. Therefore, the greater the load factor must be. *[Figure 2-8]*

To overcome this additional load factor, the helicopter must be able to produce more lift. If excess engine power is not available, the helicopter either descends or has to decelerate in order to maintain the same altitude. The load factor and, hence,

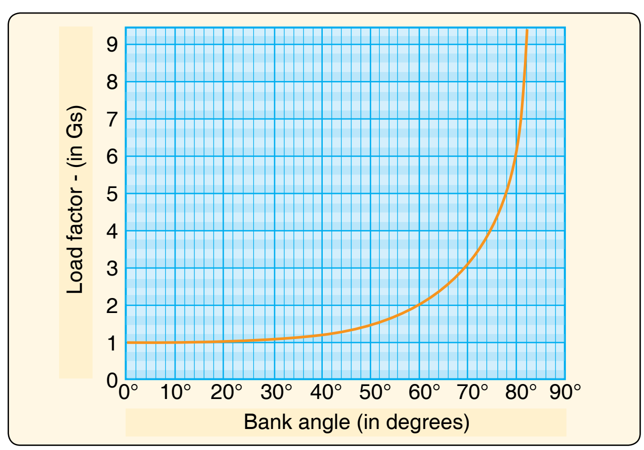

Figure 2-8. *The load factor diagram allows a pilot to calculate the amount of "G" loading exerted with various angles of bank.*

apparent gross weight increase is relatively small in banks up to 30°. Even so, under the right set of adverse circumstances, such as high-density altitude, turbulent air, high gross weight, and poor pilot technique, sufficient or excess power may not be available to maintain altitude and airspeed. Pilots must take all of these factors into consideration throughout the entire flight from the point of ascending to a hover to landing. Above 30° of bank, the apparent increase in gross weight soars. At 30° of bank, or pitch, the apparent increase is only 16 percent, but at 60°, it is twice the load on the wings and rotor disk. For example, if the weight of the helicopter is 1,600 pounds, the weight supported by the rotor disk in a 30° bank at a constant altitude would be 1,856 pounds (1,600 + 16 percent (or 256)). In a 60° bank, it would be 3,200 pounds; in an 80° bank, it would be almost six times as much, or 8,000 pounds. It is important to note that each rotor blade must support a percentage of the gross weight. In a two-bladed system, each blade of the 1,600-pound helicopter as stated above would have to lift 50 percent or 800 pounds. If this same helicopter had three rotor blades, each blade would have to lift only 33 percent, or 533 pounds. One additional cause of large load factors is rough or turbulent air. The severe vertical gusts produced by turbulence can cause a sudden increase in AOA, resulting in increased rotor blade loads that are resisted by the inertia of the helicopter.

Each type of helicopter has its own limitations that are based on the aircraft structure, size, and capabilities. Regardless of how much weight one can carry or the engine power that it may have, they are all susceptible to aerodynamic overloading. Unfortunately, if the pilot attempts to push the performance envelope the consequence can be fatal. Aerodynamic forces effect every movement in a helicopter, whether it is increasing the collective or a steep bank angle. Anticipating results from a particular maneuver or adjustment of a flight control is not good piloting technique. Instead pilots need to truly understand the capabilities of the helicopter under any and all circumstances and plan never to exceed the flight envelope for any situation.

Thrust

Thrust, like lift, is generated by the rotation of the main rotor disk. In a helicopter, thrust can be forward, rearward, sideward, or vertical. The resultant lift and thrust determines the direction of movement of the helicopter.

The solidity ratio is the ratio of the total rotor blade area, which is the combined area of all the main rotor blades, to the total rotor disk area. This ratio provides a means to measure the potential for a rotor disk to provide thrust and lift. The mathematical calculations needed to calculate the solidity ratio for each helicopter may not be of importance to most pilots but what should be are the capabilities of the rotor disk to produce and maintain lift. Many helicopter accidents are caused from the rotor disk being overloaded. Simply put, pilots attempt maneuvers that require more lift than the rotor disk can produce or more power than the helicopter's powerplant can provide. Trying to land with a nose high attitude along with any other unfavorable condition (i.e., high gross weight or wind gusts) is most likely to end in disaster.

The tail rotor also produces thrust. The amount of thrust is variable through the use of the antitorque pedals and is used to control the helicopter's yaw.

Drag

The force that resists the movement of a helicopter through the air and is produced when lift is developed is called drag. Drag must be overcome by the engine to turn the rotor. Drag always acts parallel to the relative wind. Total drag is composed of three types of drag: profile, induced, and parasite.

Profile Drag

Profile drag develops from the frictional resistance of the blades passing through the air. It does not change significantly with the airfoil's AOA but increases moderately when airspeed increases. Profile drag is composed of form drag and skin friction. Form drag results from the turbulent wake caused by the separation of airflow from the surface of a structure. The amount of drag is related to both the size and shape of the structure that protrudes into the relative wind. *[Figure 2-9]*

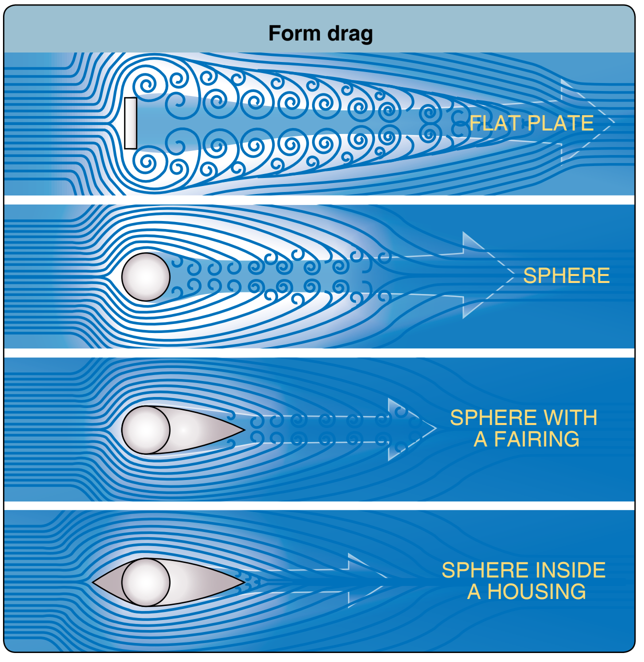

Figure 2-9. *It is easy to visualize the creation of form drag by examining the airflow around a flat plate. Streamlining decreases form drag by reducing the airflow separation.*

Skin friction is caused by surface roughness. Even though the surface appears smooth, it may be quite rough when viewed under a microscope. A thin layer of air clings to the rough surface and creates small eddies that contribute to drag.

Induced Drag

Induced drag is generated by the airflow circulation around the rotor blade as it creates lift. The high-pressure area beneath the blade joins the low-pressure area above the blade at the trailing edge and at the rotor tips. This causes a spiral, or vortex, which trails behind each blade whenever lift is being produced. These vortices deflect the airstream downward in the vicinity of the blade, creating an increase in downwash. Therefore, the blade operates in an average relative wind that is inclined downward and rearward near the blade. Because the lift produced by the blade is perpendicular to the relative wind, the lift is inclined aft by the same amount. The component of lift that is acting in a rearward direction is induced drag. *[Figure 2-10]*

As the air pressure differential increases with an increase in AOA, stronger vortices form, and induced drag increases. Since the blade's AOA is usually lower at higher airspeeds, and higher at low speeds, induced drag decreases as airspeed increases and increases as airspeed decreases. Induced drag is the major cause of drag at lower airspeeds.

Parasite Drag

Parasite drag is present any time the helicopter is moving through the air. This type of drag increases with airspeed. Non-lifting components of the helicopter, such as the cabin, rotor mast, tail, and landing gear, contribute to parasite drag. Any loss of momentum by the airstream, due to such things as openings for engine cooling, creates additional parasite drag. Because of its rapid increase with increasing airspeed, parasite drag is the major cause of drag at higher airspeeds. Parasite drag varies with the square of the velocity; therefore, doubling the airspeed increases the parasite drag four times.

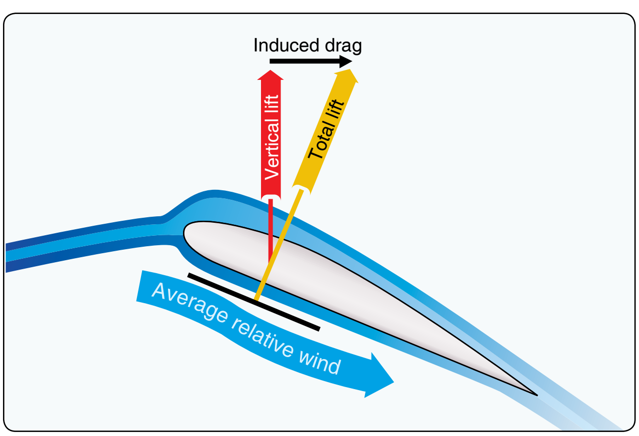

Figure 2-10. *The formation of induced drag is associated with the downward deflection of the airstream near the rotor blade.*

Total Drag

Total drag for a helicopter is the sum of all three drag forces. *[Figure 2-11]* As airspeed increases, parasite drag increases, while induced drag decreases. Profile drag remains relatively constant throughout the speed range with some increase at higher airspeeds. Combining all drag forces results in a total drag curve. The low point on the total drag curve shows the airspeed at which drag is minimized. This is the point where the lift-to-drag ratio is greatest and is referred to as L/D_{MAX}. At this speed, the total lift capacity of the helicopter, when compared to the total drag of the helicopter, is most favorable. This is an important factor in helicopter performance.

Airfoil

Helicopters are able to fly due to aerodynamic forces produced when air passes around the airfoil. An airfoil is any surface producing more lift than drag when passing through the air at a suitable angle. Airfoils are most often associated with production of lift. Airfoils are also used for stability (fin), control (elevator), and thrust or propulsion (propeller or rotor). Certain airfoils, such as rotor blades, combine some of these functions. The main and tail rotor blades of the helicopter are airfoils, and air is forced to pass around the blades by mechanically powered rotation. In some conditions, parts of the fuselage, such as the vertical and horizontal stabilizers, can become airfoils. Airfoils are carefully structured to accommodate a specific set of flight characteristics.

Airfoil Terminology and Definitions

- Blade span—the length of the rotor blade from center of rotation to tip of the blade.

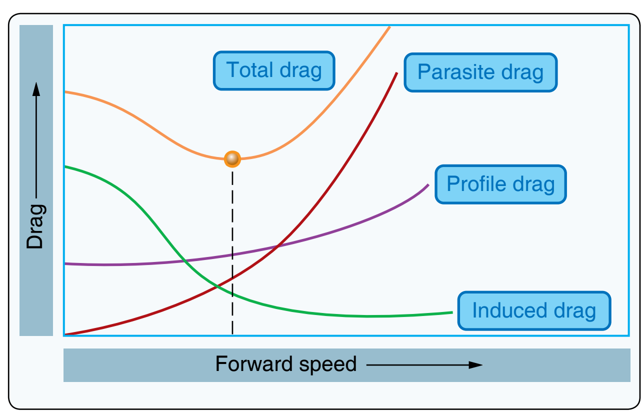

Figure 2-11. *The total drag curve represents the combined forces of parasite, profile, and induced drag and is plotted against airspeed.*

- Chord line—a straight line intersecting leading and trailing edges of the airfoil. *[Figure 2-12]*
- Chord—the length of the chord line from leading edge to trailing edge; it is the characteristic longitudinal dimension of the airfoil section.
- Mean camber line—a line drawn halfway between the upper and lower surfaces of the airfoil. *[Figure 2-12]*

  The chord line connects the ends of the mean camber line. Camber refers to curvature of the airfoil and may be considered as curvature of the mean camber line. The shape of the mean camber is important for determining aerodynamic characteristics of an airfoil section. Maximum camber (displacement of the mean camber line from the chord line) and its location help to define the shape of the mean camber line. The location of maximum camber and its displacement from the chord line are expressed as fractions or percentages of the basic chord length. By varying the point of maximum camber, the manufacturer can tailor an airfoil for a specific purpose. The profile thickness and thickness distribution are important properties of an airfoil section.
- Leading edge—the front edge of an airfoil. *[Figure 2-12]*
- Flightpath velocity—the speed and direction of the airfoil passing through the air. For airfoils on an airplane, the flightpath velocity is equal to true airspeed (TAS). For helicopter rotor blades, flightpath velocity is equal to rotational velocity, plus or minus a component of directional airspeed. The rotational velocity of the rotor blade is lowest closer to the hub and increases outward towards the tip of the blade during rotation.
- Relative wind—defined as the airflow relative to an airfoil and is created by movement of an airfoil through the air. This is rotational relative wind for rotary-wing aircraft and is covered in detail later. As an induced airflow may modify flightpath velocity, relative wind experienced by the airfoil may not be exactly opposite its direction of travel.
- Trailing edge—the rearmost edge of an airfoil.
- Induced flow—the downward flow of air through the rotor disk.
- Resultant relative wind—relative wind modified by induced flow.
- AOA—the angle measured between the resultant relative wind and chord line.
- Angle of incidence (AOI)—the angle between the chord line of a blade and rotor hub. It is usually referred to as blade pitch angle. For fixed airfoils, such as vertical fins or elevators, angle of incidence is the angle between the chord line of the airfoil and a selected reference plane of the helicopter.
- Center of pressure—the point along the chord line of an airfoil through which all aerodynamic forces are considered to act. Since pressures vary on the surface of an airfoil, an average location of pressure variation is needed. As the AOA changes, these pressures change, and the center of pressure moves along the chord line.

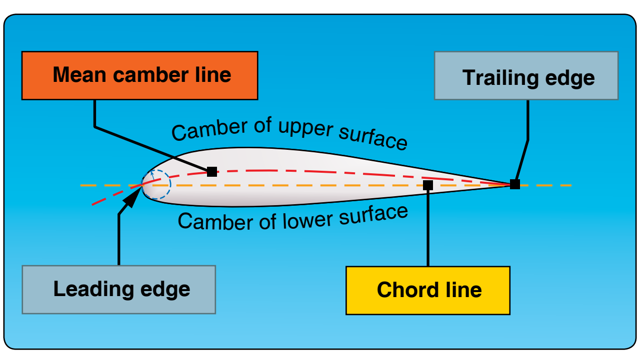

Figure 2-12. *Aerodynamic terms of an airfoil.*

Airfoil Types

Symmetrical Airfoil

The symmetrical airfoil is distinguished by having identical upper and lower surfaces. *[Figure 2-13]* The mean camber line and chord line are the same on a symmetrical airfoil, and it produces no lift at zero AOA. Most light helicopters incorporate symmetrical airfoils in the main rotor blades.

Nonsymmetrical Airfoil (Cambered)

The nonsymmetrical airfoil has different upper and lower surfaces, with a greater curvature of the airfoil above the chord line than below. *[Figure 2-13]* The mean camber line and chord line are different. The nonsymmetrical airfoil design can produce useful lift at zero AOA. A nonsymmetrical design

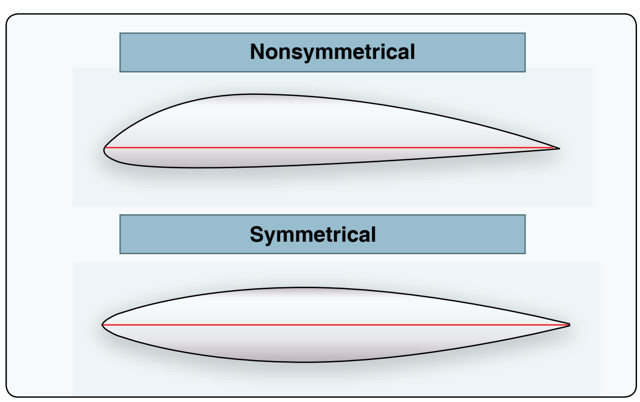

Figure 2-13. *The upper and lower curvatures are the same on a symmetrical airfoil and vary on a nonsymmetrical airfoil.*

has advantages and disadvantages. The advantages are more lift production at a given AOA than a symmetrical design, an improved lift-to-drag ratio, and better stall characteristics. The disadvantages are center of pressure travel of up to 20 percent of the chord line (creating undesirable torque on the airfoil structure) and greater production costs.

Blade Twist

Because of lift differential due to differing rotational relative wind values along the blade, the blade should be designed with a twist to alleviate internal blade stress and distribute the lifting force more evenly along the blade. Blade twist provides higher pitch angles at the root where velocity is low and lower pitch angles nearer the tip where velocity is higher. This increases the induced air velocity and blade loading near the inboard section of the blade. *[Figure 2-14]*

Rotor Blade and Hub Definitions

- Hub—on the mast, the attaching point for the root of the blade, and the axis about which the blades rotate. *[See Figure 1-7]*
- Tip—the farthest outboard section of the rotor blade
- Root—the inner end of the blade and is the point that attaches to the hub
- Twist—the change in blade incidence from the root to the outer blade

The angular position of the main rotor blades (as viewed from above, as they rotate about the vertical axis of the mast) is measured from the helicopter's longitudinal axis, and usually from its nose. The radial position of a segment of the blade is the distance from the hub as a fraction of the total distance.

Airflow and Reactions in the Rotor Disk

Relative Wind

Knowledge of relative wind is essential for an understanding of aerodynamics and its practical flight application for the pilot. Relative wind is airflow relative to an airfoil. Movement of an airfoil through the air creates relative wind. Relative wind moves in a direction parallel to but opposite of the movement of the airfoil. *[Figure 2-15]*

There are two parts to wind passing a rotor blade:

- Horizontal part—caused by the blades turning plus movement of the helicopter through the air *[Figure 2-16]*
- Vertical part—caused by the air being forced down through the rotor blades plus any movement of the air relative to the blades caused by the helicopter climbing or descending *[Figures 2-17* and *2-18]*

Rotational Relative Wind (Tip-Path Plane)

The rotation of rotor blades as they turn about the mast produces rotational relative wind (tip-path plane). The term rotational refers to the method of producing relative wind. Rotational relative wind flows opposite the physical flightpath of the airfoil, striking the blade at 90° to the leading edge and parallel to the plane of rotation; and it is constantly changing in direction during rotation. Rotational relative wind velocity is highest at blade tips, decreasing uniformly to zero at the axis of rotation (center of the mast). *[Figure 2-19]*

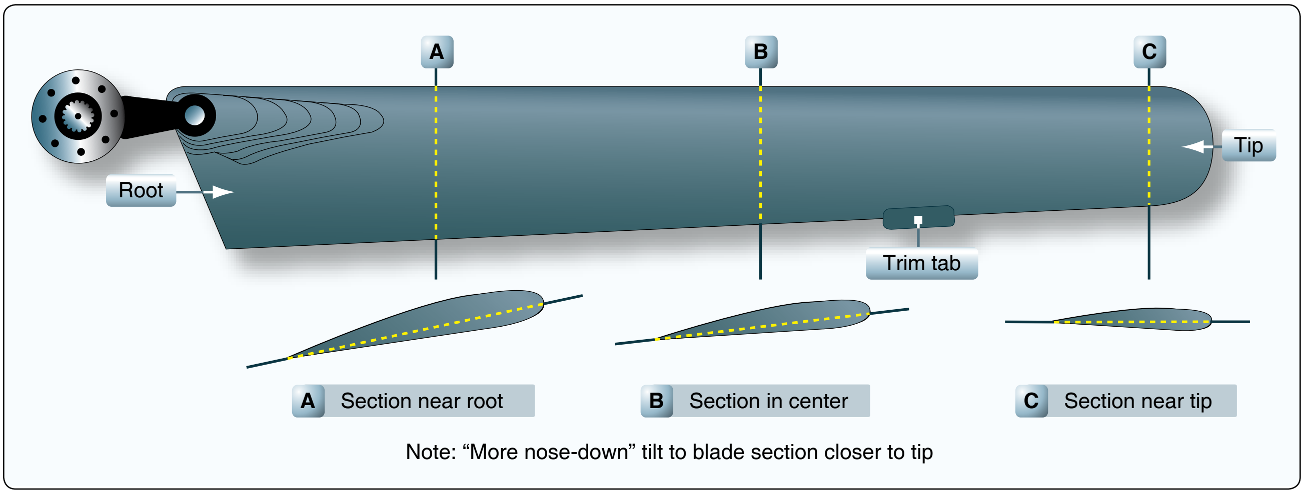

Figure 2-14. *Blade twist.*

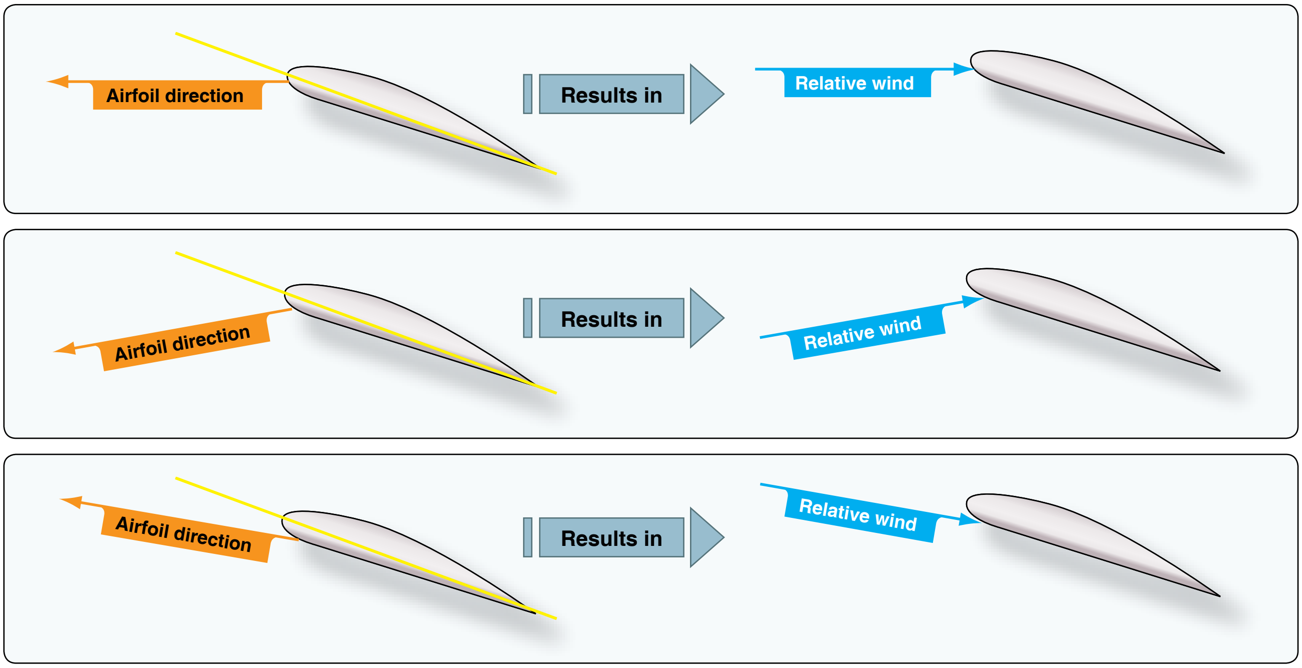

Figure 2-15. *Relative wind.*

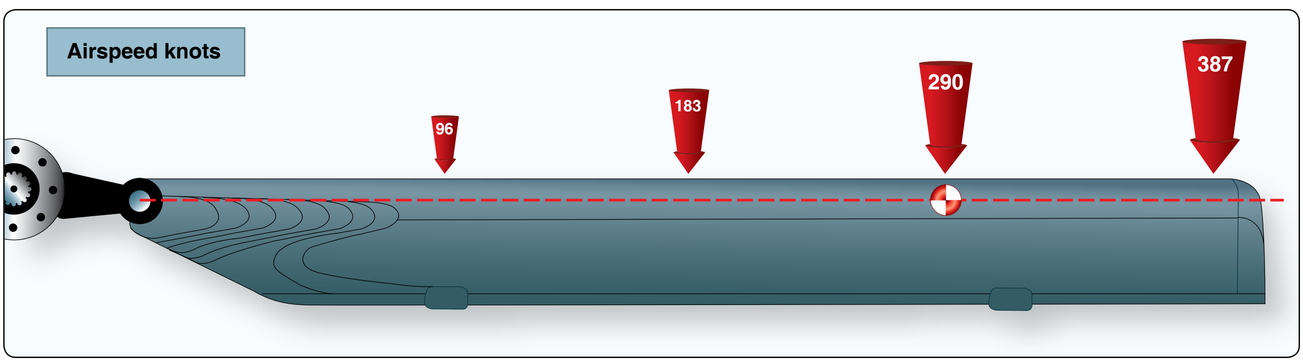

Figure 2-16. *Horizontal component of relative wind.*

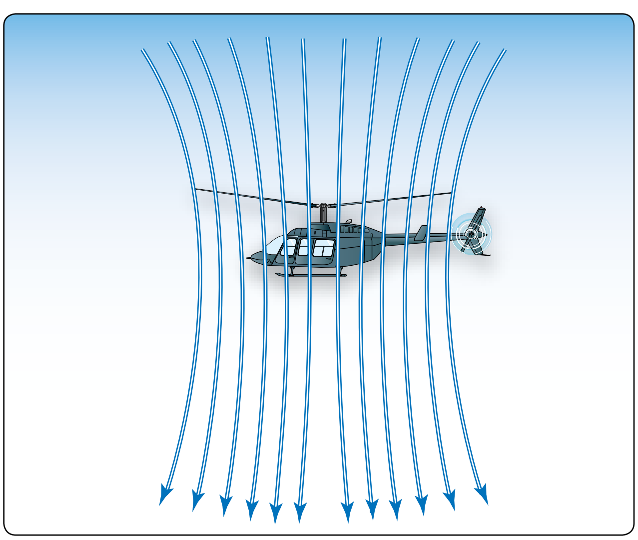

Figure 2-17. *Induced flow.*

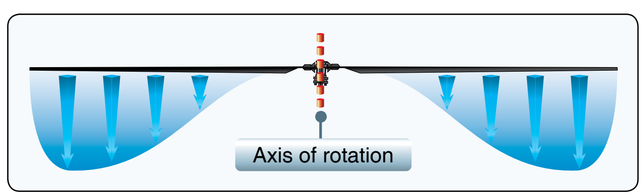

Figure 2-18. *Normal induced flow velocities along the blade span during hovering flight. Downward velocity is highest at the blade tip where blade speed is highest. As blade speed decreases nearer the center of the disk, downward velocity is less.*

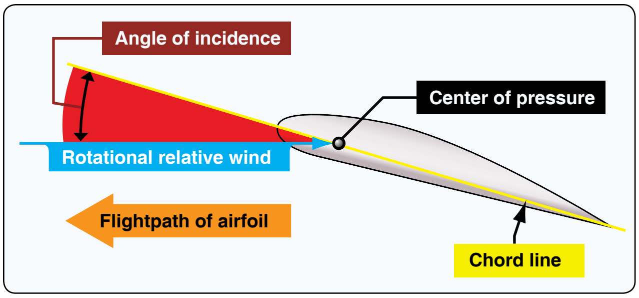

Figure 2-19. *Rotational relative wind.*

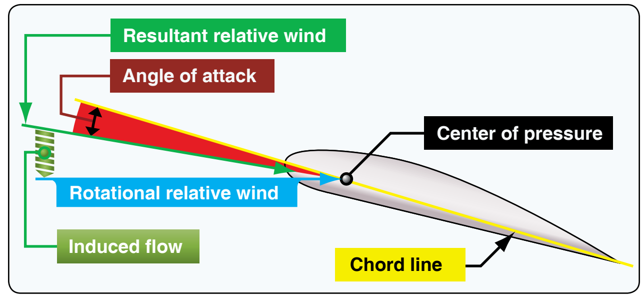

Figure 2-20. *Resultant relative wind.*

Resultant Relative Wind

The resultant relative wind at a hover is rotational relative wind modified by induced flow. This is inclined downward at some angle and opposite the effective flightpath of the airfoil, rather than the physical flightpath (rotational relative wind). The resultant relative wind also serves as the reference plane for development of lift, drag, and total aerodynamic force (TAF) vectors on the airfoil. *[Figure 2-20]* When the helicopter has horizontal motion, airspeed further modifies the resultant relative wind. The airspeed component of relative wind results from the helicopter moving through the air. This airspeed component is added to, or subtracted from, the rotational relative wind depending on whether the blade is advancing or retreating in relation to helicopter movement. Introduction of airspeed relative wind also modifies induced flow. Generally, the downward velocity of induced flow is reduced. The pattern of air circulation through the disk changes when the aircraft has horizontal motion. As the helicopter gains airspeed, the addition of forward velocity results in decreased induced flow velocity. This change results in an improved efficiency (additional lift) being produced from a given blade pitch setting.

Induced Flow (Downwash)

At flat pitch, air leaves the trailing edge of the rotor blade in the same direction it moved across the leading edge; no lift or induced flow is being produced. As blade pitch angle is increased, the rotor disk induces a downward flow of air through the rotor blades creating a downward component of air that is added to the rotational relative wind. Because the blades are moving horizontally, some of the air is displaced downward. The blades travel along the same path and pass a given point in rapid succession. Rotor blade action changes the still air to a column of descending air. Therefore, each blade has a decreased AOA due to the downwash. This downward flow of air is called induced flow (downwash). It is most pronounced at a hover under no-wind conditions. *[Figure 2-21]*

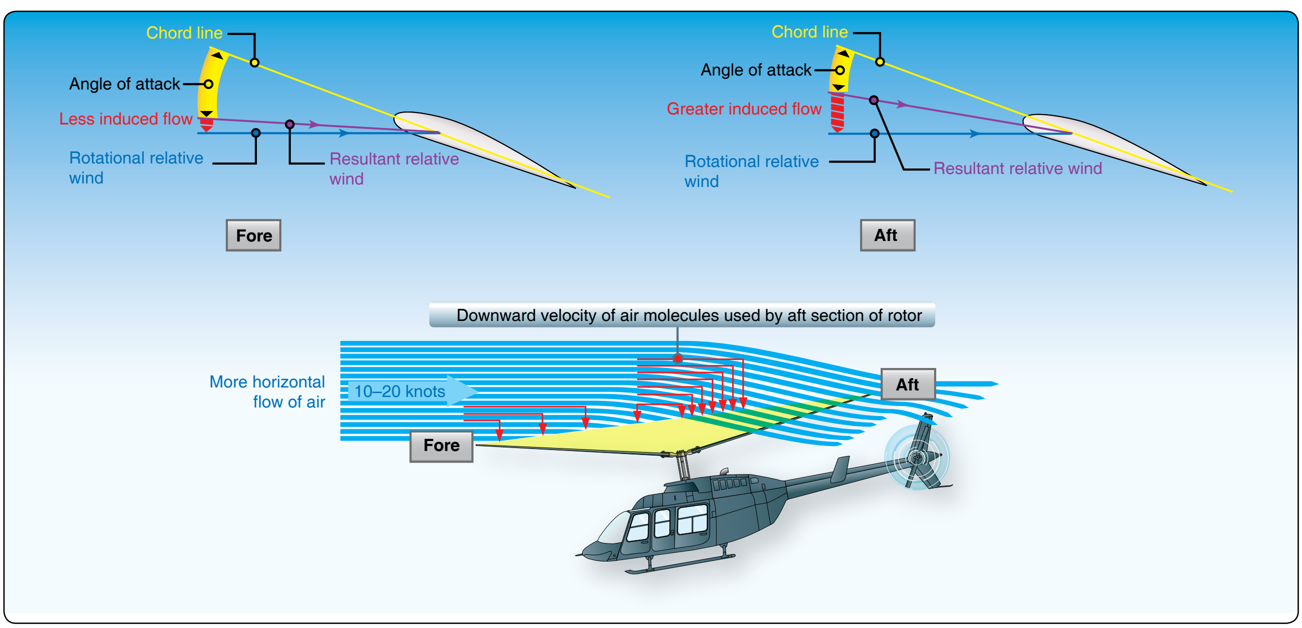

Figure 2-21. *A helicopter in forward flight, or hovering with a headwind or crosswind, has more molecules of air entering the aft portion of the rotor disk. Therefore, at the rear of the rotor disk, the angle of attack is less and the induced flow is greater.*

In Ground Effect (IGE)

Ground effect is the increased efficiency of the rotor disk caused by interference of the airflow when near the ground. The air pressure or density is increased, which acts to decrease the downward velocity of air. Ground effect permits relative wind to be more horizontal, lift vector to be more vertical, and induced drag to be reduced. These conditions allow the rotor disk to be more efficient. Maximum ground effect is achieved when hovering over smooth hard surfaces. When hovering over surfaces as tall grass, trees, bushes, rough terrain, and water, maximum ground effect is reduced. Rotor efficiency is increased by ground effect to a height of about one rotor diameter (measured from the ground to the rotor disk) for most helicopters. Since the induced flow velocities are decreased, the AOA is increased, which requires a reduced blade pitch angle and a reduction in induced drag. This reduces the power required to hover IGE. *[Figure 2-22]*

Out of Ground Effect (OGE)

The benefit of placing the helicopter near the ground is lost above IGE altitude. Above this altitude, the power required to hover remains nearly constant, given similar conditions (such as wind). Induced flow velocity is increased, resulting in a decrease in AOA and a decrease in lift. Under the correct circumstances, this downward flow can become so localized that the helicopter and locally disturbed air will sink at alarming rates. This effect is called vortex ring state (formerly referenced as settling-with-power) and is discussed at length in Chapter 11, Helicopter Emergencies and Hazards. A higher blade pitch angle is required to maintain the same AOA as in IGE hover. The increased pitch angle also creates more drag. This increased pitch angle and drag requires more power to hover OGE than IGE. *[Figure 2-23]*

Rotor Blade Angles

There are two angles that enable a rotor disk to produce the lift required for a helicopter to fly: angle of incidence and angle of attack.

Angle of Incidence

Angle of incidence is the angle between the chord line of a main or tail rotor blade and its rotor disk. It is a mechanical angle rather than an aerodynamic angle and is sometimes referred to as blade pitch angle. *[Figure 2-24]* In the absence of induced flow, AOA and angle of incidence are the same. Whenever induced flow, up flow (inflow), or airspeed modifies the relative wind, the AOA is different from the angle of incidence. Collective input and cyclic feathering (see page 2-12) change the angle of incidence. A change in the angle of incidence changes the AOA, which changes the coefficient of lift, thereby changing the lift produced by the airfoil.

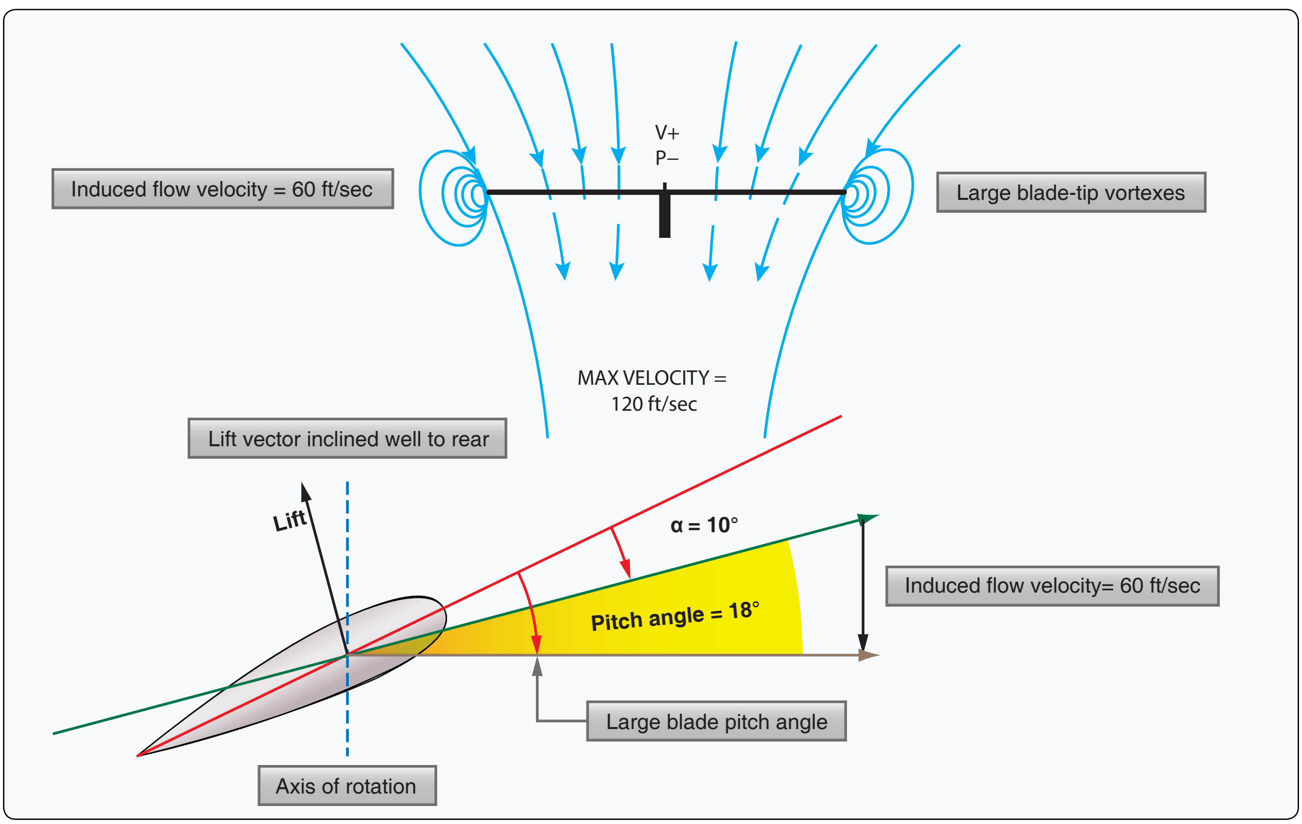

Figure 2-22. *In ground effect (IGE).*

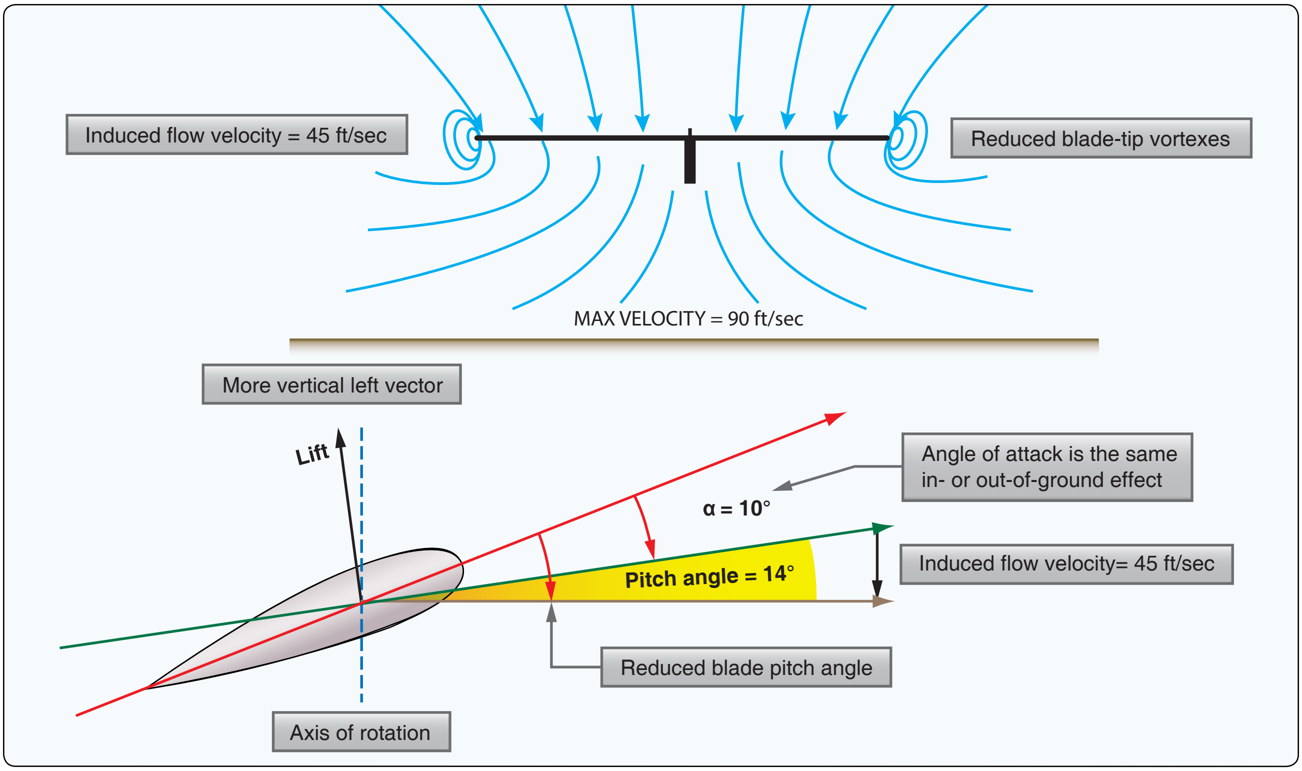

Figure 2-23. *Out of ground effect (OGE).*

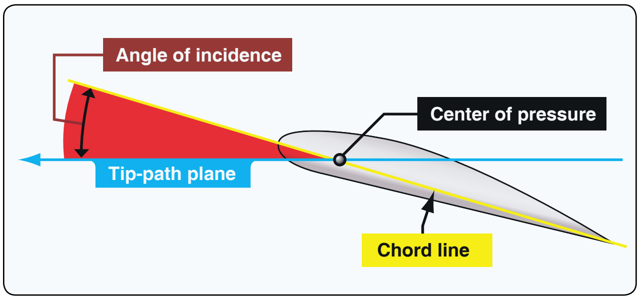

Figure 2-24. *Angle of incidence.*

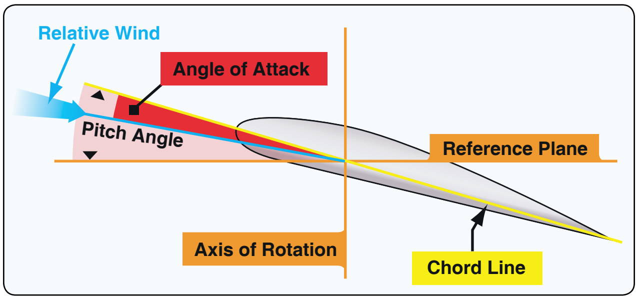

Figure 2-25. *The AOA is the angle between the airfoil chord line and resultant relative wind.*

Angle of Attack

AOA is the angle between the airfoil chord line and resultant relative wind. *[Figure 2-25]* It is an aerodynamic angle and not easy to measure. It can change with no change in the blade pitch angle (angle of incidence, discussed earlier).

When the AOA is increased, air flowing over the airfoil is diverted over a greater distance, resulting in an increase of air velocity and more lift. As the AOA is increased further, it becomes more difficult for air to flow smoothly across the top of the airfoil. At this point, the airflow begins to separate from the airfoil and enters a burbling or turbulent pattern. The turbulence results in a large increase in drag and loss of lift in the area where it is taking place. Increasing the AOA increases lift until the critical angle of attack is reached. Any increase in the AOA beyond this point produces a stall and a rapid decrease in lift (refer to the Low Rotor RPM and Rotor Stall section of Chapter 11, Helicopter Emergencies and Hazards).

Several factors may change the rotor blade AOA. The pilot has little direct control over AOA except indirectly through the flight control input. Collective and cyclic feathering help to make these changes. Feathering is the rotation of the blade about its longitudinal axis by collective/cyclic inputs causing changes in blade pitch angle. Collective feathering changes angle of incidence equally and in the same direction on all rotor blades simultaneously. This action changes AOA, which changes coefficient of lift (CL), and affects overall lift of the rotor disk.

Cyclic feathering changes the blade's AOA differentially around the rotor disk and creates a differential lift. Aviators use cyclic feathering to control attitude of the rotor disk. It is the means to control rearward tilt of the rotor (blowback) caused by flapping action and (along with blade flapping) counteract dissymmetry of lift (discussed in chapter 3). Cyclic feathering causes attitude of the rotor disk to change but does not change the amount of net lift the rotor disk is producing.

Most of the changes in AOA come from change in airspeed and rate of climb or descent; others such as flapping occur automatically due to the rotor system design. Flapping is the up and down movement of rotor blades about a hinge on a fully articulated rotor system. A semi-rigid system does not have a hinge but flap as a unit. A rigid rotor system has no vertical or horizontal hinges, so the blades cannot flap or drag, but they can flex. By flexing, the blades themselves compensate for the forces which previously required rugged hinges. It occurs in response to changes in lift due to changing velocity or cyclic feathering. No flapping occurs when the tip-path plane is perpendicular to the mast. The flapping action alone, or along with cyclic feathering, controls dissymmetry of lift. Flapping is the primary means of compensating for dissymmetry of lift.

Pilots adjust AOA through normal control manipulation of the pitch angle of the blades. If the pitch angle is increased, the AOA increases; if the pitch angle is reduced, the AOA is reduced.

Powered Flight

In powered flight (hovering, vertical, forward, sideward, or rearward), the total lift and thrust forces of a rotor are perpendicular to the rotor disk.

Hovering Flight

Hovering is the most challenging part of flying a helicopter. This is because a helicopter generates its own gusty air while in a hover, which acts against the fuselage and flight control surfaces. The end result is constant control inputs and corrections by the pilot to keep the helicopter where it is required to be. Despite the complexity of the task, the control inputs in a hover are simple. The cyclic is used to eliminate drift in the horizontal plane, controlling forward, backward, right and left movement or travel. The throttle, if not governor controlled, is used to control revolutions per minute (rpm). The collective is used to maintain altitude. The pedals are used to control nose direction or heading. It is the interaction of these controls that makes hovering difficult, since an adjustment in any one control requires an adjustment of the other two, creating a cycle of constant correction. During hovering flight, a helicopter maintains a constant position over a selected point, usually a few feet above the ground. The ability of the helicopter to hover comes from the both the lift component, which is the force developed by the main rotor(s) to overcome gravity and aircraft weight, and the thrust component, which acts horizontally to accelerate or decelerate the helicopter in the desired direction. Pilots direct the thrust of the rotor disk by using the cyclic to rotate the rotor disk plane relative to the horizon. They do this in order to induce travel or compensate for the wind and hold a position. At a hover in a no-wind condition, all opposing forces (lift, thrust, drag, and weight) are in balance; they are equal and opposite. Therefore, lift and weight are equal, resulting in the helicopter remaining at a stationary hover. *[Figure 2-26]*

While hovering, the amount of main rotor thrust can be adjusted to maintain the desired hovering height. This is done by changing the angle of incidence (by moving the collective) of the rotor blades, and hence their AOA. Changing the AOA changes the drag on the rotor blades, and the power delivered by the engine must change as well to keep the rotor speed constant.

The weight that must be supported is the total weight of the helicopter and its occupants. If the amount of lift is greater than the actual weight, the helicopter accelerates upwards until the lift force equals the weight of the helicopter; if lift is less than weight, the helicopter accelerates downward.

The drag of a hovering helicopter is mainly induced drag incurred while the blades are producing lift. There is, however, some profile drag on the blades as they rotate through the air and a small amount of parasite drag from the non-lift-producing surfaces of the helicopter, such as the rotor hub, cowlings, and

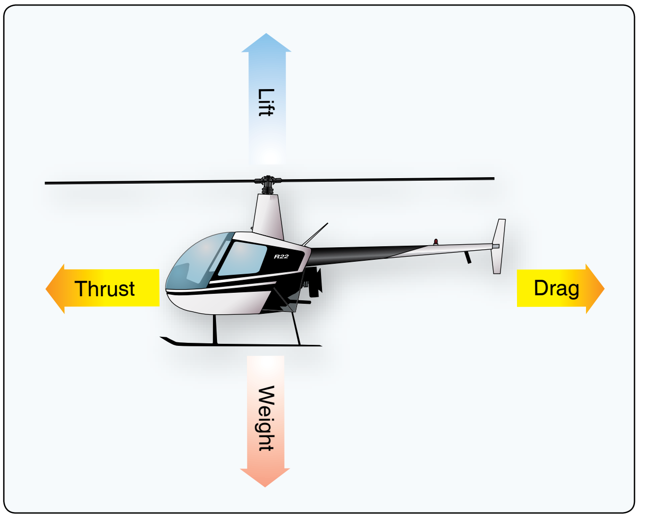

Figure 2-26. *To maintain a hover at a constant altitude, the lift must equal the weight of the helicopter. Thrust must equal any wind and tail rotor thrust to maintain position. The power must be sufficient to turn the rotors and overcome the various drags and frictions involved.*

landing gear. Throughout the rest of this discussion, the term "drag" includes induced, profile and parasite drag.

An important consequence of producing thrust is torque. As discussed earlier, Newton's Third Law states: for every action there is an equal and opposite reaction. Therefore, as the engine turns the main rotor disk in a counterclockwise direction, the helicopter fuselage wants to turn clockwise. The amount of torque is directly related to the amount of engine power being used to turn the main rotor disk. As power changes, torque changes.

To counteract this torque-induced turning tendency, an antitorque rotor or tail rotor is incorporated into most helicopter designs. A pilot can vary the amount of thrust produced by the tail rotor in relation to the amount of torque produced by the engine. As the engine supplies more power to the main rotor, the tail rotor must produce more thrust to overcome the increased torque effect. This control change is accomplished through the use of antitorque pedals (See page 3-4).

Translating Tendency (Drift)

During hovering flight, a single main rotor helicopter tends to move in the direction of tail rotor thrust. This lateral (or sideward) movement is called translating tendency. *[Figure 2-27]*

To counteract this tendency, one or more of the following features may be used. All examples are for a counterclockwise rotating main rotor disk.

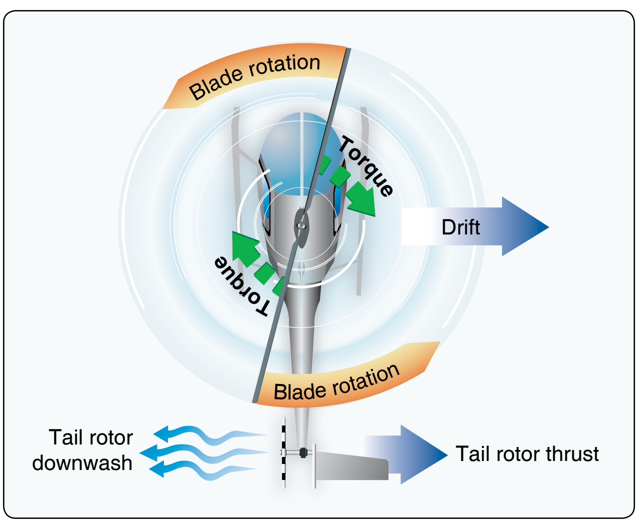

Figure 2-27. *A tail rotor is designed to produce thrust in a direction opposite torque. The thrust produced by the tail rotor is sufficient to move the helicopter laterally.*

- The main transmission is mounted at a slight angle to the left (when viewed from behind) so that the rotor mast has a built-in tilt to oppose the tail rotor thrust.
- Flight controls can be rigged so that the rotor disk is tilted to the left slightly when the cyclic is centered. Whichever method is used, the tip-path plane is tilted slightly to the left in the hover.
- The transmission is mounted so the rotor shaft is vertical with respect to the fuselage, the helicopter "hangs" left skid low in the hover. (The opposite is true for rotor disks turning clockwise when viewed from above.)
- The helicopter fuselage will also be tilted when the tail rotor is below the main rotor disk and supplying antitorque thrust. The fuselage tilt is caused by the imperfect balance of the tail rotor thrust against the main rotor torque in the same plane. The helicopter tilts due to two separate forces, the main rotor disk tilt to neutralize the translating tendency and the lower tail rotor thrust below the plane of the torque action.
- In forward flight, the tail rotor continues to push to the right, and the helicopter makes a small angle with the wind when the rotors are level and the slip ball is in the middle (See page 12-2). This is called inherent sideslip. For some larger helicopters, the vertical fin or stabilizer is often designed with the tail rotor mounted on them to correct this side slip and to eliminate some of the tilting at a hover. (By mounting the tail rotor on top of the vertical fin or pylon, the antitorque is more in line with or closer to the horizontal plane of torque, resulting in less airframe (or body) lean from the tail rotor.) Also, having the tail rotor higher off the ground reduces the risk of objects coming in contact with the blades, but at the cost of increased weight and complexity.

Pendular Action

Since the fuselage of the helicopter, with a single main rotor, is suspended from a single point and has considerable mass, it is free to oscillate either longitudinally or laterally in the same way as a pendulum. This pendular action can be exaggerated by overcontrolling; therefore, control movements should be smooth and not exaggerated. *[Figure 2-28]*

The horizontal stabilizer helps to level the helicopter in forward flight. However, in rearward flight, the horizontal stabilizer can press the tail downward, resulting in a tail strike if the helicopter is moved rearward into the wind. Normally, with the helicopter mostly into the wind, the horizontal stabilizer experiences less headwind component as the helicopter begins rearward travel (downwind). When

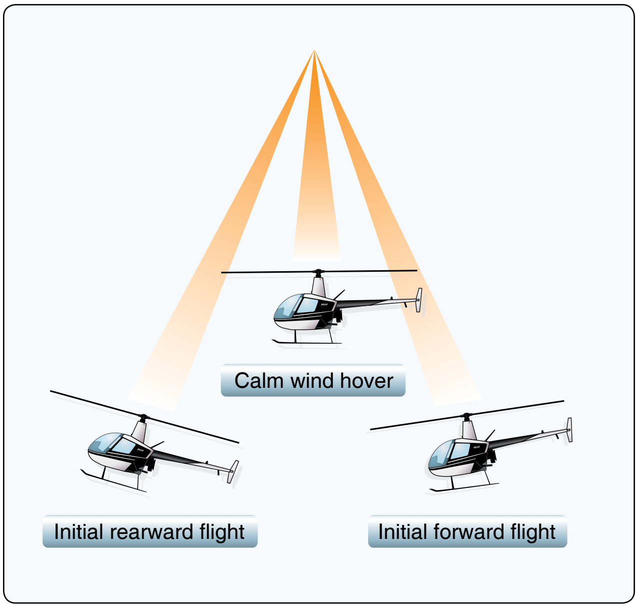

Figure 2-28. *Because the helicopter's body has mass and is suspended from a single point (the rotor mast head), it tends to act much like a pendulum.*

rearward flight groundspeed equals the windspeed, then the helicopter is merely hovering in a no-wind condition. However, rearward hovering into the wind requires considerable care and caution to prevent tail strikes.

It is important to note that there is a difference in the amount of pendular action between a semirigid system and a fully articulated system. Because of the hard connection (offset) of the latter, the centrifugal force pulling out on the blades is transferred to the fuselage, and the fuselage tends to follow the rotor attitude. The semirigid system is a true pendulum, with thrust required to create a moment around the fuselage CG to allow for control of the fuselage. This comes into play later when mast bumping is discussed.

Coning

In order for a helicopter to generate lift, the rotor blades must be turning. Rotor disk rotation drives the blades into the air, creating a relative wind component without having to move the airframe through the air as with an airplane or glider. Depending on the motion of the blades and helicopter airframe, many factors cause the relative wind direction to vary. The rotation of the rotor disk creates centrifugal force (inertia), which tends to pull the blades straight outward from the main rotor hub: the faster the rotation, the greater the centrifugal force, the slower the rotation, the smaller the centrifugal force. This force gives the rotor blades their rigidity and, in turn, the strength to support the weight of the helicopter. The maximum centrifugal force generated is determined by the maximum operating rotor revolutions per minute (rpm).

As lift on the blades is increased (in a takeoff, for example), two major forces are acting at the same time—centrifugal force acting outward, and lift acting upward. The result of these two forces is that the blades assume a conical path instead of remaining in the plane perpendicular to the mast. This can be seen in any helicopter when it takes off; the rotor disk changes from flat to a slight cone shape. *[Figure 2-29]*

If the rotor rpm is allowed to go too low (below the minimum power-on rotor rpm, for example), the centrifugal force becomes smaller and the coning angle becomes much larger. In other words, should the rpm decrease too much, at some point the rotor blades fold up with no chance of recovery.

Coriolis Effect (Law of Conservation of Angular Momentum)

The Coriolis Effect is also referred to as the law of conservation of angular momentum. It states that the value of angular momentum of a rotating body does not change unless an external force is applied. In other words, a rotating body continues to rotate with the same rotational velocity until some external force is applied to change the speed of rotation. Angular momentum is the moment of inertia (mass times distance from the center of rotation squared) multiplied by the speed of rotation.

Changes in angular velocity, known as angular acceleration and deceleration, take place as the mass of a rotating body is moved closer to or farther away from the axis of rotation. The speed of the rotating mass varies proportionately with the square of the radius.

An excellent example of this principle in action is a figure skater performing a spin on ice skates. The skater begins rotation on one foot, with the other leg and both arms extended. The rotation of the skater's body is relatively slow. When a skater draws both arms and one leg inward, the moment of inertia (mass times radius squared) becomes

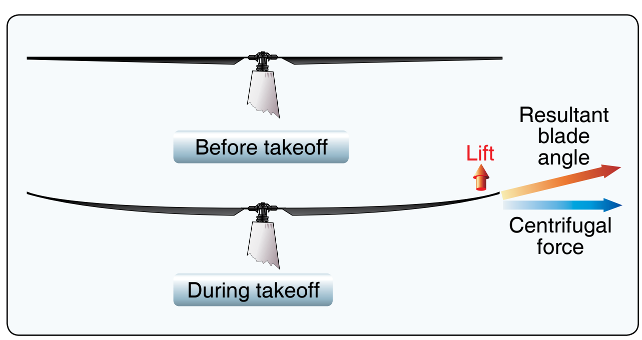

Figure 2-29. *During takeoff, the combination of centrifugal force and lift cause the rotor disk to cone upward.*

much smaller and the body is rotating almost faster than the eye can follow. Because the angular momentum must, by law of nature, remain the same (no external force applied), the angular velocity must increase.

The rotor blade rotating about the rotor hub possesses angular momentum. As the rotor begins to cone due to G-loading maneuvers, the diameter of the rotor disk shrinks. Due to conservation of angular momentum, the blades increase speed even though the blade tips have a shorter distance to travel due to reduced disk diameter. The action results in an increase in rotor rpm which causes a slight increase in lift. Most pilots arrest this increase of rpm with an increase in collective pitch. This increase in blade rpm lift is somewhat negated by the slightly smaller disk area as the blades cone upward.

Gyroscopic Precession

The spinning main rotor of a helicopter acts like a gyroscope. As such, it has the properties of gyroscopic action, one of which is precession. Gyroscopic precession is the resultant action or deflection of a spinning object when a force is applied to this object. This action occurs approximately 90° in the direction of rotation from the point where the force is applied (or 90° later in the rotation cycle). *[Figure 2-30]*

Examine a two-bladed rotor disk to see how gyroscopic precession affects the movement of the tip-path plane. Moving the cyclic pitch control increases the angle of incidence of one rotor blade with the result of a greater lifting force being applied at that point in the plane of rotation. This same control movement simultaneously decreases the angle of incidence of the other blade the same amount, thus

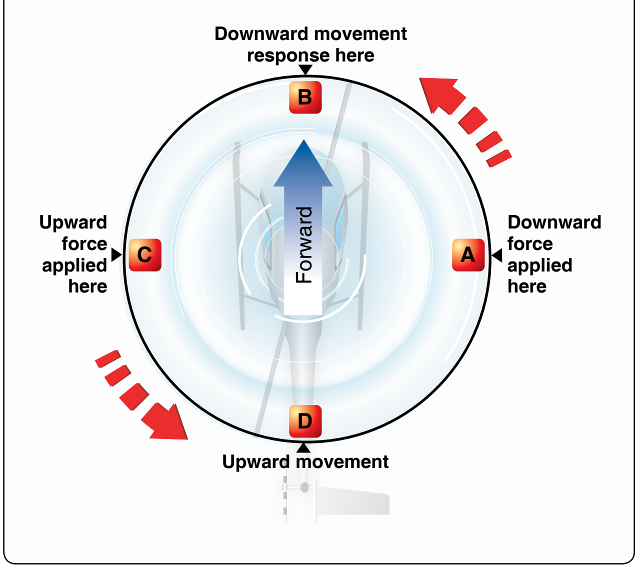

Figure 2-30. *Gyroscopic precession.*

decreasing the lifting force applied at that point in the plane of rotation. The blade with the increased angle of incidence tends to flap up; the blade with the decreased angle of incidence tends to flap down. Because the rotor disk acts like a gyro, the blades reach maximum deflection at a point approximately 90° later in the plane of rotation. *Figure 2-31* illustrates the result of a forward cyclic input. The retreating blade angle of incidence is increased, and the advancing blade angle of incidence is decreased resulting in a tipping forward of the tip-path plane, since maximum deflection takes place 90° later when the blades are at the rear and front, respectively. In a rotor disk using three or more blades, the movement of the cyclic pitch control changes the angle of incidence of each blade an appropriate amount so that the end result is the same.

Vertical Flight

Hovering is actually an element of vertical flight. Increasing the angle of incidence of the rotor blades (pitch) while keeping their rotation speed constant generates additional lift and the helicopter ascends. Decreasing the pitch causes the helicopter to descend. In a no-wind condition in which lift and thrust are less than weight and drag, the helicopter descends vertically. If lift and thrust are greater than weight and drag, the helicopter ascends vertically. *[Figure 2-32]*

Forward Flight

In steady forward flight, with no change in airspeed or vertical speed, the four forces of lift, thrust, drag, and weight must be in balance. Once the tip-path plane is tilted forward, the total lift-thrust force is also tilted forward. This resultant lift-thrust force can be resolved into two components—lift acting vertically upward and thrust acting horizontally in the direction of flight. In addition to lift and thrust, there is weight (the downward acting force) and drag (the force opposing the motion of an airfoil through the air). *[Figure 2-33]*

In straight-and-level, unaccelerated forward flight (straight-and-level flight is flight with a constant heading and at a constant altitude), lift equals weight and thrust equals drag. If lift exceeds weight, the helicopter accelerates vertically until the forces are in balance; if thrust is less than drag, the helicopter slows down until the forces are in balance. As a helicopter initiates a move forward, it begins to lose altitude because lift is lost as thrust is diverted forward. However, as the helicopter begins to accelerate from a hover, the rotor disk becomes more efficient due to translational lift (see translational lift on page 2-19). The result is excess power over that which is required to hover. Continued acceleration causes an even larger increase in airflow through the rotor disk (up to a maximum determined by drag and the engine's limit of power), and more efficient flight. In order to maintain unaccelerated flight, the pilot must understand that with

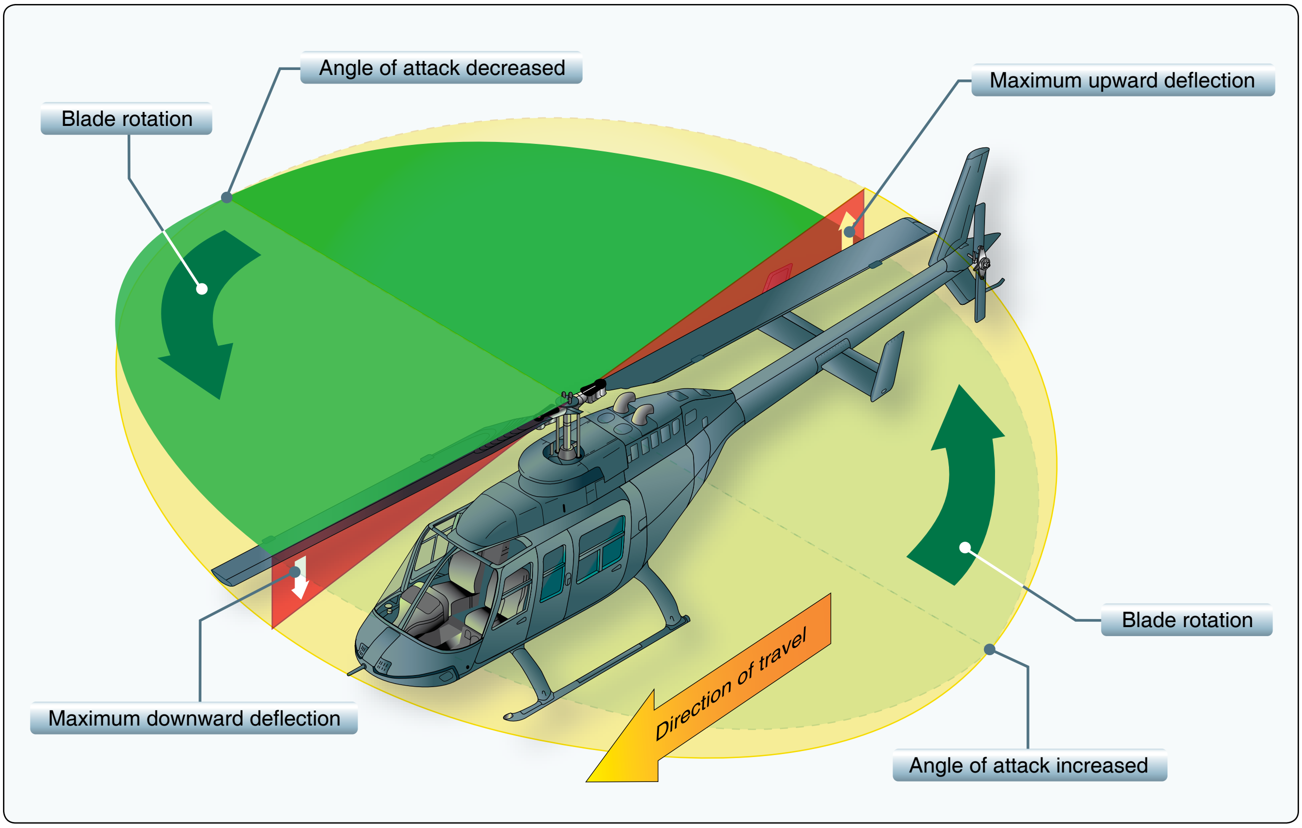

Figure 2-31. *As each blade passes the 90° position on the left in a counterclockwise main rotor blade rotation, the maximum increase in angle of incidence occurs. As each blade passes the 90° position to the right, the maximum decrease in angle of incidence occurs. Maximum deflection takes place 90° later—maximum upward deflection at the rear and maximum downward deflection at the front—and the tip-path plane tips forward.*

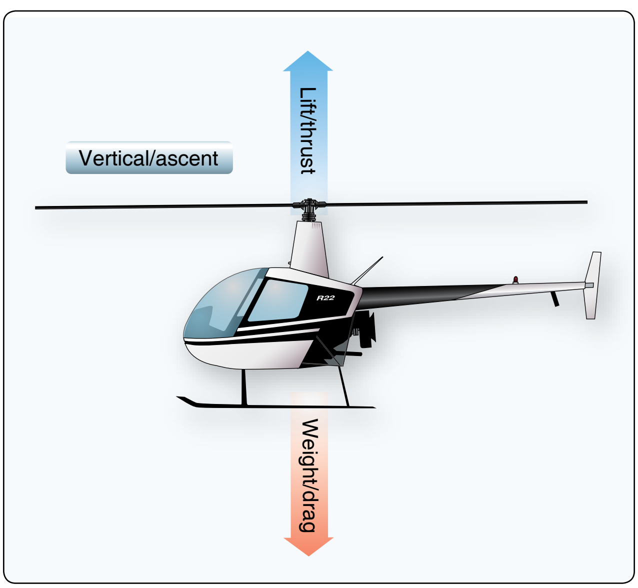

Figure 2-32. *Balanced forces: hovering in a no-wind condition.*

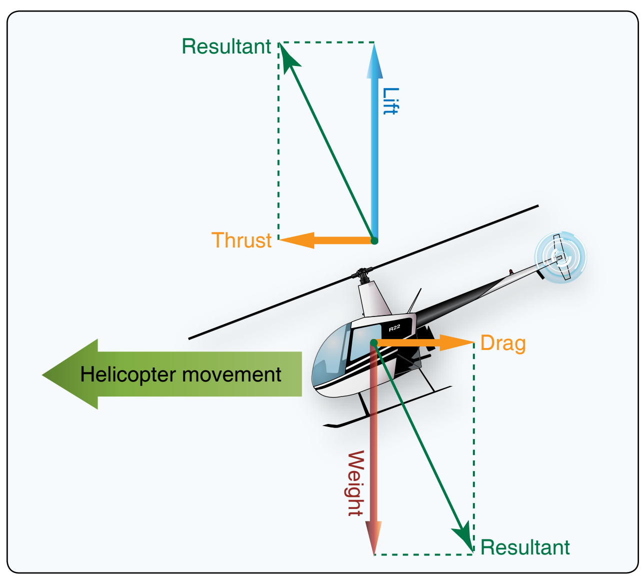

Figure 2-33. *To transition to forward flight, more lift and thrust must be generated to overcome the forces of weight and drag.*

any changes in power or in cyclic movement, the helicopter begins either to climb or to descend. Once straight-and-level flight is obtained, the pilot should make note of the power (torque setting) required and not make major adjustments to the flight controls. *[Figure 2-34]*

Airflow in Forward Flight

Airflow across the rotor disk in forward flight varies from airflow at a hover. In forward flight, air flows opposite the aircraft's flightpath. The velocity of this air flow equals the helicopter's forward speed. Because the rotor blades turn in a circular pattern, the velocity of airflow across a blade depends on the position of the blade in the plane of rotation at a given instant, its rotational velocity, and airspeed of the helicopter. Therefore, the airflow meeting each blade varies continuously as the blade rotates. The highest velocity of airflow occurs over the right side (3 o'clock position) of the helicopter (advancing blade in a rotor disk that turns counterclockwise) and decreases to rotational velocity over the nose. It continues to decrease until the lowest velocity of airflow occurs over the left side (9 o'clock position) of the helicopter (retreating blade). As the blade continues to rotate, velocity of the airflow then increases to rotational velocity over the tail. It continues to increase until the blade is back at the 3 o'clock position.

The advancing blade in *Figure 2-35,* position A, moves in the same direction as the helicopter. The velocity of the air meeting this blade equals rotational velocity of the blade plus wind velocity resulting from forward airspeed. The retreating blade (position C) moves in a flow of air moving in the opposite direction of the helicopter. The velocity of airflow meeting this blade equals rotational velocity of the blade minus wind velocity resulting from forward airspeed. The blades (positions B and D) over the nose and tail move essentially at right angles to the airflow created by forward airspeed; the velocity of airflow meeting these blades equals the rotational velocity. This results in a change to velocity of airflow all across the rotor disk and a change to the lift pattern of the rotor disk.

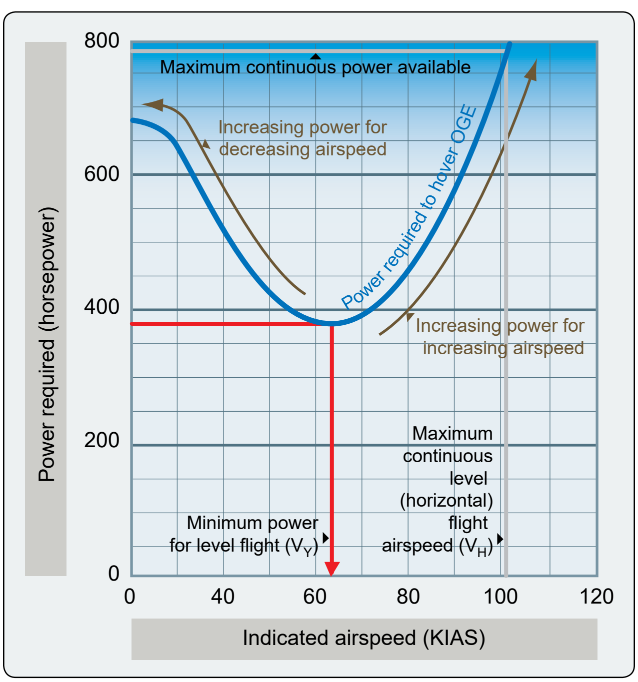

Figure 2-34. *Power versus airspeed chart.*

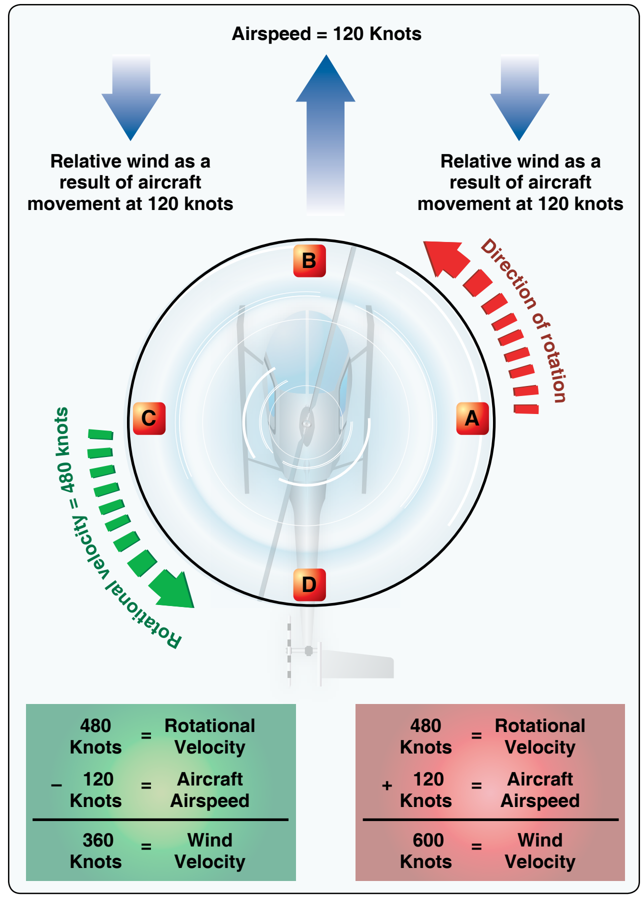

Figure 2-35. *Airflow in forward flight.*

Advancing Blade

As the relative wind speed of the advancing blade increases, the blade gains lift and begins to flap up. It reaches its maximum upflap velocity at the 3 o'clock position, where the wind velocity is the greatest. This upflap creates a downward flow of air and has the same effect as increasing the induced flow velocity by imposing a downward vertical velocity vector to the relative wind which decreases the AOA.

Retreating Blade

As relative wind speed of the retreating blade decreases, the blade loses lift and begins to flap down. It reaches its maximum downflap velocity at the 9 o'clock position, where wind velocity is the least. This downflap creates an upward flow of air and has the same effect as decreasing the induced flow velocity by imposing an upward velocity vertical vector to the relative wind which increases the AOA.

Dissymmetry of Lift

Dissymmetry of lift is the differential (unequal) lift between advancing and retreating halves of the rotor disk caused by the different wind flow velocity across each half. This difference in lift would cause the helicopter to be uncontrollable in any situation other than hovering in a calm wind. There must be a means of compensating, correcting, or eliminating this unequal lift to attain symmetry of lift.

When the helicopter moves through the air, the relative airflow through the main rotor disk is different on the advancing side from the retreating side. The relative wind encountered by the advancing blade is increased by the forward speed of the helicopter, while the relative wind speed acting on the retreating blade is reduced by the helicopter's forward airspeed. Therefore, as a result of the relative wind speed, the advancing blade side of the rotor disk can produce more lift than the retreating blade side. *[Figure 2-36]*

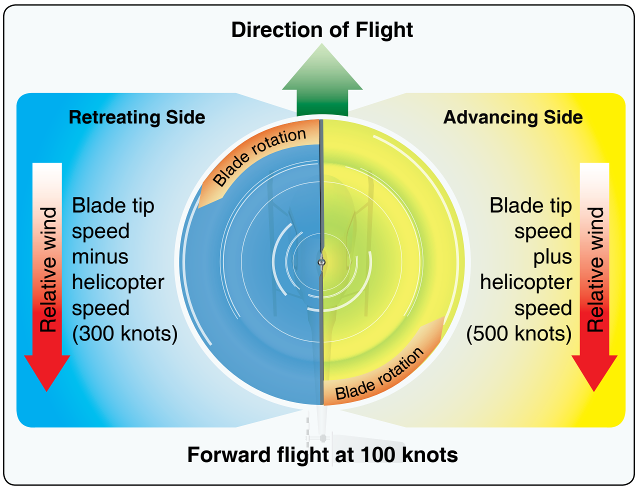

Figure 2-36. *The blade tip speed of this helicopter is approximately 400 knots. If the helicopter is moving forward at 100 knots, the relative windspeed on the advancing side is 500 knots. On the retreating side, it is only 300 knots. This difference in speed causes a dissymmetry of lift.*

If this condition were allowed to exist, a helicopter with a counterclockwise main rotor blade rotation would roll to the left because of the difference in lift. In reality, the main rotor blades flap and feather automatically to equalize lift across the rotor disk. Articulated rotor disks, usually with three or more blades, incorporate a horizontal hinge (flapping hinge) to allow the individual rotor blades to move, or flap up and down as they rotate. A semi-rigid rotor disk (two blades) utilizes a teetering hinge, which allows the blades to flap as a unit. When one blade flaps up, the other blade flaps down.

As shown in *Figure 2-37,* as the rotor blade reaches the advancing side of the rotor disk (A), it reaches its maximum up flap velocity. When the blade flaps upward, the angle between the chord line and the resultant relative wind decreases. This decreases the AOA, which reduces the amount of lift produced by the blade. At position (C), the rotor blade is now at its maximum down flapping velocity. Due to down flapping, the angle between the chord line and the resultant relative wind increases. This increases the AOA and thus the amount of lift produced by the blade.

The combination of blade flapping and slow relative wind acting on the retreating blade normally limits the maximum forward speed of a helicopter. At a high forward speed, the retreating blade stalls because of a high AOA and slow relative wind speed. This situation is called retreating blade stall and is evidenced by a nose pitch up, vibration, and a rolling tendency—usually to the left in helicopters with counterclockwise blade rotation.

Pilots can avoid retreating blade stall by not exceeding the never-exceed speed. This speed is designated V_{NE} and is indicated on a placard and marked on the airspeed indicator by a red line.

Blade flapping compensates for dissymmetry of lift in the following way. At a hover, equal lift is produced around the rotor disk with equal pitch (AOI) on all the blades and at all points in the rotor disk (disregarding compensation for translating tendency). The rotor disk is parallel to the horizon. To develop a thrust force, the rotor disk must be tilted in the desired direction of movement. Cyclic feathering changes the angle of incidence differentially around the rotor disk. For a counterclockwise rotation, forward cyclic movement decreases the angle of incidence on the right of the rotor disk and increases it on the left.

When transitioning to forward flight either from a hover or taking off from the ground, pilots must be aware that as the helicopter speed increases, translational lift becomes more effective and causes the nose to rise or pitch up (sometimes referred to as blowback). This tendency is caused by the combined effects of dissymmetry of lift and transverse flow. Pilots must correct for this tendency by maintaining a constant rotor disk attitude that will move the helicopter through the speed range in which blowback occurs. If the nose is permitted to pitch up while passing through this speed range, the aircraft may also tend to roll to the right. To correct for this tendency, the pilot must continuously move the cyclic forward as velocity of the helicopter increases until the takeoff is complete, and the helicopter has transitioned into forward flight.

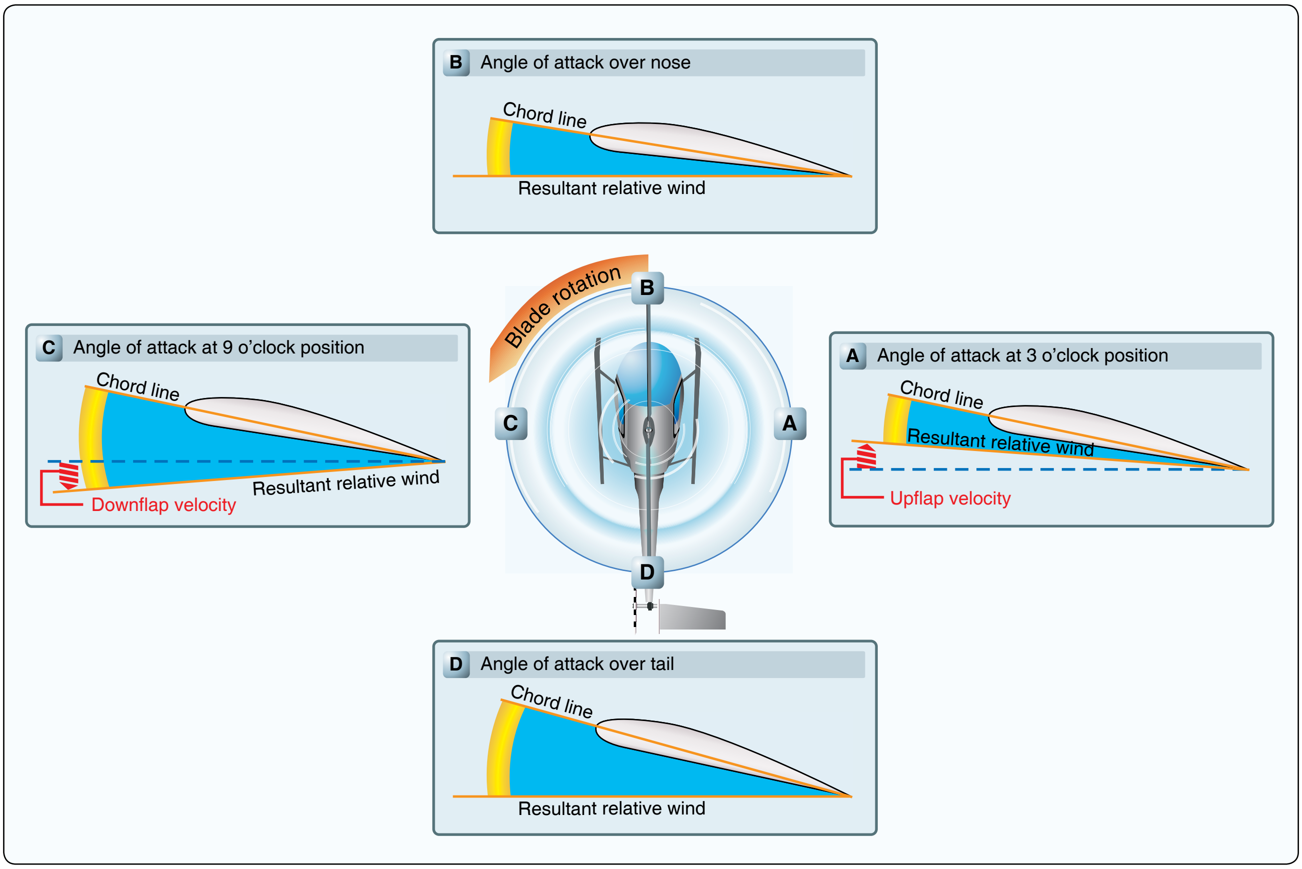

Figure 2-37. *The combined upward flapping (reduced lift) of the advancing blade and downward flapping (increased lift) of the retreating blade equalizes lift across the main rotor disk, counteracting dissymmetry of lift.*

Figure 2-38 illustrates the tilting forward of the rotor disk, which is the result of a change in pitch angle with forward cyclic. At a hover, the cyclic is centered and the pitch angle on the advancing and retreating blades is the same. At low forward speeds, moving the cyclic forward reduces pitch angle on the advancing blade and increases pitch angle on the retreating blade. This causes a slight rotor disk tilt. At higher forward speeds, the pilot must continue to move the cyclic forward. This further reduces pitch angle on the advancing blade and further increases pitch angle on the retreating blade. As a result, there is even more tilt to the rotor disk than at lower speeds.

A horizontal lift component (thrust) generates higher helicopter airspeed. The higher airspeed induces blade flapping to maintain symmetry of lift. The combination of flapping and cyclic feathering maintains symmetry of lift and desired attitude on the rotor disk and helicopter.

Translational Lift

Improved rotor efficiency resulting from directional flight is called translational lift. The efficiency of the hovering rotor disk is greatly improved with each knot of incoming wind gained by horizontal movement of the aircraft or surface wind. As the incoming wind produced by aircraft movement or surface wind enters the rotor disk, turbulence and vortices are left behind and the flow of air becomes more horizontal. In addition, the tail rotor becomes more aerodynamically efficient during the transition from hover to forward flight. *Figures 2-39* and *2-40* show the different airflow patterns at different speeds and how airflow affects the efficiency of the tail rotor.

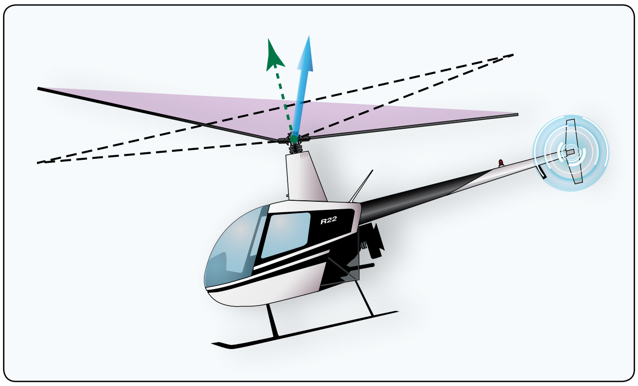

Figure 2-38. *To compensate for blowback, you must move the cyclic forward.*

Effective Translational Lift (ETL)

While transitioning to forward flight at about 16 to 24 knots, the helicopter goes through effective translational lift (ETL). As mentioned earlier in the discussion on translational lift, the rotor blades become more efficient as forward airspeed increases. Between 16 and 24 knots, the rotor disk completely outruns the recirculation of old vortices and begins to work in relatively undisturbed air. The flow of air through the rotor disk is more horizontal, which reduces induced flow and drag with a corresponding increase in angle of attach and lift. The additional lift available at this speed is referred to as the ETL, which makes the rotor disk operate more efficiently. This increased efficiency continues with increased airspeed until the best climb airspeed is reached, and total drag is at its lowest point.

As speed increases, translational lift becomes more effective, nose rises or pitches up, and aircraft rolls to the right. The combined effects of dissymmetry of lift, gyroscopic precession, and transverse flow effect cause this tendency. It is important to understand these effects and anticipate correcting for them. Once the helicopter is transitioning through ETL, the pilot needs to apply forward and left lateral cyclic input to maintain a constant rotor-disk attitude. *[Figure 2-41]*

Translational Thrust

Translational thrust occurs when the tail rotor becomes more aerodynamically efficient during the transition from hover to forward flight. As the tail rotor works in progressively less turbulent air, this improved efficiency produces more antitorque thrust, causing the nose of the aircraft to yaw left

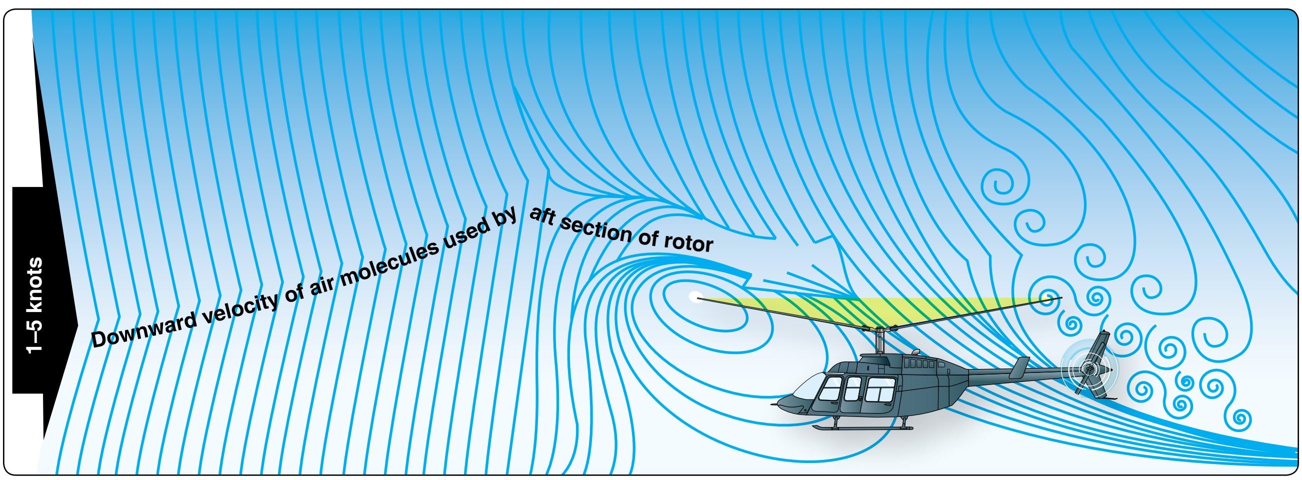

Figure 2-39. *The airflow pattern for 1–5 knots of forward airspeed. Note how the downwind vortex is beginning to dissipate and induced flow down through the rear of the rotor disk is more horizontal.*

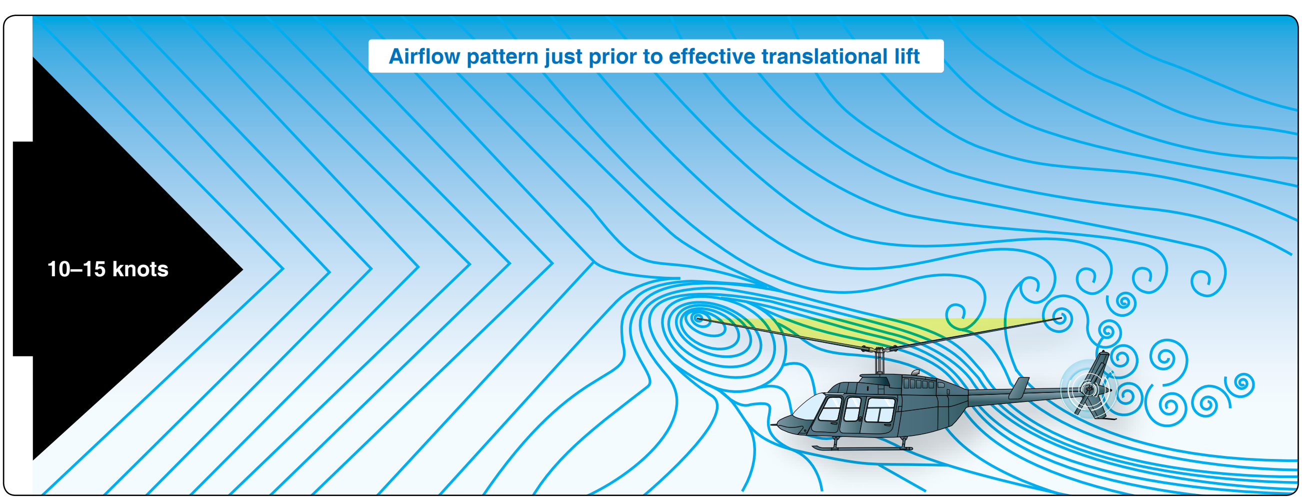

Figure 2-40. *An airflow pattern at a speed of 10–15 knots. At this increased airspeed, the airflow continues to become more horizontal. The leading edge of the downwash pattern is being overrun and is well back under the nose of the helicopter.*

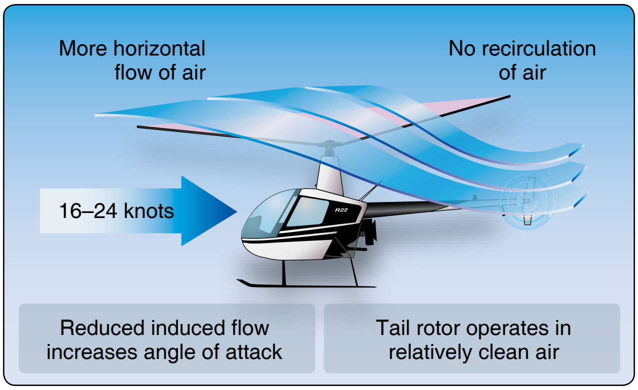

Figure 2-41. *Effective translational lift is easily recognized in actual flight by a transient induced aerodynamic vibration and increased performance of the helicopter.*

(with a main rotor turning counterclockwise) and forces the pilot to apply right pedal (decreasing the AOA in the tail rotor blades) in response. In addition, during this period, the airflow affects the horizontal components of the stabilizer found on most helicopters which tends to bring the nose of the helicopter to a more level attitude.

Induced Flow

As the rotor blades rotate, they generate what is called rotational relative wind. This airflow is characterized as flowing parallel and opposite the rotor's plane of rotation and striking perpendicular to the rotor blade's leading edge. This rotational relative wind is used to generate lift. As rotor blades produce lift, air is accelerated over the foil and projected downward. Anytime a helicopter is producing lift, it moves large masses of air vertically and down through the rotor disk. This downwash or induced flow can significantly change the efficiency of the rotor disk. Rotational relative wind combines with induced flow to form the resultant relative wind. As induced flow increases, resultant relative wind becomes less horizontal. Since AOA is determined by measuring the difference between the chord line and the resultant relative wind, as the resultant relative wind becomes less horizontal, AOA decreases. *[See Figure 2-21]*

Transverse Flow Effect

As the helicopter accelerates in forward flight, induced flow drops to near zero at the forward disk area and increases at the aft disk area. These differences in lift between the fore and aft portions of the rotor disk are called transverse flow effect. *[Figure 2-41]* This increases the AOA at the front disk area causing the rotor blade to flap up and reduces AOA at the aft disk area causing the rotor blade to flap down. Because the rotor acts like a gyro, maximum displacement occurs 90° in the direction of rotation. The result is a tendency for the helicopter to roll slightly to the right as it accelerates through approximately 20 knots or if the headwind is approximately 20 knots.

Transverse flow effect is recognized by increased vibrations of the helicopter at airspeeds around 12 to 15 knots and can be produced by forward flight or from the wind while in a hover. This vibration happens at an airspeed just below ETL on takeoff and after passing through ETL during landing. The vibration happens close to the same airspeed as ETL because that is when the greatest lift differential exists between the front and rear portions of the rotor system. As such, some pilots confuse the vibration felt by transverse flow effect with passing through ETL. To counteract transverse flow effect, a cyclic input to the left may be needed.

Sideward Flight

In sideward flight, the tip-path plane is tilted in the direction that flight is desired. This tilts the total lift-thrust vector sideward. In this case, the vertical or lift component is still straight up and weight straight down, but the horizontal or thrust component now acts sideward with drag acting to the opposite side. *[Figure 2-42]*

Sideward flight can be a very unstable condition due to the parasitic drag of the fuselage combined with the lack of horizontal stabilizer for that direction of flight. Increased altitudes help with control and the pilot must always scan in the direction of flight. Movement of the cyclic in the intended direction of flight causes the helicopter to move, controls the rate of speed, and ground track, but the collective and pedals are key to successful sideward flight. Just as in forward flight, the collective keeps the helicopter from contacting the ground and the pedals help maintain the correct heading; even in sideward flight, the tail of the helicopter should remain behind you. Inputs to the cyclic should be smooth and controlled, and the pilot should always be aware of the tip-path plane in relation to the ground. *[Figure 2-43]*

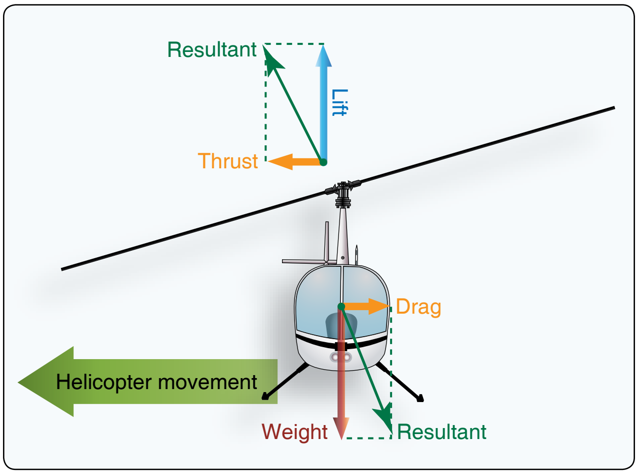

Figure 2-42. *Forces acting on the helicopter during sideward flight.*

Contacting the ground with the skids during sideward flight will most likely result in a dynamic rollover event before the pilot has a chance to react. Extreme caution should be used when maneuvering the helicopter sideways to avoid such hazards from happening. Refer to Chapter 11, Helicopter Hazards and Emergencies.

Rearward Flight

For rearward flight, the tip-path plane is tilted rearward, which, in turn, tilts the lift-thrust vector rearward. Drag now acts forward with the lift component straight up and weight straight down. *[Figure 2-44]*

Pilots must be aware of the hazards of rearward flight. Because of the position of the horizontal stabilizer, the tail end of the helicopter tends to pitch downward in rearward flight, causing the probability of hitting the ground to be greater than in forward flight. Another factor to consider in rearward flight is skid design. Most helicopter skids are not turned upward in the back, and any contact with the ground during rearward flight can put the helicopter in an uncontrollable position leading to tail rotor contact with the ground. Pilots must do a thorough scan of the area before attempting to hover rearward, looking for obstacles and terrain changes. Slower airspeeds can help mitigate risk and maintain a higher-than-normal hover altitude.

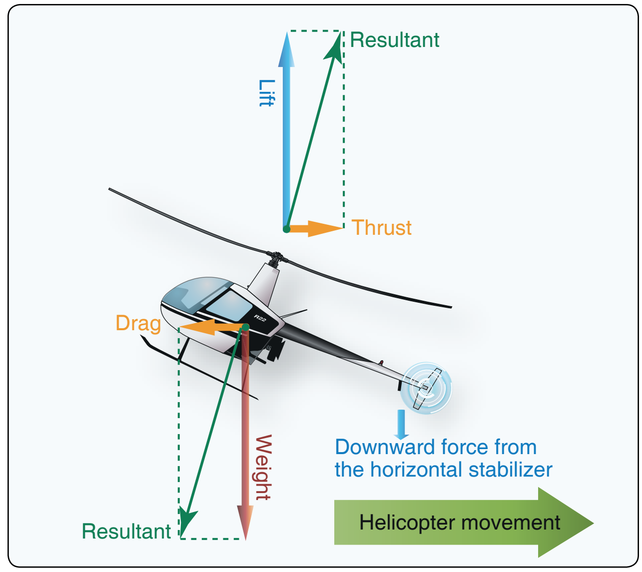

Figure 2-44. *Forces acting on the helicopter during rearward flight.*

Turning Flight

In forward flight, the rotor disk is tilted forward, which also tilts the total lift-thrust force of the rotor disk forward. When the helicopter is banked, the rotor disk is tilted sideward resulting in lift being separated into two components. Lift acting upward and opposing weight is called the vertical component of lift. Lift acting horizontally and opposing inertia (centrifugal force) is the horizontal component of lift (centripetal force). *[Figure 2-45]*

As the angle of bank increases, the total lift force is tilted more toward the horizontal, thus causing the rate of turn to increase because more lift is acting horizontally. Since the resultant lifting force acts more horizontally, the effect of lift acting

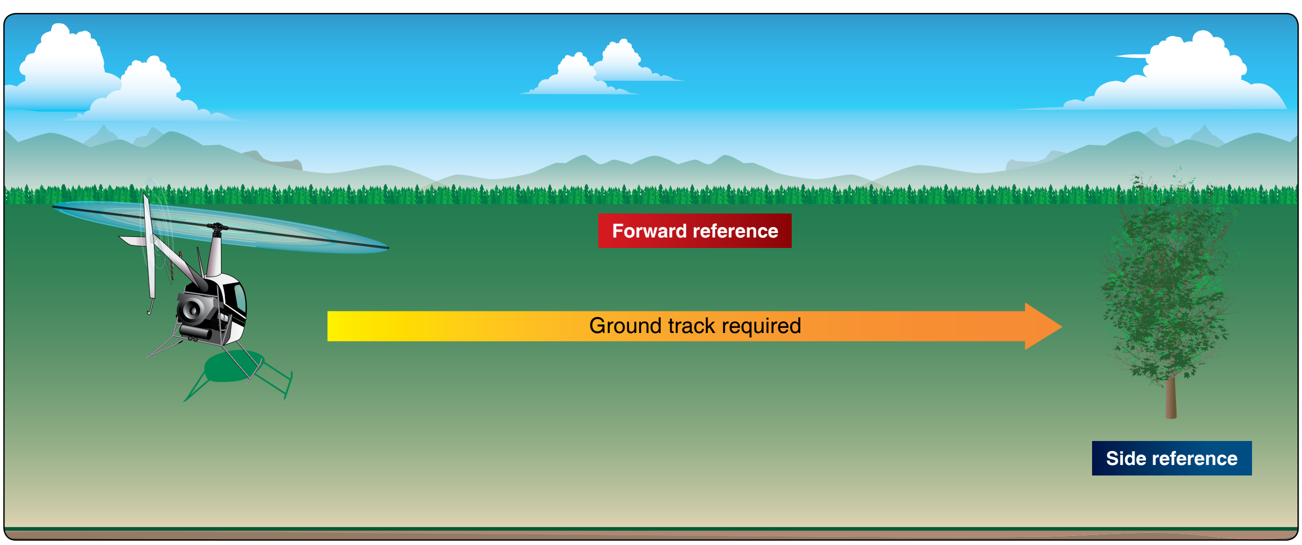

Figure 2-43. *Forces acting on the helicopter during sideward flight.*

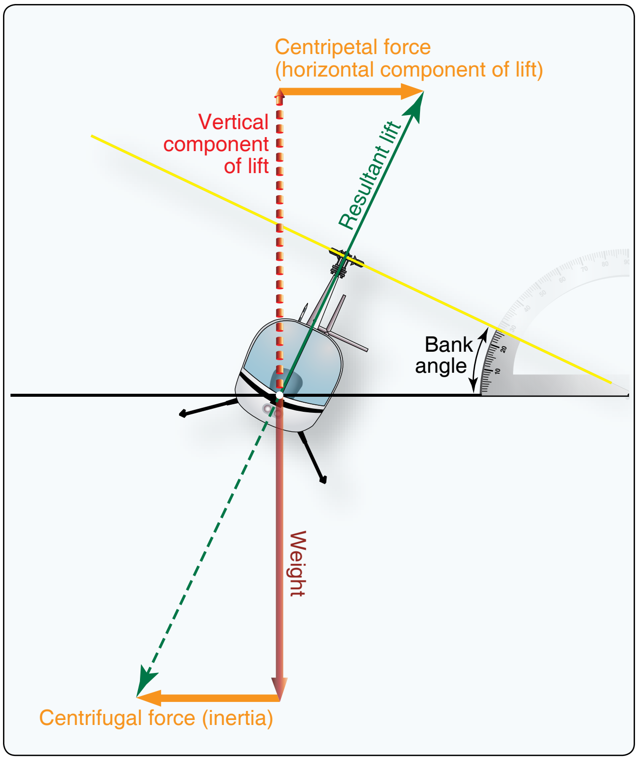

Figure 2-45. *Forces acting on the helicopter during turning flight.*

vertically is decreased. To compensate for this decreased vertical lift, the AOA of the rotor blades must be increased in order to maintain altitude. The steeper the angle of bank is, the greater the AOA of the rotor blades required to maintain altitude. Thus, with an increase in bank and a greater AOA, the resultant lifting force increases, and the rate of turn is higher. Simply put, collective pitch must be increased in order to maintain altitude and airspeed while turning. Collective pitch controls the angle of incidence and along with other factors, determines the overall AOA in the rotor disk.

Autorotation

Autorotation is the state of flight where the main rotor disk of a helicopter is being turned by the action of air moving up through the rotor rather than engine power driving the rotor. In normal, powered flight, air is drawn into the main rotor disk from above and exhausted downward, but during autorotation, air moves up into the rotor disk from below as the helicopter descends. Autorotation is permitted mechanically by a freewheeling unit, which is a special clutch mechanism that allows the main rotor to continue turning even if the engine is not running. If the engine fails, the freewheeling unit automatically disengages the engine from the main rotor allowing the main rotor to rotate freely. It is the means by which a helicopter can be landed safely in the event of an engine failure; consequently, all helicopters must demonstrate this capability in order to be certified. *[Figure 2-46]* If a decision is made to attempt an engine restart in flight (the parameters for this emergency procedure will be different for each helicopter and must be precisely followed) the pilot must reengage the engine starter switch to start the engine. Once the engine is started, the freewheeling unit will reengage the engine with the main rotor.

Vertical Autorotation

Most autorotations are performed with forward speed. For simplicity, the following aerodynamic explanation is based on a vertical autorotative descent (no forward speed) in still air. Under these conditions, the forces that cause the blades to turn are similar for all blades regardless of their position in the plane of rotation. Therefore, dissymmetry of lift resulting from helicopter airspeed is not a factor.

During vertical autorotation, the rotor disk is divided into three regions (as illustrated in *Figure 2-47*): driven region,

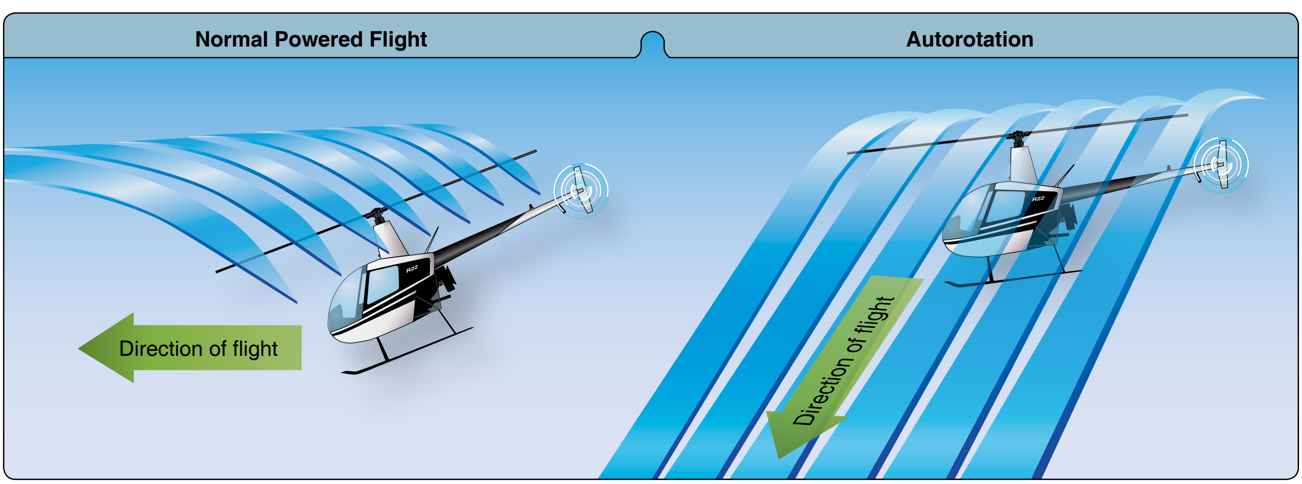

Figure 2-46. *During an autorotation, the upward flow of relative wind permits the main rotor blades to rotate at their normal speed. In effect, the blades are "gliding" in their rotational plane.*

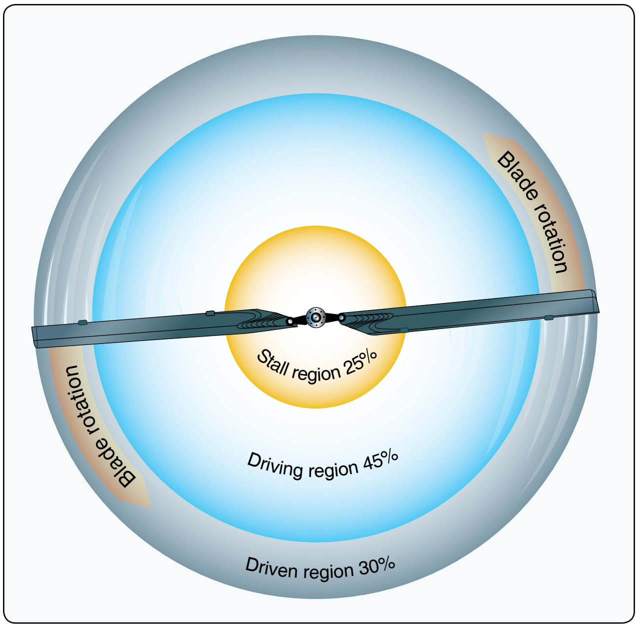

Figure 2-47. *Blade regions during autorotational descent.*

driving region, and stall region. *Figure 2-48* shows three blade sections that illustrate force vectors. Part A is the driven region, B and D are points of equilibrium, part C is the driving region, and part E is the stall region. Force vectors are different in each region because rotational relative wind is slower near the blade root and increases continually toward the blade tip. Also, blade twist gives a more positive AOA in the driving region than in the driven region. The combination of the inflow up through the rotor with rotational relative wind produces different combinations of aerodynamic force at every point along the blade.

The driven region, also called the propeller region, is nearest the blade tips. Normally, it consists of about 30 percent of the radius. In the driven region, part A of *Figure 2-48,* the TAF acts behind the axis of rotation, resulting in an overall drag force. The driven region produces some lift, but that lift is offset by drag. The overall result is a deceleration in the rotation of the blade. The size of this region varies with the blade pitch, rate of descent, and rotor rpm. When changing autorotative rpm blade pitch, or rate of descent, the size of the driven region in relation to the other regions also changes.

There are two points of equilibrium on the blade—one between the driven region and the driving region, and one between the driving region and the stall region. At points of equilibrium, TAF is aligned with the axis of rotation. Lift and drag are produced, but the total effect produces neither acceleration nor deceleration.

The driving region, or autorotative region, normally lies between 25 to 70 percent of the blade radius. Part C of *Figure 2-48* shows the driving region of the blade, which produces the forces needed to turn the blades during autorotation. Total aerodynamic force in the driving region is inclined slightly forward of the axis of rotation, producing a continual acceleration force. This inclination supplies thrust, which tends to accelerate the rotation of the blade. Driving region size varies with blade pitch setting, rate of descent, and rotor rpm.

By controlling the size of this region, a pilot can adjust autorotative rpm. For example, if the collective pitch is raised, the pitch angle increases in all regions. This causes the point of equilibrium to move inboard along the blade's span, thus increasing the size of the driven region. The stall region also becomes larger while the driving region becomes smaller. Reducing the size of the driving region causes the acceleration force of the driving region and rpm to decrease. A constant rotor rpm is achieved by adjusting the collective pitch so blade acceleration forces from the driving region are balanced with the deceleration forces from the driven and stall regions.

The inner 25 percent of the rotor blade is referred to as the stall region and operates above its maximum AOA (stall angle), causing drag, which tends to slow rotation of the blade. Part E of *Figure 2-48* depicts the stall region.

Autorotation (Forward Flight)

Autorotative force in forward flight is produced in exactly the same manner as when the helicopter is descending vertically in still air. However, because forward speed changes the inflow of air up through the rotor disk, all three regions move outboard along the blade span on the retreating side of the disk where AOA is larger. *[Figure 2-49]* With lower AOA on the advancing side blade, more of the blade falls in the driven region. On the retreating side, more of the blade is in the stall region. A small section near the root experiences a reversed flow; therefore, the size of the driven region on the retreating side is reduced.

Prior to landing from an autorotative descent (or autorotation), the pilot must flare the helicopter in order to decelerate. The pilot initiates the flare by applying aft cyclic. As the helicopter flares back, the airflow patterns change around the blades causing the rpm to increase. Pilots must adjust the collective as necessary to keep the rpm within operating limits.

Chapter Summary

This chapter introduced the basics of aerodynamic fundamentals and theory and how they relate to flying a helicopter. This chapter also explained how aerodynamics affect helicopter flight and how important it is for pilots to understand aerodynamic principles and be prepared to react to these effects. For additional information on aerodynamics, refer to the aerodynamics of flight portion of the Pilot's Handbook of Aeronautical Knowledge.

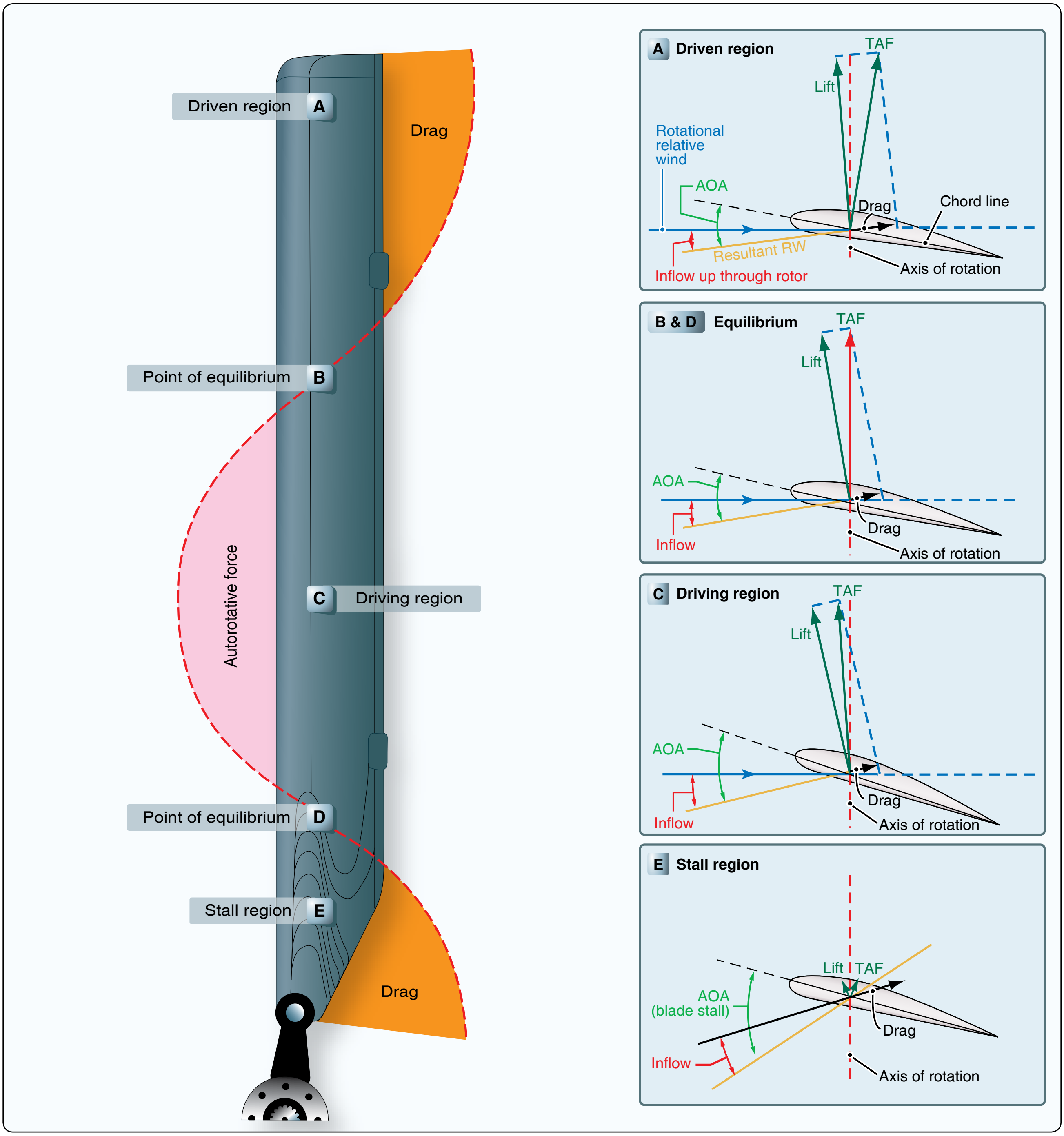

Figure 2-48. *Force vectors in vertical autorotation descent.*

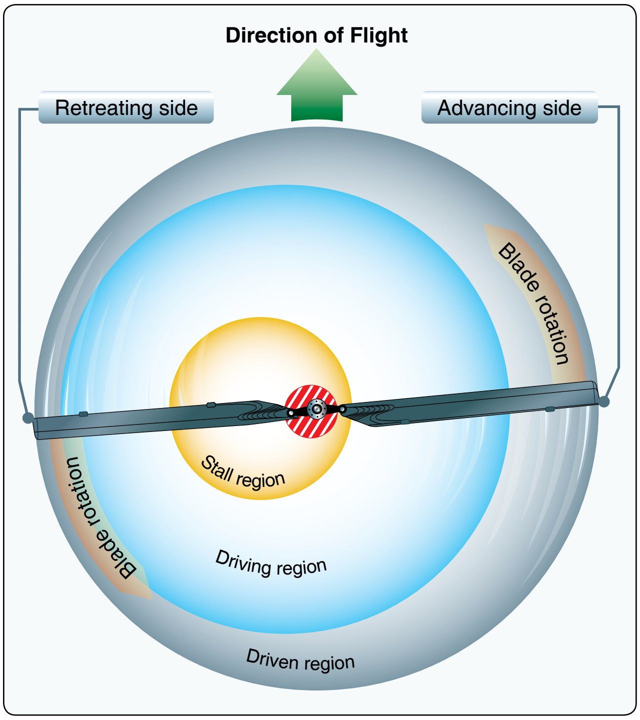

Figure 2-49. *Blade regions in forward autorotation descent.*