NAVAL AIR TRAINING COMMAND

NAS CORPUS CHRISTI, TEXAS **CNATRA P-401 (REV 09-00)**

INTRODUCTION TO HELICOPTER AERODYNAMICS WORKBOOK

AERODYNAMICS TRANSITION HELICOPTER

2000

DEPARTMENT OF THE NAVY
CHIEF OF NAVAL AIR TRAINING
NAVAL AIR STATION
CORPUS CHRISTI, TEXAS 78419-5100

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STUDENT WORKBOOK

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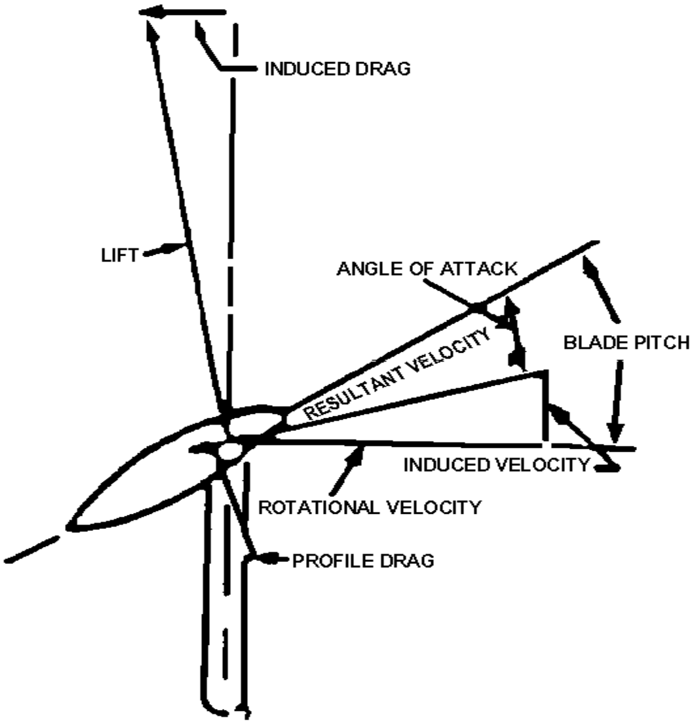

INTRODUCTION TO HELICOPTER AERODYNAMICS WORKBOOK

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CHAPTER FIVE - FLIGHT PHENOMENA

NAVAL AIR TRAINING COMMAND
ADVANCED PHASE

DISCIPLINE: **Aerodynamics**

COURSE TITLE: **Aerodynamics (Transition Helicopter)**

PREREQUISITES: **None**

TERMINAL OBJECTIVE

Upon completion of the course, "Aerodynamics, Transition Helicopter," the student will possess an understanding of aerodynamics as applied to helicopters, to include the effects of atmosphere. The student will demonstrate a functional knowledge of the material presented through successful completion of an end-of-course examination with a minimum score of 80%.

INSTRUCTIONAL MATERIAL

To implement this learning session, the instructor in charge must ensure that one copy of the NATOPS Flight Manual, Navy Model TH-57B/C Helicopter, NAVAIR 01-110-HCC-1, be available to each student.

When the material listed above has been assembled, the student will proceed in accordance with the following directions:

DIRECTIONS TO THE STUDENT

STEP 1	Complete each chapter of the course workbook text.
STEP 2	Take the review test for each chapter.
STEP 3	Attend aero review before exam.
STEP 4	Take the end-of-course examination. Remedial sessions prescribed if necessary.
STEP 5	End of this course of instruction.

AUDIOVISUAL

		Stock No.	Minutes
Chapter 1	Atmospheric Density and Helicopter Flight	4B88/5	19:30
Chapter 2	Rotor Blade Aerodynamics - Part 1	4B88/1-1	
	Rotor Blade Aerodynamics - Part 2	4B88/1-2	12:00
Chapter 3	Helicopter Powered Flight Analysis - Part 1	4B88/2-1	14:00
	Helicopter Powered Flight Analysis - Part 2	4B88/2-2	19:50
Chapter 4	Autorotational Flight	4B88/3	13:00

Chapter 5	Helicopter Flight Phenomena - Part 1	4B88/4-1	26:30
	Helicopter Flight Phenomena - Part 2	4B88/4-2	14:00
	Helicopter Flight Phenomena - Part 3	4B88/4-3	12:00

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CHAPTER ONE

THE ATMOSPHERE

TERMINAL OBJECTIVE

1.0 Upon completion of this chapter, the student will define density altitude, the factors affecting it, and the effect density altitude has on aircraft performance.

ENABLING OBJECTIVES

1.1 Recall the main gases of the air.

1.2 Recall the effect of pressure, temperature, and humidity on the density of the air.

1.3 Define pressure altitude.

1.4 Define density altitude.
  1.4.1 Recall the effect of temperature and humidity on density altitude.
  1.4.2 Compute the density altitude using a density altitude chart.
  1.4.3 Compute the density altitude using the rule of thumb formula.
  1.4.4 Recall the relationship between helicopter performance and density altitude.

THE ATMOSPHERE

ATMOSPHERIC PROPERTIES

Helicopter aerodynamics is the branch of physics dealing with the forces and pressures exerted by air in motion. The atmosphere, the mass of air, which completely envelops the earth, is composed of varying and nonvarying constituents. The nonvarying constituents include oxygen (21%) and nitrogen (78%). The varying constituents include CO2, argon, hydrogen, helium, neon, krypton, and water vapor, which will vary from negligible amounts to approximately 4% by volume (100% relative humidity). Air is a fluid and is affected by changes in temperature, pressure, and humidity.

ATMOSPHERIC PRESSURE

Atmospheric pressure at any altitude is a result of the downward pressure exerted from the mass of air above that altitude. The air at the surface of the earth will be under a greater pressure than air further up a given column of air. **Pressure altitude** is defined as an altitude corresponding to a particular static air pressure in the standard atmosphere. The **standard atmosphere** corresponds to the temperature and pressure of the standard day (15° C, 29.92 or 10MB, 14.7 psi at sea level). Therefore, the pressure altitude of a given static air pressure corresponds to the actual altitude only in the rare case where atmospheric conditions between sea level and the aircraft's altimeter correspond exactly to that of the standard atmosphere.

ATMOSPHERIC DENSITY AND POWER REQUIRED

Atmospheric density is also greatest at the earth's surface and the atmosphere becomes less dense, or contains fewer molecules per unit volume, as distance from the earth's surface increases. Atmospheric density also decreases with an increase in temperature or humidity. Heated air expands, causing the air molecules to move farther apart, thus decreasing air density per unit volume. As relative humidity increases, water vapor molecules, which have a smaller molecular mass than oxygen and nitrogen molecules, displace some air molecules in a given volume, creating a decrease in density in a given volume.

Density altitude is the altitude in the standard atmosphere corresponding to a particular air density. It is pressure altitude corrected for temperature and humidity. Air density affects the aerodynamic forces on the rotor blades and the burning of fuel in the engine, affecting both power required and power available. For a given set of atmospheric conditions, the total power required to drive the rotor depends on three separate requirements, which have a common factor -- rotor drag. Each power requirement is considered separately, and will be discussed in greater depth in a later section.

1. **Rotor Profile Power (RPP)**. This is the power requirement to overcome friction drag of the blades. RPP assumes a constant minimum pitch angle and a constant coefficient of drag value. As density altitude increases and air density decreases, drag, and therefore RPP, will decrease. However, blade stall begins sooner, so more of the blade is in stall, increasing profile power.

2. **Induced power**. This is the power associated with producing rotor thrust and must be sufficient to overcome the induced drag which increases proportionally to thrust. In order to maintain rotor thrust as air density decreases, angle of attack (AOA) must be increased by increasing pitch on the rotor blades. The resulting increase in rotor drag requires an increase in induced power to maintain a constant N_r. Increased density altitude affects induced power significantly.

3. **Parasite power**. This is the power required to overcome the friction drag of all the aircraft components, rotor blades being the exception. Parasite drag is constant for a given IAS. As density altitude (DA) increases, TAS increases, and parasite drag will decrease slightly.

The combination of these ups and downs result in greater power required at a higher density altitude.

Power required, the amount of power necessary to maintain a constant rotor speed, is adversely affected by increased DA and decreased rotor efficiency. The pitch angle of the blades must be increased to increase the AOA during high DA conditions in order to generate the same amount of lift generated during low DA conditions. Increased pitch angle results from an increased collective setting, which demands more power from the engine.

DA also affects **power available**, or engine performance. Turbine engine performance will be adversely affected by an increase in DA. As DA increases, the compressor must increase rotational speed (N_g) to maintain the same mass flow of air to the combustion chamber; and the bottom line is, when maximum N_g is reached on a high DA day, there is a lower mass flow of air for combustion, and therefore (because of fuel metering) a lower fuel flow as well. Thus, with increased DA, power available from a gas turbine engine is reduced.

Since DA affects helicopter rotor and engine performance, it is a necessary consideration for safe preflight planning. It can be determined in two ways: deriving a value from NATOPS charts (figure 1-1) or a “rule of thumb” which can be used in the aircraft when no chart is available (see figure 1-2).

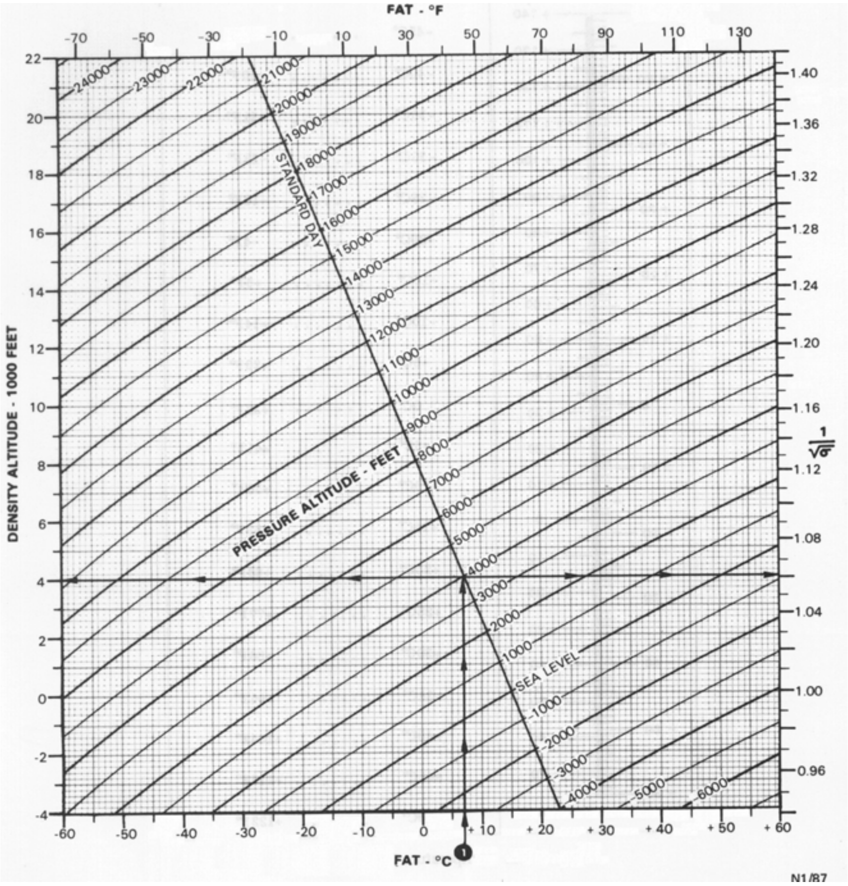


Figure 1-1
Density Altitude/Temperature Conversion Chart

Increase DA 100' for each 10% increase in relative humidity

$$[\text{OAT @ ALT } (^\circ\text{C.}) - \text{STAND TEMP @ ALT}] \times 120 \text{ ft.} + \frac{(\text{RH})}{10\%} \times 100 + \text{PA} = \text{DA}$$

STAND TEMP - 15° C. at sea level and cools 2° per 1000 ft.

RH - Relative Humidity
PA - Pressure Altitude

Example:

PA = 4000 ft.
RH = 70%
OAT = 17° C.

First find the standard temperature at altitude.

$$15^\circ - (4000 \times 2^\circ/1000 = 7^\circ\text{C.}$$

$$\text{DA} = [17^\circ\text{ C.} - 7^\circ\text{ C.}]\ 120 \text{ ft.} + \left(\frac{70\%}{10\%}\right) 100 + 4000$$

$$= 1200 \text{ ft.} + 700 \text{ ft.} + 4000 \text{ ft.}$$

$$= 5900 \text{ ft.}$$

Figure 1-2

CHAPTER ONE REVIEW QUESTIONS

1. Oxygen comprises approximately ________ percent of the earth's atmosphere.

2. Air density changes in direct proportion to ____________ and inverse proportion to____________, ____________, and ____________.

3. Compared to dry air, the density of air at 100% humidity is

   a. 4% more dense.
   b. about the same.
   c. decreased 1 percent per 1000'.
   d. less dense.

4. The altitude of a given static air pressure in the standard atmosphere is_______________.

5. Density altitude is pressure altitude corrected for _______________ and _______________.

6. When relative humidity is 50%, the moist air is half as dense as dry air. ____(True/False)

7. As temperature increases above standard day conditions, density altitude increases/decreases and air density increases/decreases.

8. Using the Density Altitude Chart on page 1-4, find the density altitude for a pressure altitude of 3500', temperature of 240C, and relative humidity of 50%. ______________

9. Using the rule of thumb formula, calculate the density altitude for a pressure altitude of 6000', temperature of 170C, and relative humidity of 50%. __________________________

10. An increase in humidity increases/decreases density altitude, which increases/decreases rotor efficiency.

11. State the effects that increased density altitude has on power available and power required. ____

CHAPTER ONE REVIEW ANSWERS

1. 21
2. pressure . . . altitude . . . temperature . . . humidity
3. d
4. pressure altitude
5. temperature . . . humidity
6. false
7. increases . . . decreases
8. 5900'
9. 8180'
10. increases . . . decreases
11. Power available decreases and power required increases.

CHAPTER TWO

TERMINAL OBJECTIVE

2.0 Upon completion of this chapter, the student will be able to construct a blade element diagram, defining each of its components, and state their interrelationships. The student will be able to identify the forces acting on the rotor system and their effects on the system.

ENABLING OBJECTIVES

2.1 Draw a blade element diagram.

2.1.1 Define the following terms: Airfoil, chord line, tip-path-plane, aerodynamic center, rotor disk, pitch angle, linear flow, induced flow, angle of attack, lift, induced drag, profile drag, thrust, and in-plane drag.

2.1.2 State the relationships between induced flow, linear flow, and relative wind; between relative wind and angle of attack; between pitch angle and angle of attack.

2.2 Differentiate between and characterize the symmetrical and nonsymmetrical airfoils.

2.3 Define geometric twist and state why it is used in helicopter design.

2.4 Define flapping.

2.5 Define geometric imbalance.

2.5.1 State how geometric imbalance affects horizontal blade movement (lead/lag).

2.6 Differentiate between and characterize the three types of rotor systems in use today.

2.6.1 State the method by which flapping is accomplished in each system.

2.6.2 State the method by which geometric imbalance is compensated for or eliminated in each system.

ROTOR BLADE AERODYNAMICS

DEFINITIONS

To begin our discussion of rotary wing aerodynamics, we will start with a few basic definitions using figure 2-1 as a reference. A chord line is the line connecting the leading edge of the blade to the tip of the trailing edge. The chord is defined as the distance between these two points. The camber line is the line halfway between the upper and lower surface, camber being the distance between camber line and chord line (figure 2-2). The tip-path-plane (TPP) is defined as the plane of rotation of the rotor blade tips as the blades rotate (figure 2-3). The area of the circle bounded in the TPP is the rotor disk, which is very apparent from an overhead view.

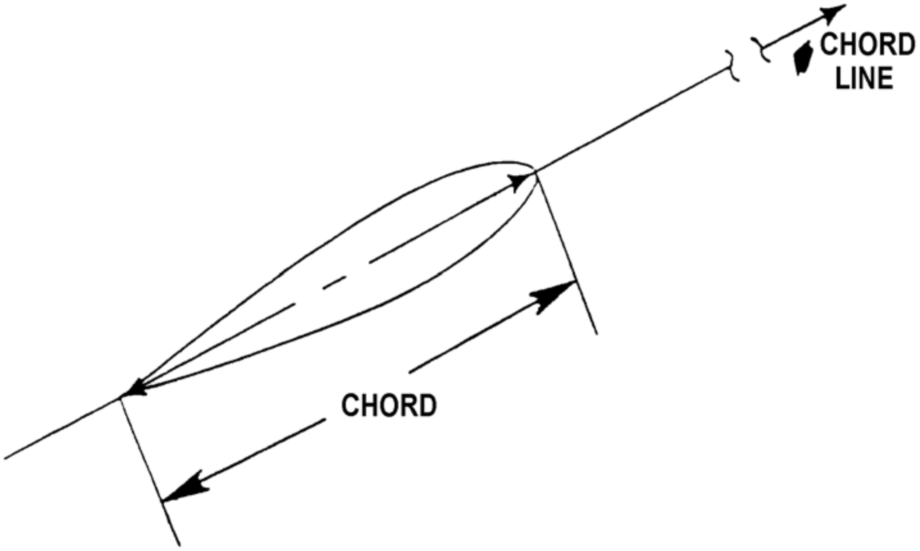


Figure 2-1 Chord

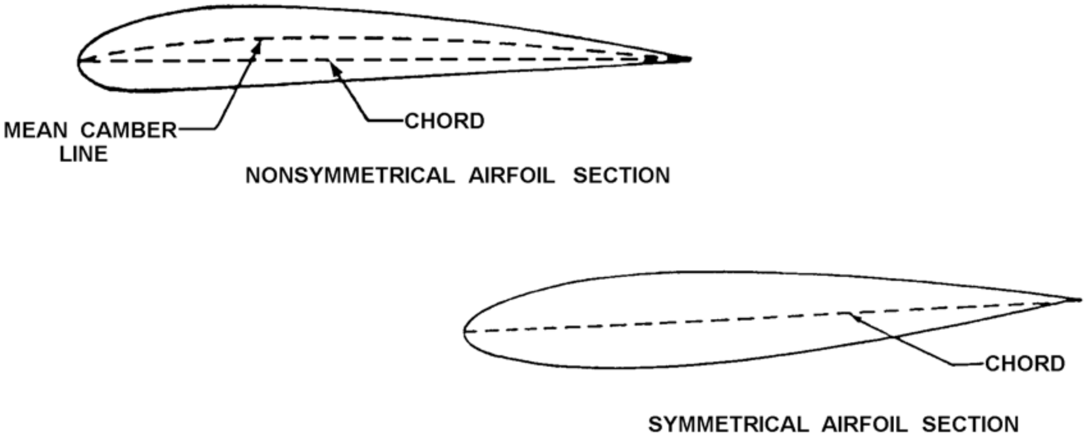


Figure 2-2 Camber

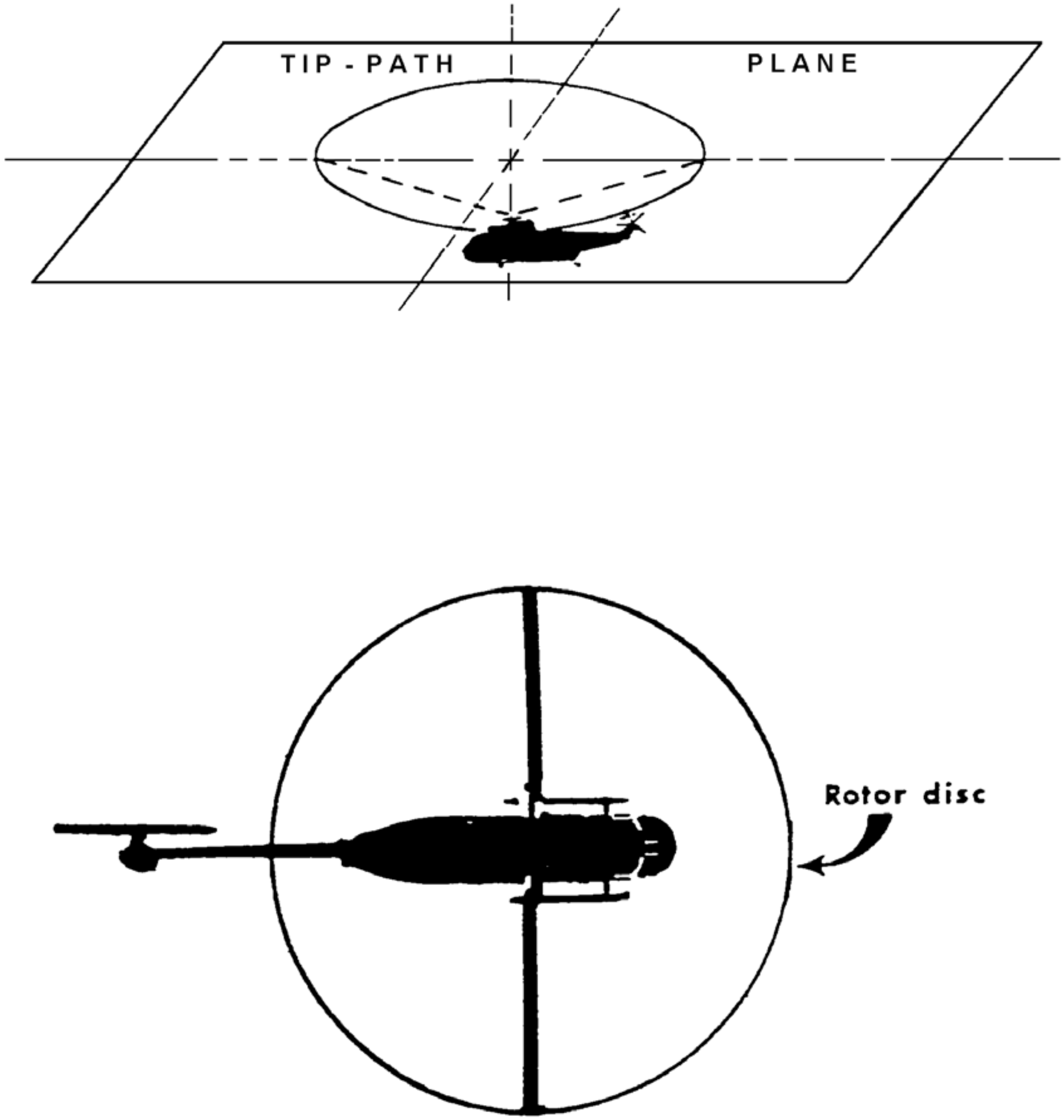


Figure 2-3

As the rotor blades rotate about the axis, a horizontal flow of air opposite the direction of blade travel is produced. This is called rotational flow, or linear flow. Rotational flow is parallel to the TPP, and at constant RPM in a no-wind hover, the speed of rotational flow is directly proportional to the distance from the hub, increasing with increasing distance from the hub (figure 2-4).

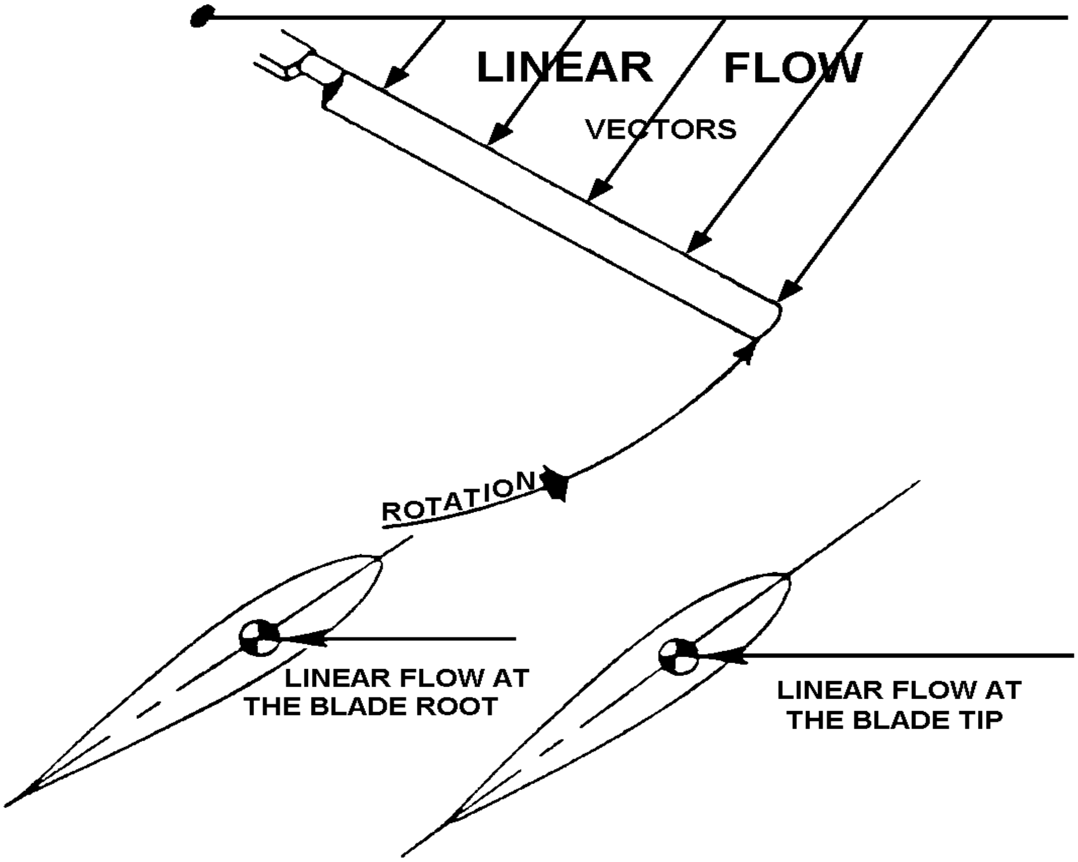


Figure 2-4

THEORIES OF HELICOPTER FLIGHT

Helicopter aerodynamicists support two theories of helicopter flight: The Momentum Theory and the Blade Element Theory.

Newton's observation, which states that for every action there is an equal and opposite reaction, is the basis of the Momentum Theory. For a helicopter to remain suspended in a no-wind hover, production of upward rotor thrust is the action, and downward velocity in the rotor wake is the reaction. Rotor thrust is the total aerodynamic force produced in the rotor system, which is used to overcome the weight of the helicopter to achieve flight. Another observation of Newton states a force is equal to acceleration times mass. For a helicopter in a steady-state no-wind hover, force = rotor thrust, acceleration is the change in velocity of the air well above the rotor disk to the speed of the air below the rotor disk, and the mass = the amount of air flowing through the rotor disk per second (figure 2-5).

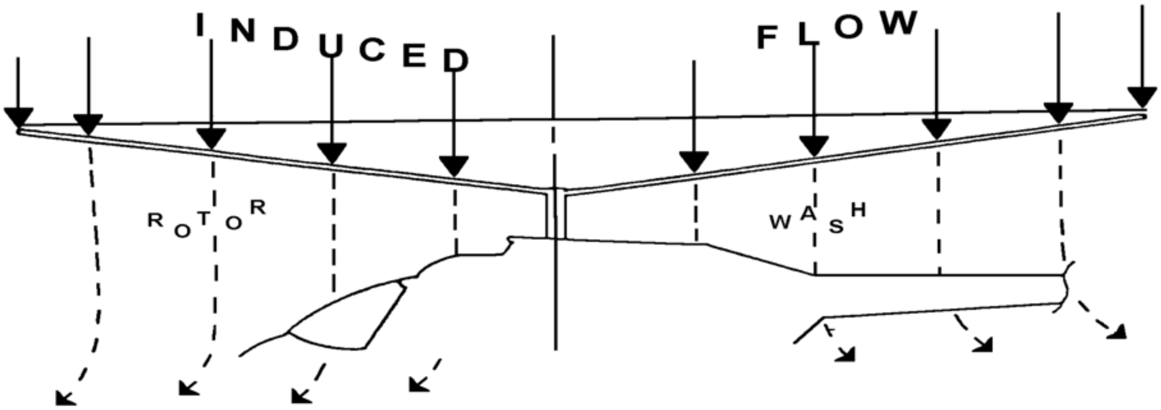


Figure 2-5

The Momentum Theory adequately provides an explanation for no-wind, hovering flight, but it does not cover all of the bases.

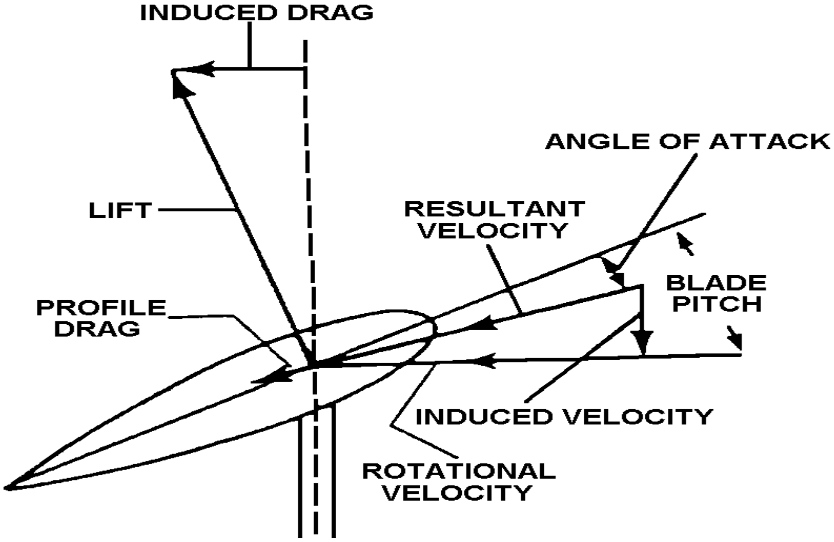


Figure 2-6

The Blade Element Theory picks up where the Momentum Theory leaves off. The conditions at the blade element are diagramed in figure 2-6. The blade “sees” a combination of rotational flow and downward induced flow (figure 2-7) called relative wind, a downward pointing velocity vector. The AOA is the angle formed between the relative wind and the chord line, and the pitch angle is formed between the TPP and the chord line. Lift, which is the total aerodynamic force perpendicular to the local vector velocity, or relative wind, is tilted aft. This rearward component generated by lift is induced drag, formed from the acceleration of a mass of air (downwash) and the energy spent in the creation of trailing vortices. The remaining arrow labeled profile drag is the result of air friction acting on the blade element. Profile drag is made up of viscous drag (skin friction) and wake drag, which is the drag produced from the low velocity/low static pressure air formed in the wake of each blade.

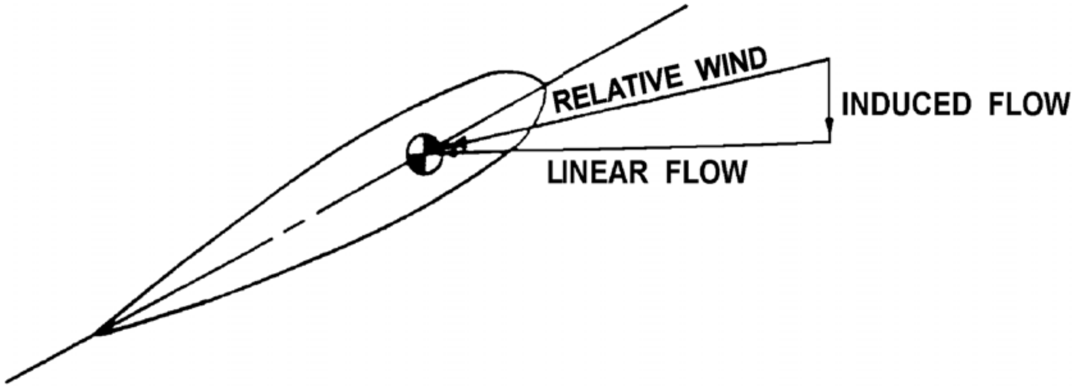


Figure 2-7

AIRFOILS

Airfoils fall into two categories: symmetrical and nonsymmetrical. A symmetrical airfoil has identical size and shape on both sides of the chord line, while a nonsymmetrical airfoil has a different shape and size on opposite sides of the chord line. Cambered airfoils are in the nonsymmetrical category (figure 2-2).

PITCHING MOMENTS

Now let us investigate the different aerodynamic characteristics of these airfoils regarding the aerodynamic center and center of pressure of each type. The aerodynamic center is the point along the chord where all changes in lift effectively take place and where the sum of the moments is constant. The sum of the moments is constant for any AOA. On a symmetrical blade, the moment is zero. The center of pressure is the point along the chord where the distributed lift is effectively concentrated and the sum of the moment is zero. On symmetrical airfoils, it is co-located with the aerodynamic center. On cambered airfoils, the center of pressure moves forward as AOA increases. The center of pressure of the upper and lower surfaces of a symmetrical airfoil act directly opposite each other. The aerodynamic center and center of pressure are co-located; therefore, no moment is produced even though the total lift force changes with change in AOA (figures 2-8 and 2-9).

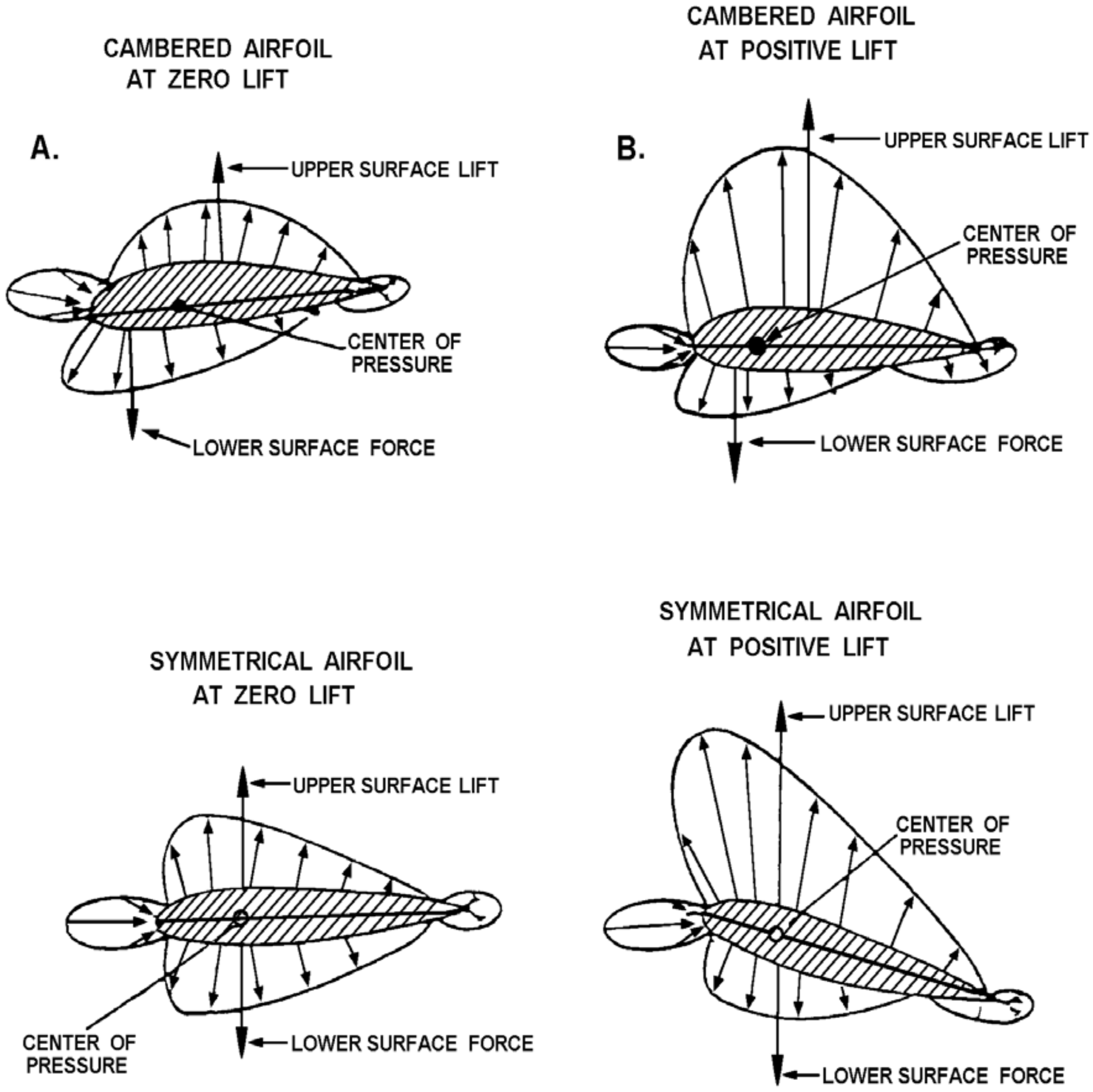

CAMBERED AIRFOIL AT ZERO LIFT
A.
UPPER SURFACE LIFT
CENTER OF PRESSURE
LOWER SURFACE FORCE
CAMBERED AIRFOIL AT POSITIVE LIFT
B.
UPPER SURFACE LIFT
CENTER OF PRESSURE
LOWER SURFACE FORCE
SYMMETRICAL AIRFOIL AT ZERO LIFT
UPPER SURFACE LIFT
CENTER OF PRESSURE
LOWER SURFACE FORCE
SYMMETRICAL AIRFOIL AT POSITIVE LIFT
UPPER SURFACE LIFT
CENTER OF PRESSURE
LOWER SURFACE FORCE

Figure 2-8

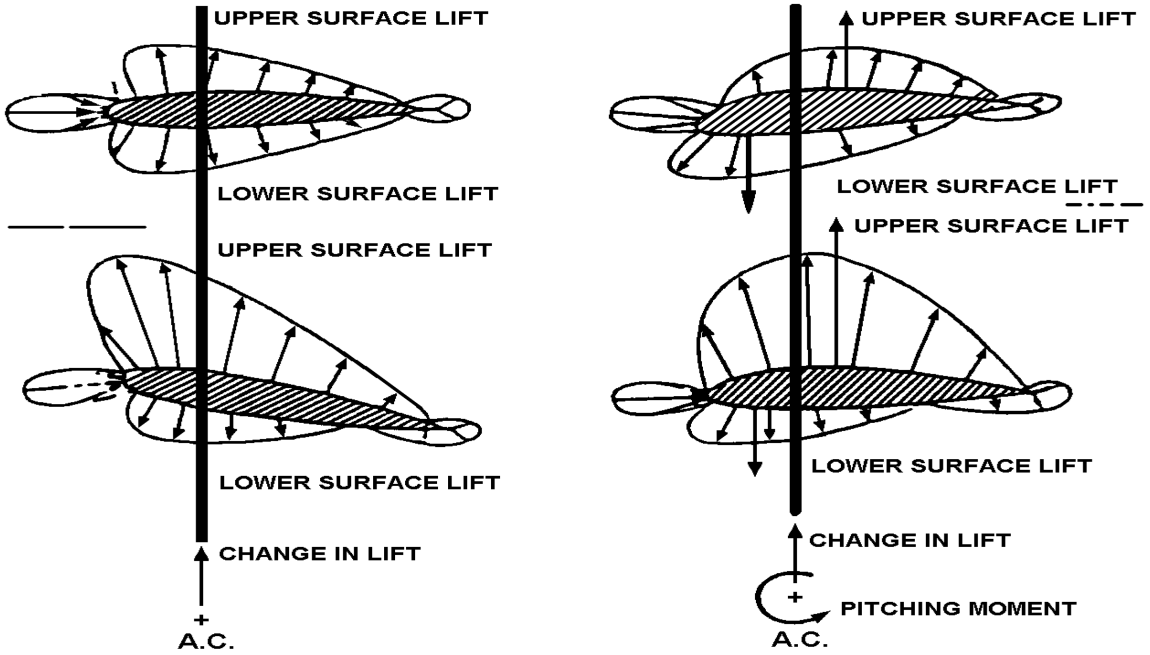


Figure 2-9

On nonsymmetrical airfoils, the center of pressure of upper and lower surfaces do not act directly opposite each other, and a pitching moment is produced. As the AOA changes, the location of the distributed pressures on the airfoil also changes. The net center of pressure (sum of upper and lower) moves forward as AOA increases and aft as AOA decreases, producing pitching moments. This characteristic makes the center of pressure difficult to use in aerodynamic analysis. Since the moment produced about the aerodynamic center remains constant for pre-stall AOA, it is used to analyze airfoil performance with lift and drag coefficients.

Pitching moments are an important consideration for airfoil selection. Torsional loads are created on the blades of positively cambered airfoils due to the nose down pitching moment produced during increased AOA. These torsional loads must be absorbed by the blades and flight control components, and initially this resulted in structural blade failure and excessive nose-down pitching at high speeds. Early helicopter engineers consequently chose symmetrical airfoils for initial designs, but have since developed cambered blades and components with high load-bearing capacity and fatigue life.

For the TH-57, rotor blade designers combined the most desirable characteristics of symmetrical and nonsymmetrical blades, resulting in the “droop-snoot” design (figure 2-10). This incorporates a symmetrical blade and a nonsymmetrical "nose" by simply lowering the nose of the blade. The resulting blade performance characteristics include low pitching moments and high stall AOA the retreating blade. The significance of this second characteristic will be covered in chapter 3.

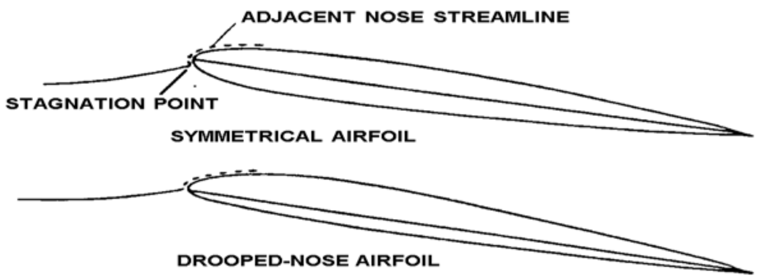


Figure 2-10

GEOMETRIC TWIST

Geometric twist is a blade design characteristic which improves helicopter performance by making lift (and induced velocity) distribution along the blade more uniform. Consider an untwisted blade. With rotational velocity being much greater at the tip than at the root, it follows that AOA and lift will also be much greater at the tip. A blade with geometric twist has greater pitch at the root than at the tip. A progressive reduction in AOA from root to tip corresponding to an increase in rotational speed creates a balance of lift throughout the rotor disk. It also delays the onset of retreating blade stall at high forward speed, due to reduced AOA. A high twist of 20 to 30 degrees is optimum for a hover, but creates severe vibrations at high speeds. No twist or low twist angles reduces the vibration at high speed, but creates inefficient hover performance. Blade designers generally use blade twist angles of 6-12 degrees as a compromise (figure 2-11).

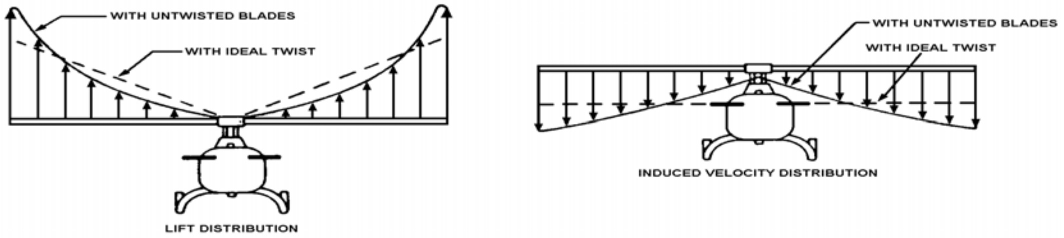


Figure 2-11

FLAPPING

In order to maneuver the helicopter the rotor disk must be tilted. The rotor blades therefore must be allowed some vertical movement. Vertical blade movement is termed flapping. Flapping occurs for other reasons as well, which will be discussed later.

LEAD AND LAG

Rotor blades also tend to move in the horizontal plane. The reason for this is angular momentum. Physics tells us angular momentum must be conserved ($MVR^2=C$). This concept is well illustrated by a spinning ice skater who increases his/her spin rate by pulling the arms toward his/her body (figure 2-12). The same sort of thing occurs while the rotors are turning. As the blade flaps its center of mass moves with respect to the center of rotation. When the blade's center of mass is closer to the center of rotation it will tend to lead (move faster). If the blade's center of mass is farther away, it will tend to lag (move slower). Geometric imbalance occurs when rotor blade centers of mass are not equidistant from the center of rotation.

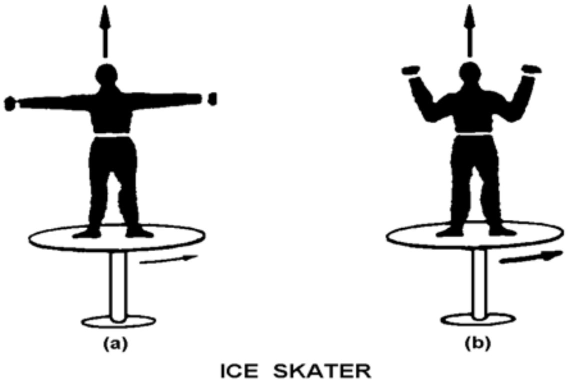


Figure 2-12

ROTOR SYSTEMS

Rotor blades generally work best as a team, the three combinations you are most likely to encounter are the semi-rigid, fully articulated, and rigid rotor systems, all of which allow for flapping and compensate for geometric imbalance. These systems allow for pilot control of the rotor blades through use of the cyclic and collective controls (figure 2-13).

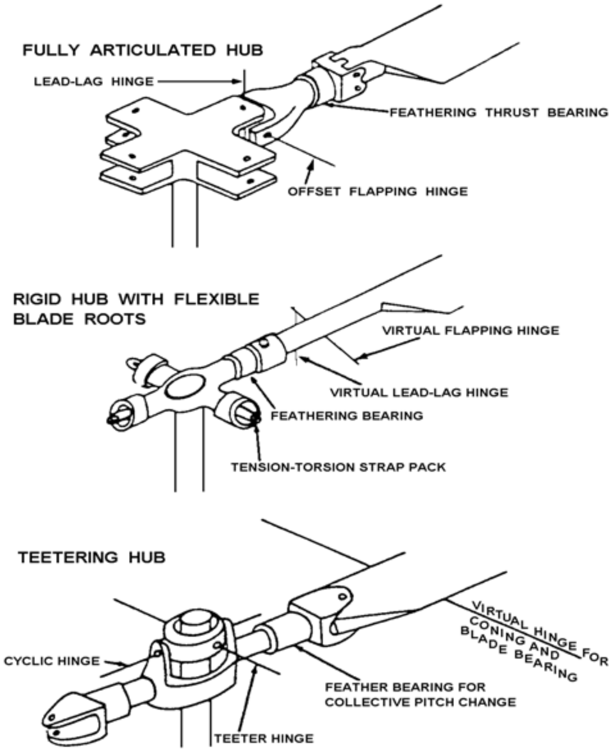


Figure 2-13

The fully articulated rotor system incorporates more than two blades. Lead/lag is possible by use of vertical hinge pins. Horizontal hinge pins allow for flapping. The movement of each blade is independent of the other blades and independent in respect to the rotor head.

The term rigid as applied to rotor systems is generally misleading due to the considerable flexibility in the systems. "Hingeless" may be a better description in most cases. The hub itself bends and twists in order to provide for flapping, lead-lag, and pitch control.

The semi-rigid rotor system uses two rotor blades and incorporates a horizontal hinge pin only for flapping. Pitch change movement is also allowed. We will spend most of our time investigating this system since it is the type you will become most intimately familiar with first.

Semi-rigid rotor systems are attractive due to their simplicity. They are limited to two blades, have fewer parts to maintain, and do not use lead-lag hinges. So how does the semi-rigid system compensate for geometric imbalance? Remember, the semi-rigid system uses underslinging. This underslung mounting is designed to align the blade's center of mass with a common flapping hinge (figure 2-14) so that both blades' centers of mass vary equally in distance from the center of rotation during flapping. The rotational speed of the system will tend to change, but this is restrained by the inertia of the engine and flexibility of the drive system. Only a moderate amount of stiffening at the blade root is necessary to handle this restriction. Simply put, underslinging effectively eliminates geometric imbalance.

Figure 2-14

CHAPTER TWO REVIEW QUESTIONS

1. Draw and label a blade element diagram for powered flight.

2. Angle of attack is found between the chord line and the__________________.

3. The _______________________ is defined by the plane described by the rotating tips of the rotor blades.

4. The vertical flow of air through the rotor system is_______________________.

5. In powered flight, increased rotational flow with constant induced flow shifts the relative wind vector toward the____________________.

6. In powered flight, as relative wind shifts toward the horizontal plane, the angle of attack __________________.

7. Changes in the pitch angle directly/inversely affect angle of attack.

8. _______________________drag is created as a result of the production of lift.

9. Regardless of angle of attack, the upper surface lift and lower surface lift of a symmetrical airfoil will act _______________ each other, and a twisting force on the blade is/is not present.

10. Pitching moments are characteristic of the __________________ airfoil.

11. The type of rotor system which is limited to two rotor blades is the ____________________.

12. The _______________________ rotor system does not incorporate mechanical hinges for flapping or lead/lag motion.

13. A vertical hinge pin is provided for lead/lag in the _______________________ rotor system.

14. Unequal radii of rotor blade centers of mass cause_________________________________.

15. Compensation for lead/lag motion in the semi-rigid rotor system is accomplished by blade __________________.

16. _______________________compensates for increased rotational velocity from blade root to tip by increasing/decreasing blade pitch from root to tip.

CHAPTER TWO REVIEW ANSWERS

1. See figure 2-6.
2. relative wind
3. tip-path-plane
4. induced flow
5. tip-path-plane or horizontal plane
6. increases
7. directly
8. induced
9. opposite . . . is not
10. nonsymmetrical
11. semi-rigid
12. rigid
13. fully-articulated
14. geometric imbalance
15. underslinging
16. geometric twist . . . decreasing

CHAPTER THREE

TERMINAL OBJECTIVE

3.0 Upon completion of this chapter, the student will be able to describe and analyze the aerodynamics of powered rotary wing flight.

ENABLING OBJECTIVES

3.1 Draw and label a power required/power available chart and a fuel flow versus airspeed chart.

3.1.1 Identify maximum endurance/loiter airspeed.

3.1.2 Identify maximum rate of climb airspeed.

3.1.3 Identify the best range airspeed and state the effects of wind components on best range airspeed.

3.2 Define torque effect.

3.2.1 State the means by which we counteract torque.

3.2.2 State the means by which we control the helicopter about the vertical axis.

3.2.3 State the means by which a multi-headed aircraft counteracts torque.

3.3 State the effect the tail rotor will have on power available to the main rotor.

3.4 State the two means by which tail rotor loading is reduced in forward flight.

3.5 State one problem created by use of a tail rotor system to counteract torque.

3.6 Define virtual axis, mechanical axis and center of gravity.

3.6.1 State the relationship between center of gravity, mechanical axis and virtual axis.

3.7 List the forces acting on the main rotor head.

3.7.1 Define centrifugal and aerodynamic force.

3.7.2 Define coning.

3.8 Interpret how a vortex is formed and how it affects the efficiency of the rotor system.

3.9 State the effect the main rotor vortices have on the tail rotor at low airspeeds.

3.10 Define ground effect by stating what causes it.

3.10.1 State how ground effect affects power required.

3.11 Define ground vortex and what causes it.

3.12 Define translational lift by stating the phenomena which cause it.

3.12.1 State how translational lift affects power required.

3.13 State the effect of dissymmetry of lift on the helicopter.

3.13.1 State the methods by which dissymmetry of lift is overcome.

3.14 State the effect of phase lag on helicopter control.

3.15 Define blowback by stating the cause.

3.15.1 Describe the effect blowback has on helicopter attitude and airspeed.

3.16 Identify fore and aft asymmetry of lift by stating its cause and how it affects helicopter flight.

POWER REQUIRED

Now, we've discussed how rotor blades and rotor systems work, let's investigate how they work with a helicopter fuselage and all of the forces that come into play. For a helicopter to remain in steady, level flight, these forces and moments must balance. These forces (figure 3-1) exist in the vertical plane, horizontal plane, and about the center of gravity in the form of pitching moments.

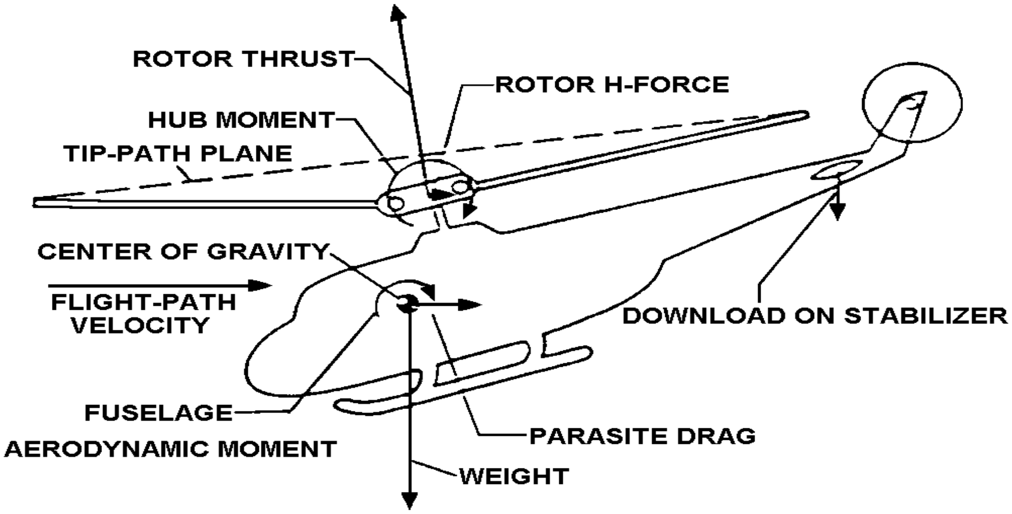


Figure 3-1

To begin the discussion of these forces, we will discuss the power required which produces these forces (figure 3-2).

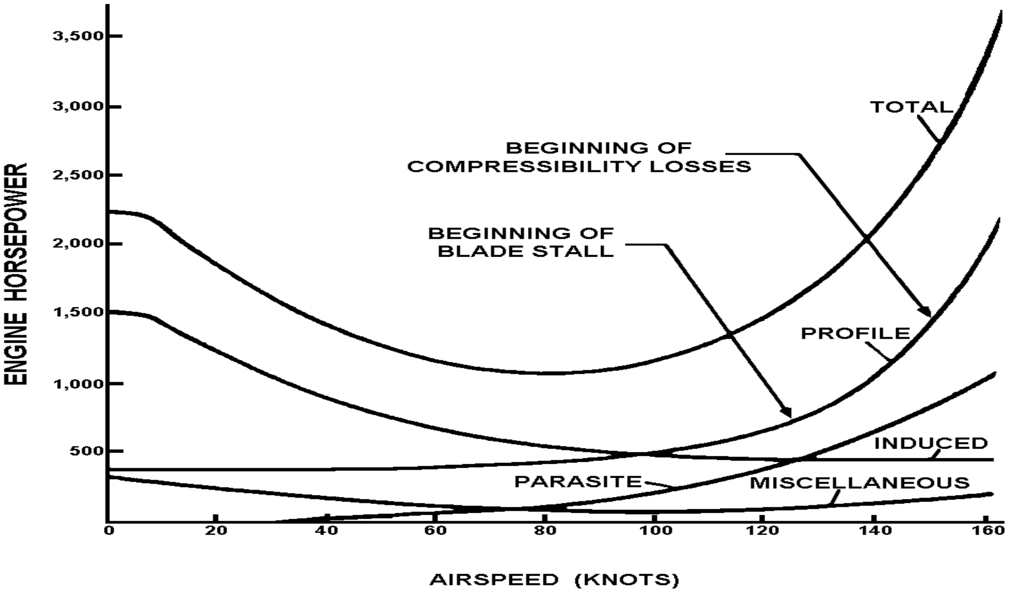


Figure 3-2

How much power does it take? In a hover, two types are necessary - induced and profile power. **Induced power**, which can be thought of as "pumping power," is power associated with the production of rotor thrust. This value is at its highest during a hover (60 - 85% of total main rotor power) and decreases rapidly as the helicopter accelerates into forward flight. The increase in mass flow of air introduced to the rotor system reduces the amount of work the rotors must produce to maintain a constant thrust. (This concept will be explained in greater detail in a later section). Therefore, induced power decreases to ¼ hover power with an increase to maximum forward speed.

Profile power, which can be thought of as "main rotor turning power," accounts for 15 - 45% of main rotor power in a hover and is used to overcome friction drag on the blades. It remains at a relatively constant level as the helicopter accelerates into forward flight due to the compensatory effect of the decrease in profile drag on the retreating blade and the increase in profile drag on the advancing blade.

In forward flight, **parasite power** joins forces with induced and profile power to overcome the parasite drag generated by all the aircraft components, excluding the rotor blades. Parasite power can be thought of as the power required to move the aircraft through the air. This power requirement increases in proportion to forward airspeed cubed. Obviously, this is inconsequential at low speed, but is significant at high speed and is an important consideration for helicopter designers to minimize drag. This is a challenging task due to design tradeoffs of the high weight and cost of aerodynamically efficient designs versus structural requirements dictated by required stiffness, mechanical travel, and loads.

The smaller horizontal force, H-force, is produced by the unbalanced profile and induced drag of the main rotor blades. Tilting the rotor disc forward from a fraction of a degree at low speed to about 10° at max speed compensates for this.

POWER REQUIRED AND POWER AVAILABLE

In the interest of better effectiveness and safety, different flight regimes are performed more efficiently at different forward speeds. The bowl-shape of the power required curve graphically illustrates the reason why (figure 3-3). Optimum speeds determined by this curve are maximum loiter time, minimum rate of descent in autorotation, best rate of climb, and maximum glide distance.

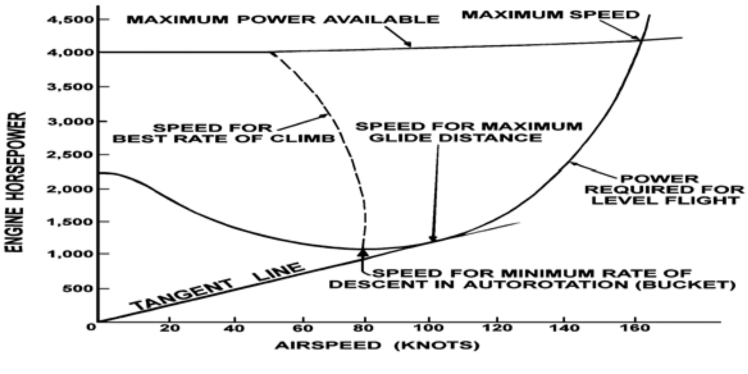


Figure 3-3

Best rate of climb airspeed is formed at the point where the difference is a maximum between power required and power available. This rate of speed can be estimated from the change in potential energy. The increase in mass flow from forward flight reduces climb power required as opposed to vertical flight. Induced power is already low in forward flight, so there is little to be gained from a significant increase in mass flow. Also, since a climbing condition produces a significant increase in parasite drag and tail rotor power requirements, excess engine power is concentrated toward those efforts instead of vertical flight.

At this speed, minimum rate of descent in an autorotation is also found, since the power required to keep the aircraft airborne is at a minimum. At this speed, the potential energy corresponding to height above the ground and gross weight can be dissipated at the slowest rate. Since the goal of achieving maximum loiter time is making the available fuel last as long as possible, and since fuel flow is proportional to engine power, maximum loiter time should also be at this point.

Stretching the glide distance in an autorotation is a totally separate situation. Maximum glide range is found at a point tangent to the power required curve on a line drawn from the origin. This gives the highest lift-to-drag ratio.

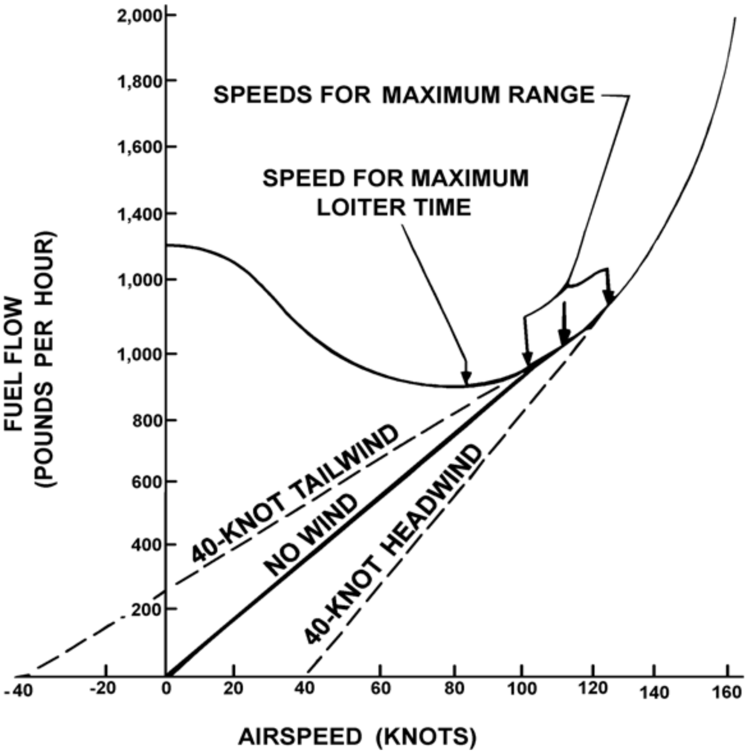


Figure 3-4

Maximum range speed is found on the fuel flow curve (figure 3-4) by drawing a line tangent to the curve from the origin. This ratio of speed to fuel flow shows the distance one can travel on a pound of fuel on a no-wind day. If there is a head wind, the line should be originated at the head wind value, which derives a higher speed and lower range. For a tail wind, the optimum airspeed decreases, but the range increases significantly.

TORQUE

The next major force we will discuss affecting the fuselage is torque. As the main rotor blades rotate, the fuselage will rotate the opposite direction if unopposed. An antitorque system is necessary to counteract this rotational force. This system must generate enough thrust to counteract main rotor torque in climbs, directional control at this high power setting, and sufficient directional control in autorotation and low speed flight. Available types are the conventional system, fenestron (fan-in-fin), and NOTAR (fan-in-boom). When a helicopter incorporates two main rotor systems, like the CH-46, rotating the systems in opposite directions, effectively equalizing the torque from each system, compensates for the torque effect. We will focus on the conventional system (figure 3-5).

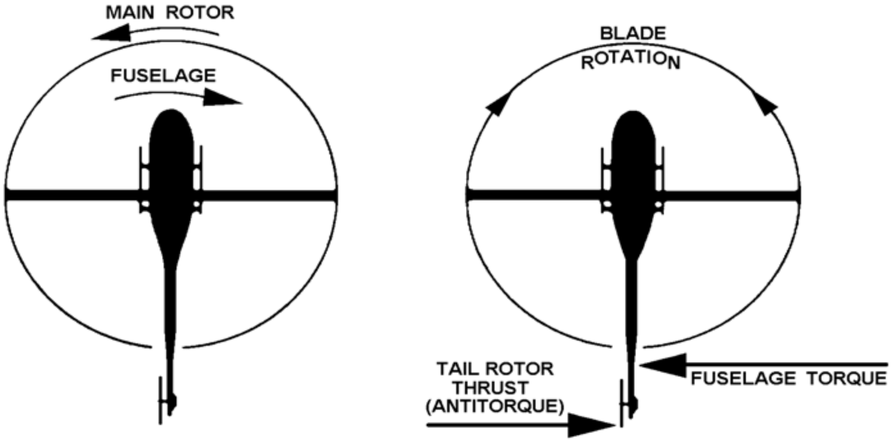


Figure 3-5

A conventional system requires little power, produces good yaw control, and works just like the main rotor system. Since the tail rotor is subject to the same drag forces, power is required to overcome these forces. Therefore, different pitch angles on the tail rotor blades require different power settings. As pitch angle is increased, power required will increase.

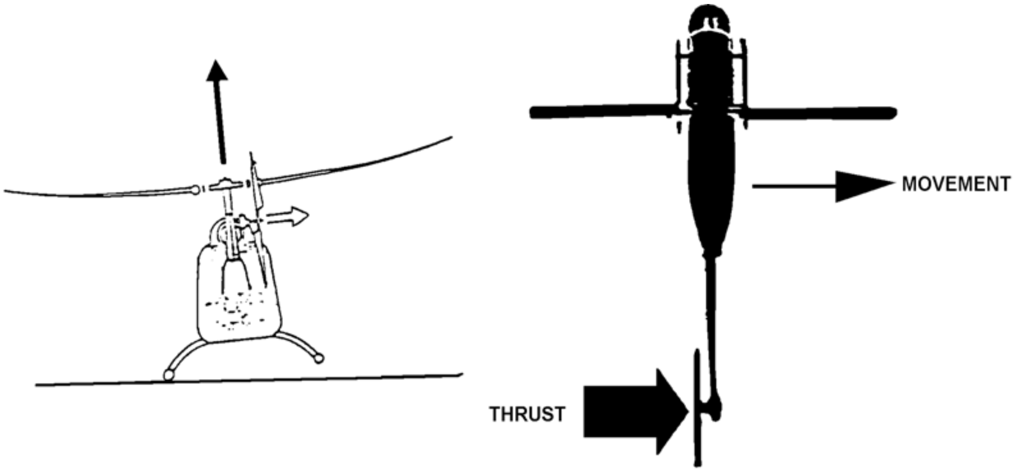


Figure 3-6

While the tail rotor system produces antitorque effect, it also produces thrust in the horizontal plane, causing the aircraft to drift right laterally in a hover (figure 3-6). Tilting the main rotor system to the left with the cyclic so that the aircraft can remain over a spot in a hover compensates for this. This causes the aircraft fuselage to tilt slightly to the left in a hover and touch down left skid first in a vertical landing.

In a no-wind hover, the tail rotor provides all of the antitorque compensation. As the aircraft moves into forward flight, the tail rotor is assisted in this compensatory effort by the weather-vaning effect and the vertical stabilizer. The increased parasitic drag produced on the longitudinal surface of the aircraft as the relative wind increases causes the aircraft to "steer" into the relative wind. This weather-vaning effect will increase proportionally with airspeed and provide minor assistance to the antitorque effect (figure 3-7).

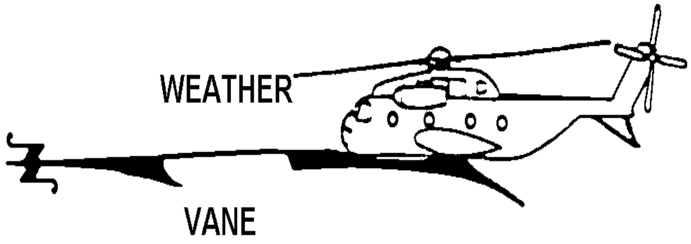


Figure 3-7

At higher speeds, tail rotor power requirements are significantly reduced by mounting a vertical stabilizer shaped like an airfoil, which produces lift opposite the direction of the torque effect. By reducing the power required on the tail rotor, more engine power is now available to drive the main rotor system (figure 3-8).

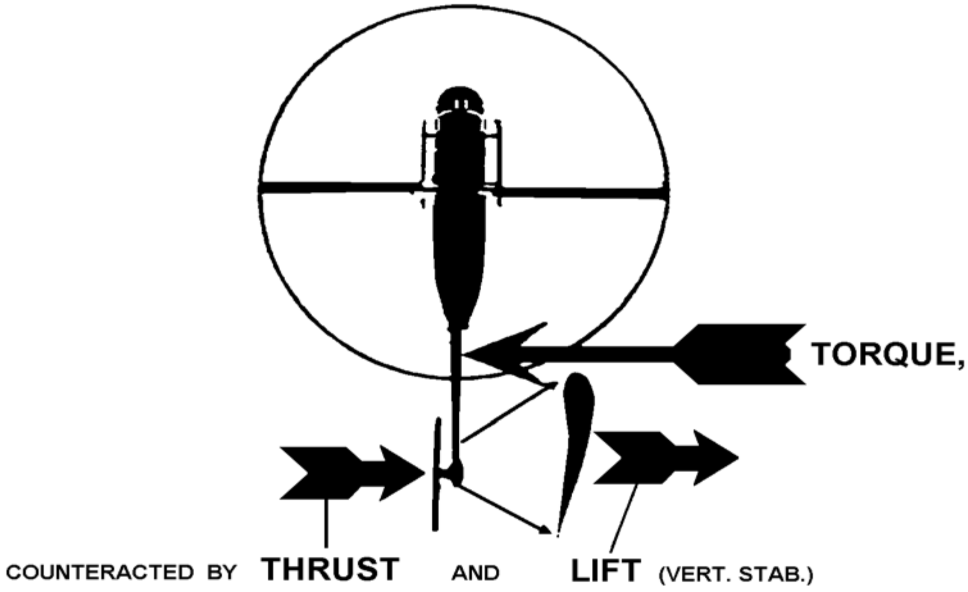


Figure 3-8

STABILITY AND CONTROL

From our discussion so far, it may seem that in a hover, all forces balance out, and once a stable position has been set (collective setting to produce enough power, cyclic position to maintain a position over the ground, and enough antitorque compensation to offset torque effect), no further control inputs are required to maintain a hover. It will become readily apparent as you embark on a mission to hover this is not the case. Helicopters are inherently unstable in a hover, response to control inputs are not immediate, and the rotor systems produce their own gusty air, all of which must be corrected for constantly by the pilot.

CENTER OF GRAVITY

Because the fuselage of the aircraft is suspended beneath the rotor system, it reacts to changes in attitude of the rotor disk like a pendulum. When the tip-path-plane shifts, the total aerodynamic force and virtual axis (the apparent axis of rotation) will shift, but the mechanical axis (the actual axis of rotation) and the center of gravity, which is ideally aligned with the mechanical axis, lag behind. As the center of gravity attempts to align itself with the virtual axis, the mechanical axis (which is rigidly connected to the fuselage) also shifts, and the aircraft accelerates (see figure 3-9).

In the case of high-speed forward flight, the nose of the aircraft would be low due to the tilt of the rotor disk and moment due to fuselage drag. To compensate for this, a cambered horizontal stabilizer is incorporated to provide a downward lifting force on the tail of the aircraft. Therefore, the aircraft fuselage maintains a near level attitude during cruise flight.

Figure 3-9

This misalignment of the axes is a principal cause of pilot instability during helicopter flight. Because the results of cyclic inputs are not manifested in instantaneous fuselage attitude changes, there is a tendency for pilots to initiate corrections with excessively large inputs. As the fuselage catches up with the tip-path-plane, the pilot realizes the gravity of his error and attempts to correct with an equal and opposite input, creating the same problem in another direction. Called "pilot-induced oscillation," this situation can be described as "getting behind the motion." Since this phenomenon is unpredictable and does not always occur, the best advice to a pilot in this situation is: relax for a second and let the aircraft settle down (figure 3-10).

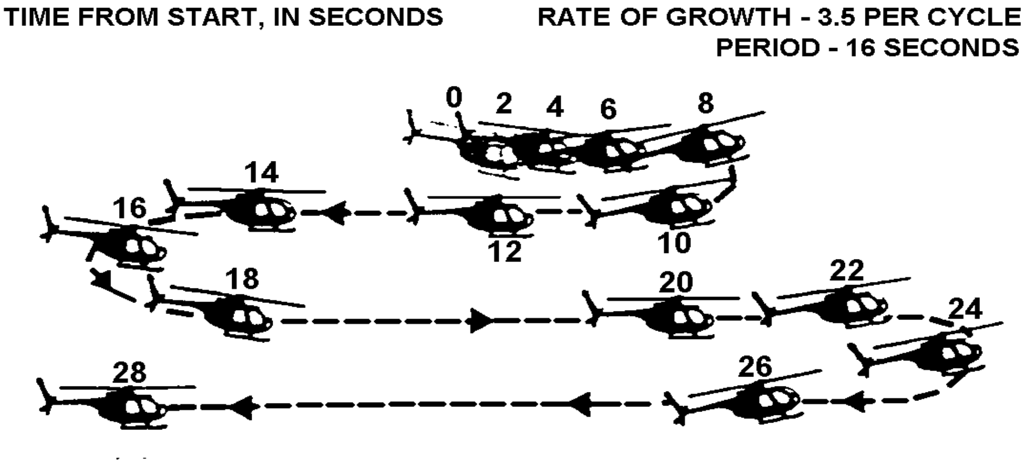


Figure 3-10

The center of gravity (CG) is considered the balancing point of a body for weight and balance purposes. The CG is determined by summing moments about a datum and dividing by the weight. In the case of the TH-57, the datum is defined as the nose of the helicopter, and the moment arms are measured in inches behind the nose of the aircraft. A moment is determined by multiplying the moment arm (inches) by the weight in that particular area (passengers, fuel, baggage, etc.). Once the moments are summed, the sum is divided by the total weight, and this quotient will be the arm of the CG behind the nose in inches.

When the CG is not aligned with the mechanical axis, the cyclic control must be sufficiently displaced to compensate the unbalanced CG condition. The helicopter fuselage will be tilted so that the heaviest end or side will be lower in a hover. Changing the CG of the aircraft will require the cyclic control to be repositioned. If cargo, fuel, or personnel are loaded or unloaded, the new CG will require compensating cyclic. An aft CG will require forward cyclic and forward CG will require aft cyclic. Corresponding movements would be required for lateral CG displacements. The limit of cyclic authority plays the most important role in determining the CG limits of a helicopter. However, full displacement of the cyclic does not define the limit; the limit must be maintained within the cyclic authority to ensure adequate control and a margin of safety.

If the safe CG limits are exceeded, the aircraft will enter uncontrollable flight. Full cyclic displacement will be unable to compensate for the extreme CG, and the aircraft will roll or pitch in the direction of the extreme CG, likely resulting in aircraft damage or destruction.

CONING

As the rotor blades turn, centrifugal force is created which pulls the blades outward from the hub. When lift (or aerodynamic force) is created and combines with centrifugal force coning occurs (see figure 3-11). Coning increases as lift increases.

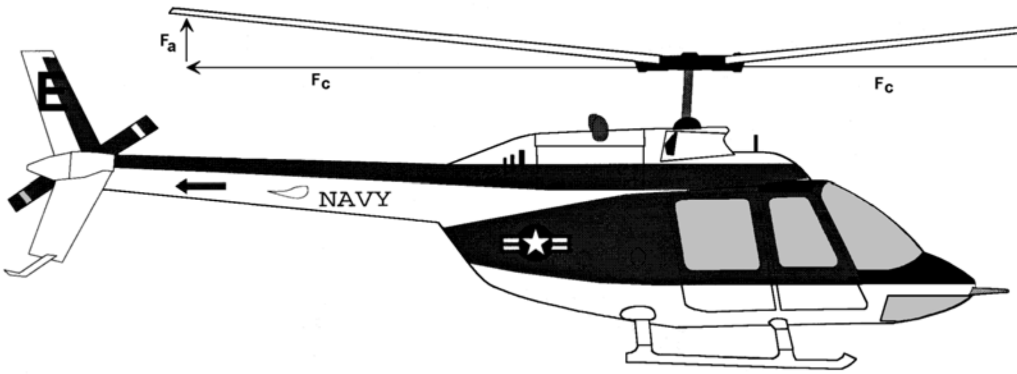


Figure 3-11

VORTICES

As the rotor blades rotate and lift is produced, high pressure is formed below the blade and low pressure above the blade. The sharp trailing edge of the blade keeps the high-pressure air from the low-pressure area on most of the blade, except for the tip, where nothing prevents the air from curling up from the bottom of the blade to the top. This air continues to spiral and drops off to form the trailing tip vortex. This vortex continues to spin, and the velocity drops off with increasing distance from the origin. In a hover, the vortices of one revolution impinge on the vortices of the following revolutions, causing an uneven path of the vortices, which eventually destroy each other. These tip vortices affect the induced velocity through the rotor system, and due to this impingement and resultant unsteadiness in the flow field, a rotor system in a hover creates its own gusty air, requiring the pilot to constantly correct to maintain a hover (figure 3-12).

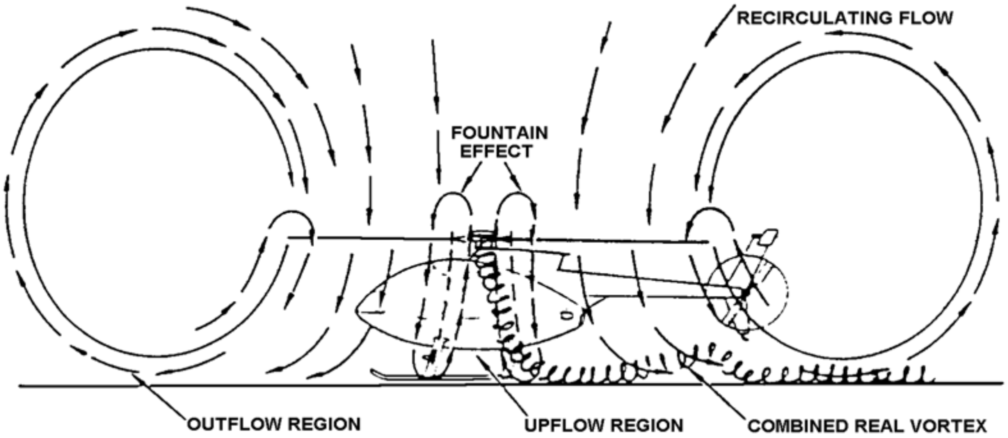
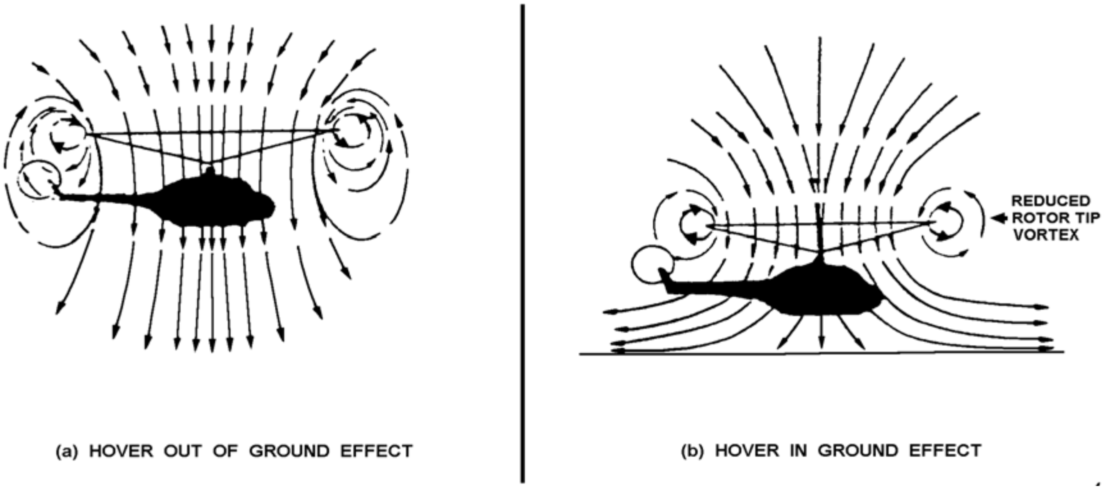


Figure 3-12

To balance the tip vortices, another vortex is formed at the blade root which writhes around erratically through and around the main rotor system. This root vortex has an equal and opposite effect on the tip vortex, which the pilot must correct. This usually manifests itself in heading changes as the root vortex impinges on the tail rotor and generally occurs when within one rotor diameter of the ground. Main rotor vortices can also affect the tail rotor during specific wind conditions which are covered in the TH-57 NATOPS Manual.

GROUND EFFECT

While the helicopter is in a hover and in other flight conditions close to the ground, it encounters ground effect (figure 3-13), a favorable aerodynamic phenomenon which requires less power. Less power is required because there is less induced drag to overcome while "in ground effect."



(a) HOVER OUT OF GROUND EFFECT

(b) HOVER IN GROUND EFFECT

Figure 3-13

Since all of the induced velocities are reduced in ground effect and the velocity of air which flows through the rotor system and reaches the ground goes to zero, induced drag is reduced and less engine power is required (figure 3-14). As the helicopter moves vertically from the ground to a distance out of ground effect (approximately one rotor diameter), the blades "see" a greater induced velocity because the flow of air in the wake below the rotors is unimpeded. Combined with rotational velocity, the resultant velocity is pointed slightly more downward, tilting the lift vector aft, increasing the induced drag and power required to hover. The power savings can amount to as much as 20%.

Figure 3-14

GROUND VORTEX

During transition to forward flight the pilot will encounter several phenomena exclusive to helicopter flight which, although encountered almost simultaneously, are discussed separately in the following sections. The first is ground vortex.

As the helicopter accelerates from a hover in ground effect to forward flight, benefits of ground effect can be lost at an altitude of less than ½ rotor diameter and airspeed between 5 and 20 knots. This is called ground vortex. As the helicopter moves forward, the rotor downwash mixes with increased relative wind to create a rotating vortex, which eventually causes an increased downwash through the rotor system. This simulates a climbing situation, increasing power required. Eventually this vortex is overrun at a higher speed. These flow patterns are better described in figure 3-15.

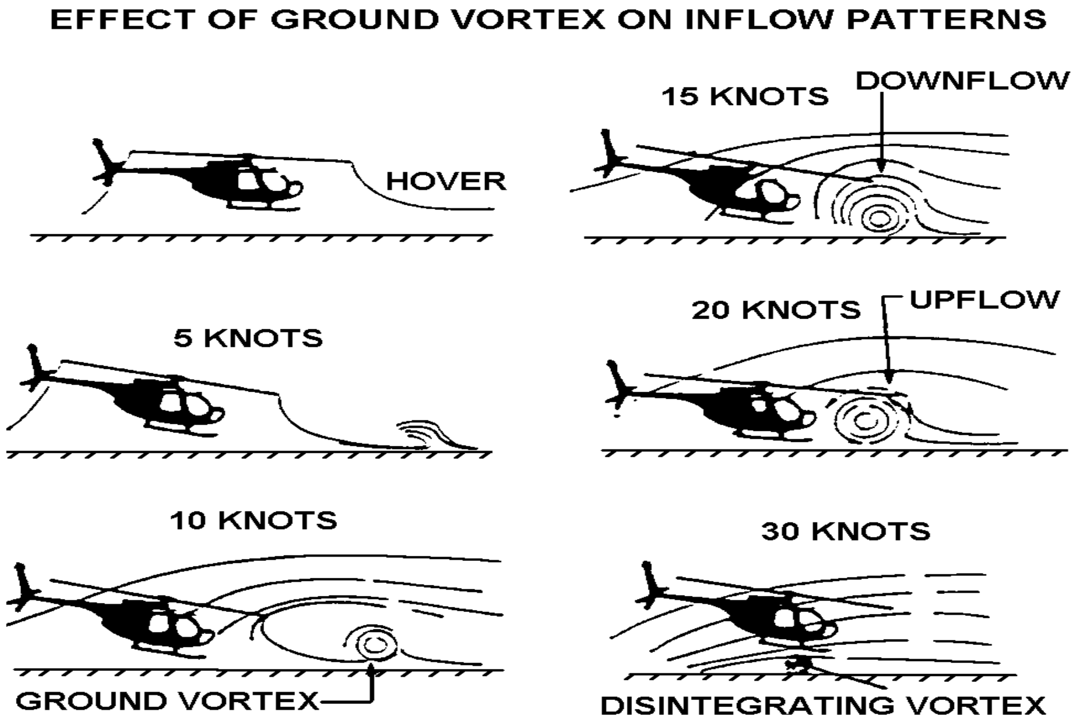


Figure 3-15

TRANSLATIONAL LIFT

About the same time ground vortex is overrun, the helicopter encounters another beneficial aerodynamic effect called translational lift. This phenomenon occurs due to a decrease in induced velocity. How is induced velocity reduced? Recall that during a hover we have a nearly vertical mass airflow through the rotor disk and the continuous recirculation of our own wingtip vortices, both of which contribute to a high induced flow (see figure 3-16). When transitioning to forward flight the rotor outruns this continuous recirculation of old wingtip vortices and begins to work in relatively undisturbed air. Moreover, the mass airflow through the rotors becomes more horizontal as airspeed increases (see figure 3-17). Both effects combine to cause a sharp decrease in induced flow, induced drag and, therefore, power required. Depending on wind conditions, the onset of translational lift and ground vortex may or may not be noticed or encountered during transition to forward flight.

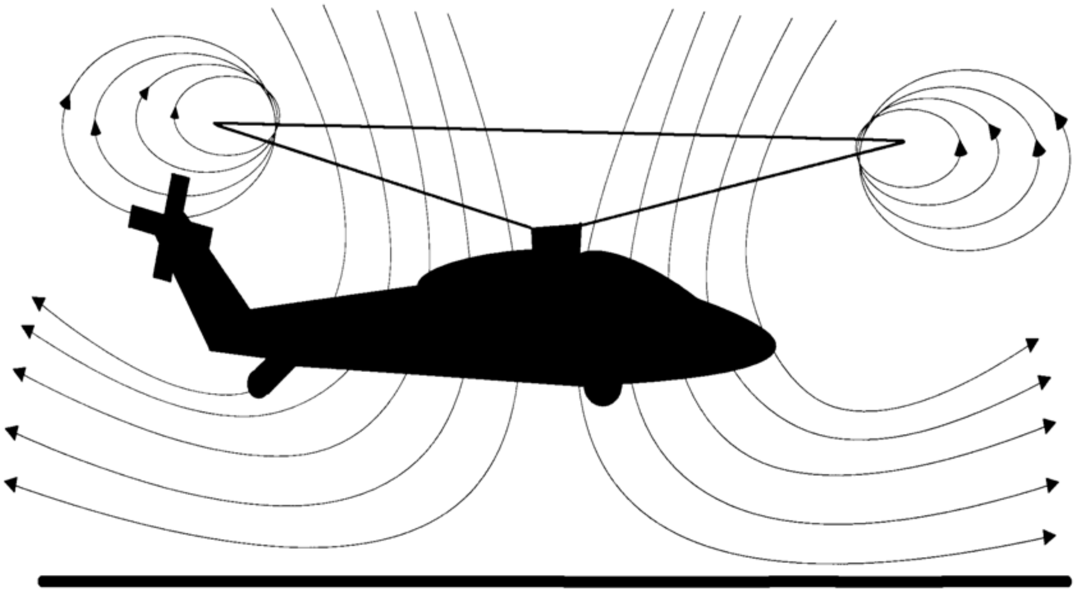


Figure 3-16

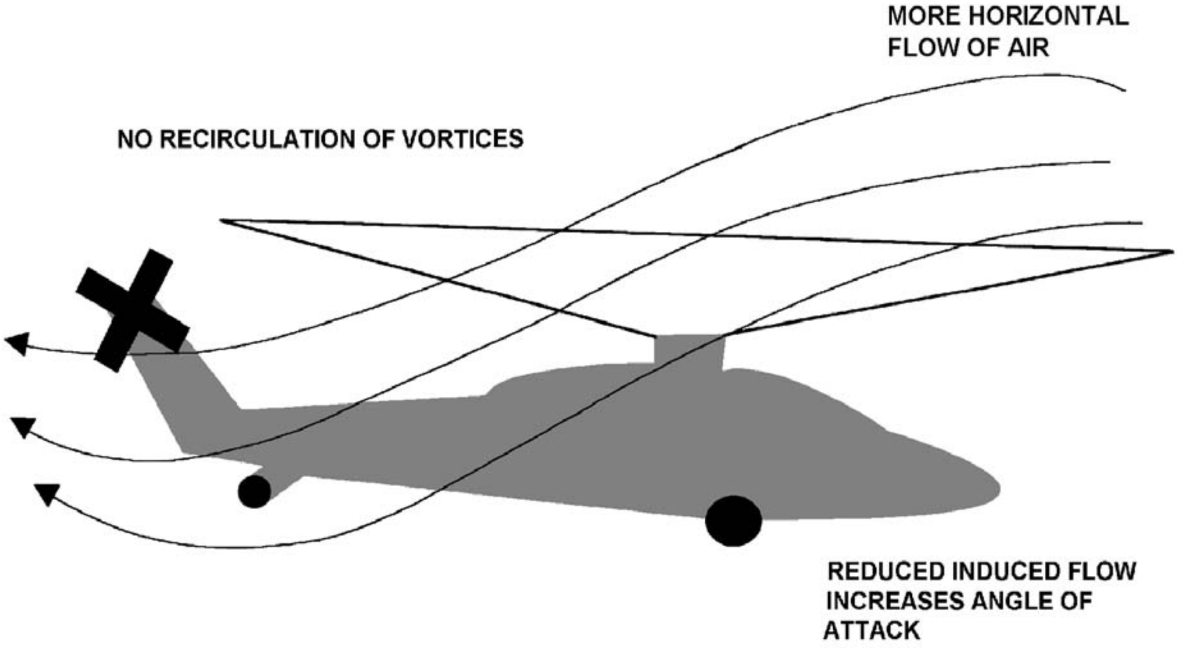


Figure 3-17

DISSYMMETRY OF LIFT

To begin this discussion, we need to backtrack all the way to rotor system control. In a no-wind hover, the rotational velocity each blade sees throughout each revolution is equal. In forward flight, the velocity distribution varies (figure 3-18). The advancing side of the rotor disc sees a combination of rotor speed and forward airspeed (movement through the air mass) which is faster than the retreating side, which sees a combination of rotor speed and a "reduced" forward airspeed. For a given pitch setting, and AOA, an equal amount of lift will be produced throughout the rotor disc in a no-wind hover, but in forward flight, the advancing side will generate more lift, thus developing a rolling moment. The ingenious method of equalizing this dissymmetry of lift in forward flight is to allow the blades to flap. By connecting the blades to the hub by a method which allows a flexible up-down motion, the advancing blade, which encounters higher lift, begins to flap upward. The retreating blade, which encounters less lift, flaps downward. Flapping equilibrium is found at a point where the rotor system has an AOA which compensates for changes in airspeed throughout the rotor disk revolution.

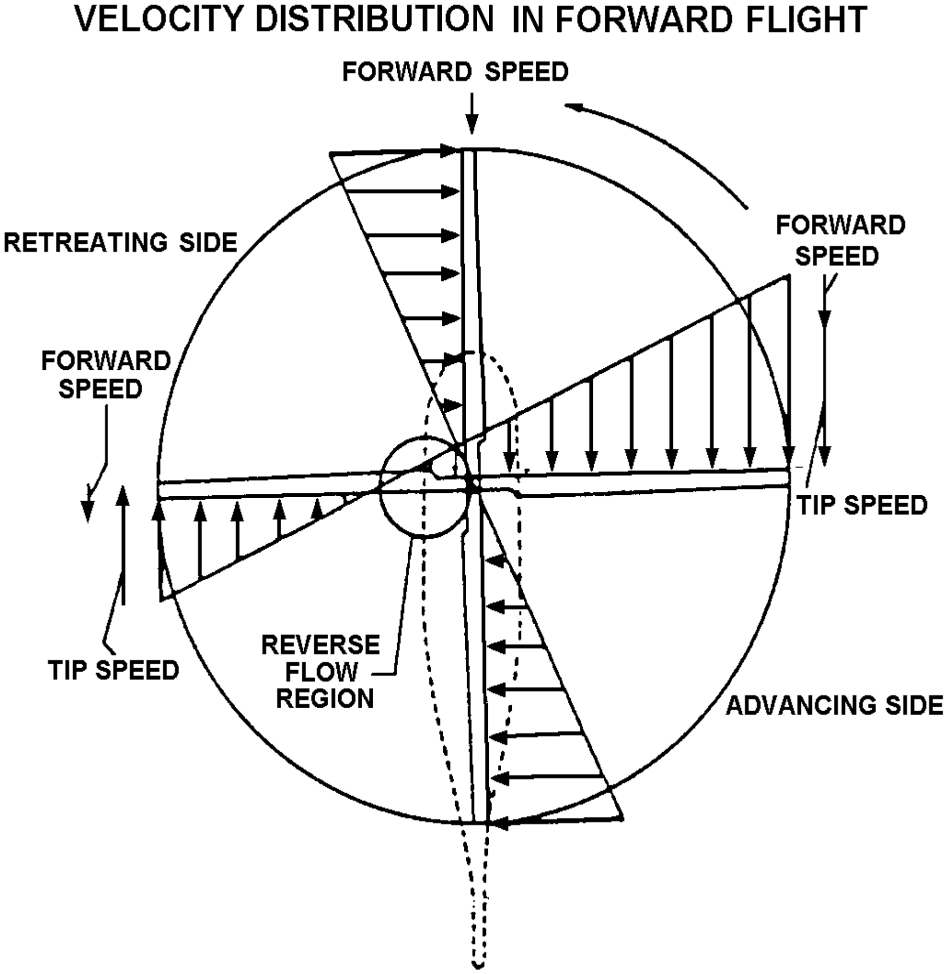


Figure 3-18

PHASE LAG

The advancing blade will encounter its highest rotational speed 90° prior to a position over the nose of the aircraft, but does not experience the highest degree of flapping at this point (figure 3-19). In fact, this maximum flapping occurs over the nose, 90° later, due to a principle of a dynamic system in resonance. A system in resonance receives a periodic excitation force sympathetic with the natural frequency of the system. The flapping frequency of a centrally hinged system is equal to the speed of rotation. Therefore, maximum response occurs 90° after maximum periodic excitation. This is termed phase lag. In order for a helicopter in forward flight to roll into a left turn, maximum lift must be realized at the right "wing" position and minimum lift must be realized at the left "wing" position. Therefore, maximum AOA must occur at the 180° position and minimum AOA must occur at the 360° position. To obtain the appropriate response 90° after maximum excitation, logic tells us forward cyclic is the appropriate input to initiate a left turn. No wonder helicopters are such a challenge to fly! Well, they are challenging, but not for this reason. Inputs are translated 90° prior mechanically, thanks to some design engineers who had a little foresight.

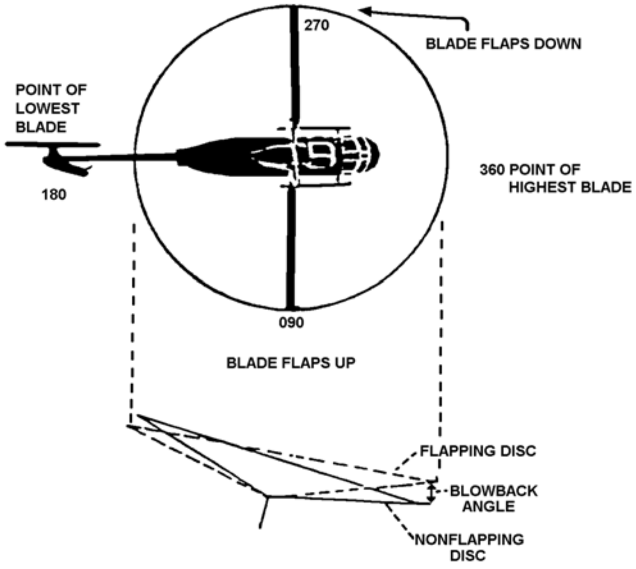


Figure 3-19

BLOWBACK

Let's get back to dissymmetry of lift. As the aircraft moves forward, the advancing blade "sees" a higher airspeed, and the resultant dissymmetry of lift causes the blades to flap to a maximum 90° later due to phase lag. This extra lift generated over the nose causes the nose to pitch up. Conversely, the nose will tend to pitch down as the aircraft decelerates. The combined effect of dissymmetry of lift and reduced induced velocity defines this transition to a more efficient flight regime, called translational lift. The pitch-up tendency of the aircraft as it accelerates and the pitch-down tendency as it decelerates are known as rotor blowback (figure 3-20).

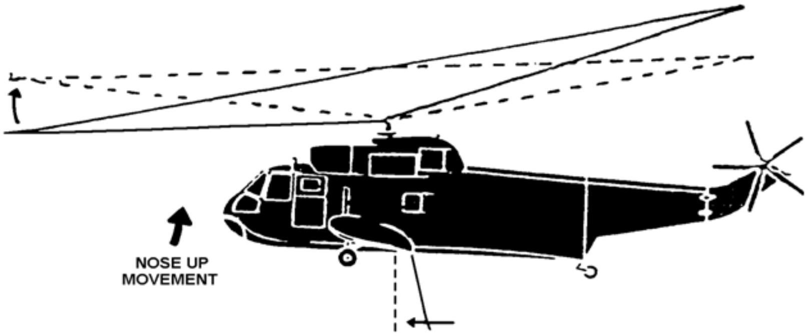


Figure 3-20

Forward cyclic input in proportion to degree of blowback must be used to maintain a constant rate of acceleration. Aft cyclic will be required during deceleration.

As the helicopter transitions to a hover from a decelerating glide slope as in a normal approach, it often experiences an uncommanded nose-up tendency -- not nose-down as described above. This is referred to as Pendulum Effect, and it occurs in response to increased collective pitch. Although collective blade pitch is increased proportionally, forward flight dissymmetry of lift is augmented. This overrides the effects of decelerating rotor blowback and causes the nose of the aircraft to pitch up (figure 3-20).

TRANSVERSE FLOW AND CONING

Another phenomenon which occurs at about 15-20 kts is a non-uniform induced velocity flow pattern across the rotor, or transverse flow. The wake vortices behind the rotor create nearly twice the induced velocity at the trailing edge of the rotor disk as compared to the leading edge, where it is approximately zero (figure 3-21).

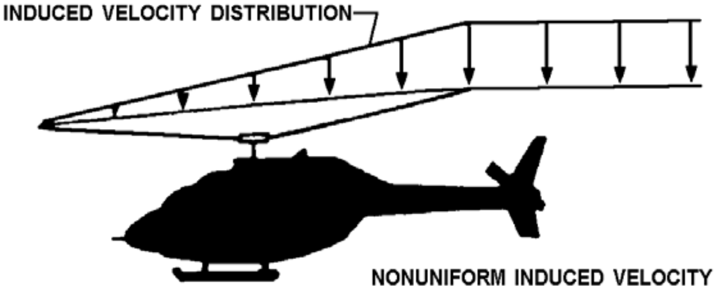


Figure 3-21

This causes the blade over the nose to see an increase in AOA and, coupled with phase lag, makes the rotor flap up on the left side. A sudden left cyclic input during acceleration may be necessary to counteract this flapping. This fore-and-aft asymmetry of lift continues in forward flight due to coning (figure 3-22), a steady upward flapping due to blade lift and centrifugal force. In slow forward flight, coning causes the component of inflow to be more "up" in the blade over the nose in comparison to the component of inflow over the tail.

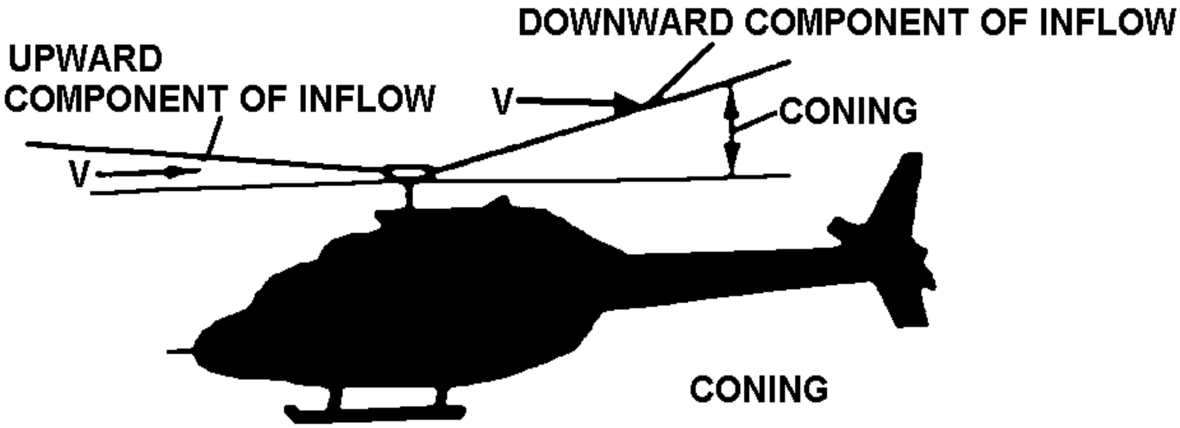


Figure 3-22

Therefore, the lift on the retreating blade is low because the rotational speed it “sees” is low. The lift on the advancing blade is low because it must not overbalance the lift on the retreating side. The blades over the nose and tail have the primary responsibility of producing the lift necessary to keep the helicopter airborne in forward flight.

CHAPTER THREE REVIEW QUESTIONS

1. To make a hovering turn to the left in no-wind conditions, one must <u>increase/decrease</u> tail rotor thrust.

2. How does a multi-rotor headed helicopter account for torque effect? ___________________ ______________________________

3. Power required by the tail rotor to maintain heading while increasing collective setting will <u>increase/decrease</u>, therefore <u>increasing/decreasing</u> power available to the main rotor system.

4. The ___________________________ effect and ___________________________ provide anti torque compensation in forward flight.

5. How does tail rotor thrust affect vertical takeoffs and landings?_______________________.

6. The apparent axis of rotation of the main rotor system is called the____________________.

7. The actual axis of rotation is called the_________________________________.

8. The center of mass of the entire aircraft is called the_________________________________.

9. When the virtual axis is displaced, the ____________________________ will attempt to align itself with it, causing ___________________________.

10. Why is cyclic authority lost when center of gravity is out of limits?____________________ __________________________

11. The phenomenon requiring control inputs 90 degrees ahead of the location of desired result. ____

12. When a helicopter enters forward flight, the advancing blade generates more lift than the retreating blade, causing ____.

13. ___________________________causes the nose to pitch <u>up/down</u> because of blade flapping over the nose caused by the combined effects of________________ and ____________.

14. Translational lift is caused by an increase of _______________________ introduced to the rotor system and a decrease of _________________________.

15. Ground effect is caused by a reduction of_________________________ due to helicopter operations within________ rotor diameter of the ground.

16. The resultant upward displacement of the rotor blades due to___________________ and ______________________is called coning.

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CHAPTER THREE REVIEW ANSWERS

1. increase

2. The rotor systems turn in opposite directions, canceling the torque effect.

3. increase . . . decreasing

4. weather vaning . . . vertical stabilizer

5. Tail rotor thrust causes a right drift requiring left cyclic for vertical takeoffs and landings. This is why the right skid lifts off first and touches down last.

6. virtual axis

7. mechanical axis

8. center of gravity

9. mechanical axis . . . acceleration

10. One cannot tilt the rotor system enough to allow the virtual axis to offset the extremely displaced center of gravity.

11. phase lag

12. dissymmetry of lift

13. blowback . . . up . . . dissymmetry of lift . . . phase lag

14. mass flow of air . . . induced velocity

15. induced velocity

16. centrifugal force . . . blade lift

CHAPTER FOUR

TERMINAL OBJECTIVE

4.0 Upon completion of this chapter, the student will be able to describe and analyze the aerodynamics associated with unpowered rotary flight.

ENABLING OBJECTIVES

4.1 Define autorotation.

4.2 Draw and label a blade element diagram for autorotation.

4.3 Define pro-autorotative force.

4.4 Define anti-autorotative force.

4.5 State the three phases required to transition from powered to unpowered flight.

4.6 State the effects of a flare in autorotation.

4.7 State the variables that affect autorotative descent.

4.8 State the purpose of the height-velocity diagram.

FLOW STATES AND DESCENDING FLIGHT

Now we have an understanding of powered flight, we can move on to discuss the conditions of flow through the rotor system. These are the normal thrusting state, vortex ring state, windmill brake state, and autorotative state.

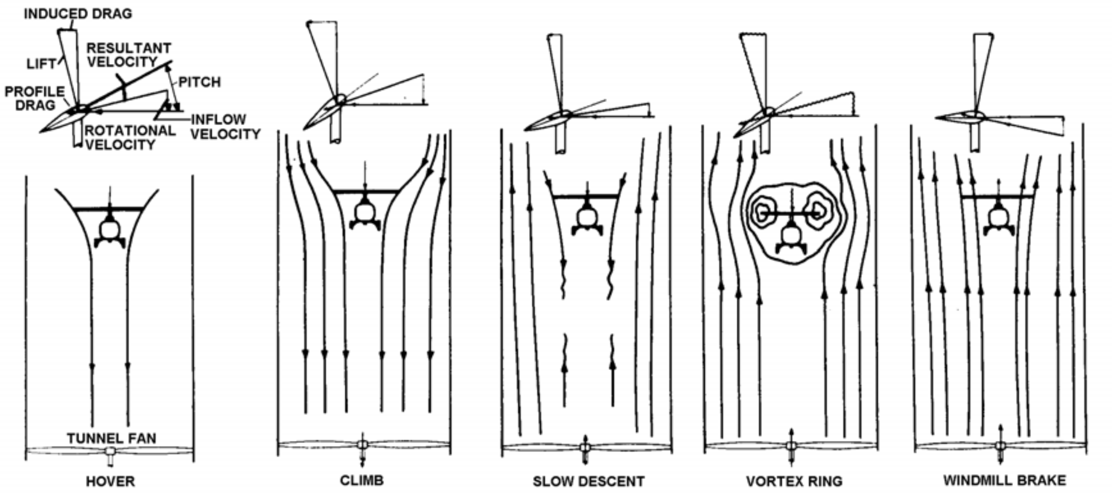

Figure 4-1

Beginning with the normal thrusting state, we will use an analogy of a tunnel fan (see figure 4-1). There are three possibilities of normal thrust -- hover, climb, and slow descent. For a hover, envision the fan turned off with the rotor producing a downward flow. For a climb, think of a fan pulling air down through the tunnel and rotor, increasing the induced flow through the rotor. For a slow descent, reverse the direction of the fan to blow air up the tunnel, decreasing the rotor downwash, but not enough to reverse the downwash near the rotor.

Now turn the speed of the fan enough to equalize the flow of air going up the tunnel with the rotor induced downwash. At this point, rotor tip vortices are not allowed to move from the vicinity of the rotor, enveloping the outer rim of the rotor in a bubble of air. Thrust developed by the rotor becomes essentially negligible, and the helicopter descent rate increases dramatically. This is known as vortex ring state. The onset of vortex ring state varies with types of helicopters because the onset varies proportionally in regards to descent rate and hover induced velocity. The helicopter enters this state at about ¼ induced velocity, peaks at ¾ induced velocity, and becomes clear of this phenomenon at approximately 1¼ induced velocity. Flight path descent profiles also determine the length of stay in this state, and there is evidence descent angles of 70° are worse than those of 90°. Approach angles less than 50° combined with forward speeds of 15 - 30 kts allow enough new mass flow of air to blow the tip vortices behind the rotor system. The TH-57 should avoid descent rates greater than 800 ft/min, less than 40 kts IAS, and descent angles greater than 45°.

As the fan is turned up to maximum, the net flow becomes upward through the rotor. The rotor actually takes some energy from the passing wind and slows it down, but since rotor systems can't store or dissipate energy like windmills generating electricity, the point is academic

-- the length of time you will remain airborne in the windmill brake state is simply a function of terminal velocity.

Comparing the diagrams of conditions at the blade element (figure 4-1), we can observe collective pitch required to maintain a constant thrust changes, due to the net flow through the rotor disk. Additionally, in a climb, the flow causes the lift vector to tilt back, thus increasing the power required. The opposite happens in the windmill brake state and low rates of descent. During vortex ring state, the conditions are similar to those conditions in a climb, so collective pitch setting and power required must be high to maintain vortex ring state. Therefore, reducing collective setting to reduce pitch is a recovery technique for this condition.

AUTOROTATION

Continuing to lower the collective to minimum pitch transitions the helicopter from vortex ring state to vertical autorotation state. A majority of the flow will be upwards through the rotor system, but due to the presence of induced downflow, one may still classify it as being in vortex ring state (figure 4-2).

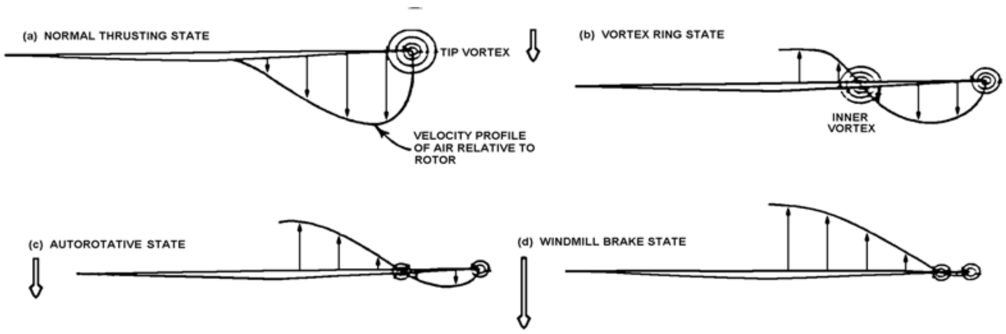

Figure 4-2

There are differences, though. The lift vector becomes tilted forward (figure 4-3), providing enough power to drive the tail rotor and gearboxes without the engine. Drag of the blades is also overcome.

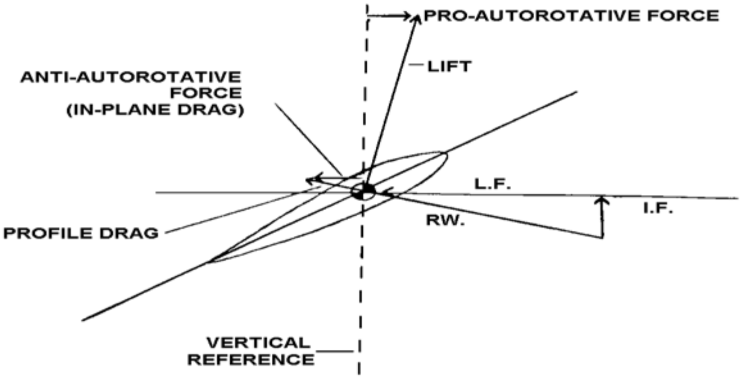

Figure 4-3
Blade Element in Autorotation

Compared to the vortex ring state, vertical autorotation state is a stable condition where collective pitch settings will vary the rate of descent and rotor speed. Higher rotor speeds are attained with lower pitch settings, lower rotor speeds with higher settings. This leads to the next logical assumption, a desired range of rotor speed must exist. An excessively high rotor speed produces overstressful centrifugal loads on hubs and blade roots, which can in turn overstress the tail rotor. Rotor blades will stall at a very low rotor speed. 75% to 110% of normal rotor speed is generally safe, and in this range, rate of descent is approximately twice the hover induced velocity. This rate of descent is comparable to a helicopter descending under a parachute.

Autorotation, however, does not usually occur after entering vortex ring state. It usually follows an engine failure if the pilot initiates corrective action in a timely manner. This action centers on meticulous energy management focusing on rotor RPM and forward airspeed.

AUTOROTATION ENTRY

Once the engine selects the most convenient time and place to cease working, the power required for flight, now autorotative flight, must come from another source. This energy comes from the rate of decrease in potential energy as the helicopter loses altitude. The rotor will initially slow down, feeding on its own energy due to the power loss. **Lowering the collective** with little or no delay will stop this decay. If N_r is allowed to decay too much, the rotor will stall, allowing the helicopter to assume flying qualities of a brick. The increasing upflow of air through the rotor system effectively **reverses the airflow**, tilts the lift vector forward, increasing thrust, which can now be managed by the pilot through small pitch changes through the collective by controlling N_r (in-plane drag). Throughout this procedure, potential energy in the form of loss in altitude is traded off to place kinetic energy in the rotor system.

Now that steady state autorotation has been achieved, the pilot has the option of stretching his glide to a distant landing zone or increasing his loiter time in the air, provided sufficient altitude exists. Just suppose the engine failed and there wasn't a suitable landing site immediately in front of you, but there was one further away. What should one do? Luckily, for pilots in a somewhat stress-inducing situation, the solution is fairly logical and in line with normal reaction -- fly at optimum cruise speed (fast). This is called **maximum glide range** airspeed. It is found at a point tangent to the power required curve from a line extending from the origin. Again, there are tradeoffs, and in this case, higher speed and distance over the ground reduces time aloft and rotor speed.

Another alternative on the other end of the spectrum is **minimum rate of descent**. This occurs at the speed of minimum power required on the power required curve. If there is an available field immediately in front of you, you may use this speed for extra time aloft to ensure crew readiness for landing or make a prudent radio transmission, but there are other factors which enter the ball game as the helicopter approaches the ground.

CUSHIONING THE TOUCHDOWN

As the ground becomes more in focus, the range of safe airspeed/rotor RPM combinations narrows, and precise management of kinetic energy is necessary. At this point, your new goal is to reduce the kinetic energy along the flight path to zero at the same time ground contact is made, while trading off the stored kinetic energy in rotor RPM for thrust to maintain power requirements for flight before the blades reach a stalled condition. This may seem like a very large chunk to swallow, but if taken in small bites, the process becomes much easier (see figure 4-4).

From either of the two extreme airspeed range examples previously discussed (max glide/min rate of descent), we will assume a suitable landing zone is now easily within range. If we were at max glide at a high forward speed and associated high rate of descent, it is only logical we slow down (low rate of descent at ground contact = less pain). How slow? Minimum rate of descent sounds logical. But, even at this airspeed, the helicopter's landing gear cannot absorb the amount of energy the helicopter is carrying at ground contact. Therefore, it is advantageous to carry 5-10 kts extra airspeed over minimum rate of descent airspeed at **flare altitude**, banking on another tradeoff -- extra forward airspeed for high rotor RPM. Figure 4-4

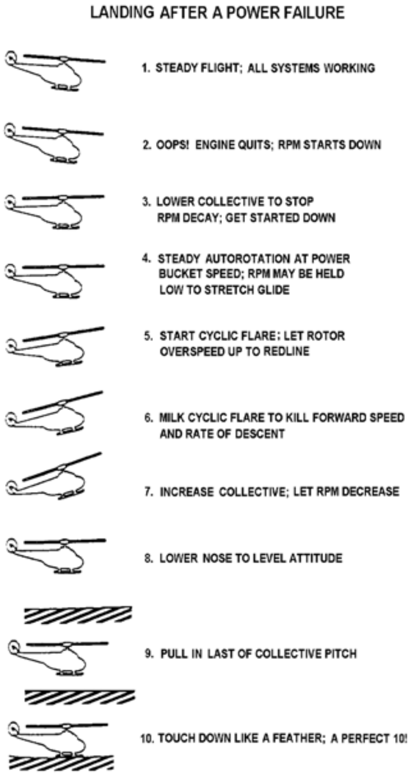

Figure 4-4

A nose-up cyclic flare (see figure 4-5) at 75-100 feet AGL (for the TH-57) increases induced flow. The resulting increase in AOA creates more lift, which decreases rate of descent. Moreover, the downward shift in relative wind tilts the left vector at blade element more forward, resulting in a larger pro-autorotative force; this increases rotor RPM. Finally, the net rotor thrust is tilted aft, and this decreases ground speed. The flare should be maintained in an effort to reach a point to where forward speed is 5-10 kts at close proximity to the ground (10-15 ft). At this point, increasing collective, increases thrust and augments braking action, using up part of the stored rotational energy. All that is left is to put in a little forward cyclic to level the aircraft and use that last rotational energy by pulling collective to cushion the landing.

If one chose to arrive at flare altitude at minimum rate of descent airspeed or less, there is little or no forward speed to trade off for this advantageous high rotor RPM. Forward speed is already low, and if too much flare is combined with an improperly timed flare (too high), forward speed may reduce to zero at a high altitude. This condition is known as becoming "vertical," and since the rotor system already has little stored energy, there will not be enough thrust available with collective increase to slow rate of descent at touchdown to a non-destructive level.

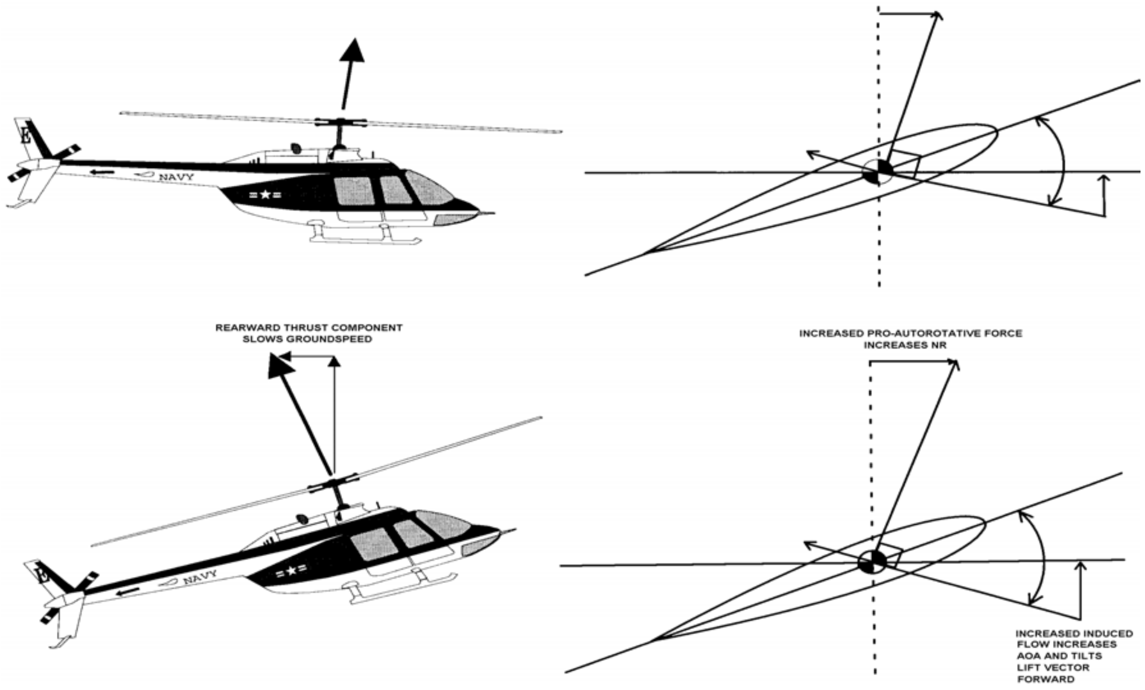

Figure 4-5

BLADE ELEMENT AND THRUST DURING STEADY STATE AUTO AND FLARE

AIRSPEED AND Nr CONTROL

Lets go back to the point where the pilot had the choice of minimum rate of descent or max glide airspeeds. Now we understand the practical side of his choices, lets explore what is happening at the blade a little more closely.

In a steady state autorotation, the induced flow has been reversed. It works with rotational flow to create relative wind from beneath the blade, which sustains the blades' rotation. One look at the blade element diagram shows in-plane drag exists; therefore, not all of the blade is producing thrust -- some of the blade is counterproductive to autorotative flight. The region breakdown is shown in figure 4-6. The pro-autorotative (auto) region represents about 45% of the blade surface. This occurs where the relative wind shifts below the tip-path-plane sufficient to produce enough driving force to overcome in-plane drag, but not enough to reach critical AOA and reach the stall region.

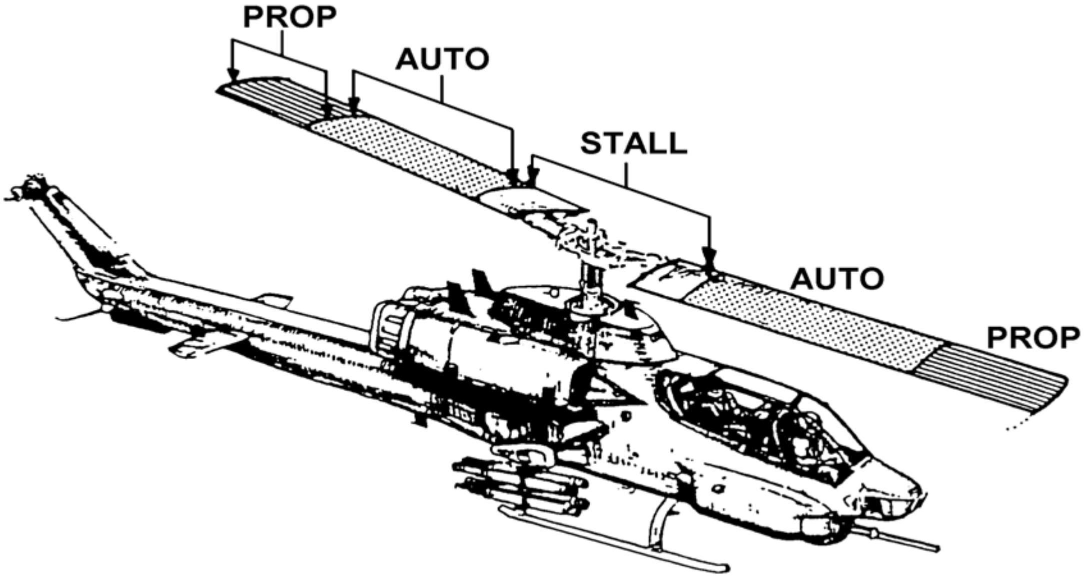

Figure 4-6

Figure 4-7 shows the Blade Element diagram for each region of the blade at a given rotor RPM. In the prop region, or anti-autorotative region, the high rotational speed combines with little induced flow, shifting the relative wind toward the horizontal. In this region, in-plane drag is greater than the driving force. In the stall region, AOA is exceeded, creating high profile drag.

If the pilot chooses minimum rate of descent, induced flow and rotational speed will increase, thus providing greater lift and time aloft. Choosing max glide decreases induced flow and rotational speed, therefore decreasing lift and time aloft.

Figure 4-7

Figure 4-8 graphically describes the range variations with RPM changes. Since the amount of blade surface producing positive autorotative driving force varies according to RPM and this driving force is synonymous with thrust produced, it is obvious the pilot has additional control over rate of descent by changing pitch through collective application. Excessively high N_r produces less driving force and a higher rate of descent, and very low N_r leads to low driving force in proportion to high drag associated with a stalled profile. There is an optimum RPM range (94-95% for the TH-57), which produces the greatest net driving force and minimum descent rate. It is in the best interest of the pilot to strive for this RPM range until reaching flare altitude.

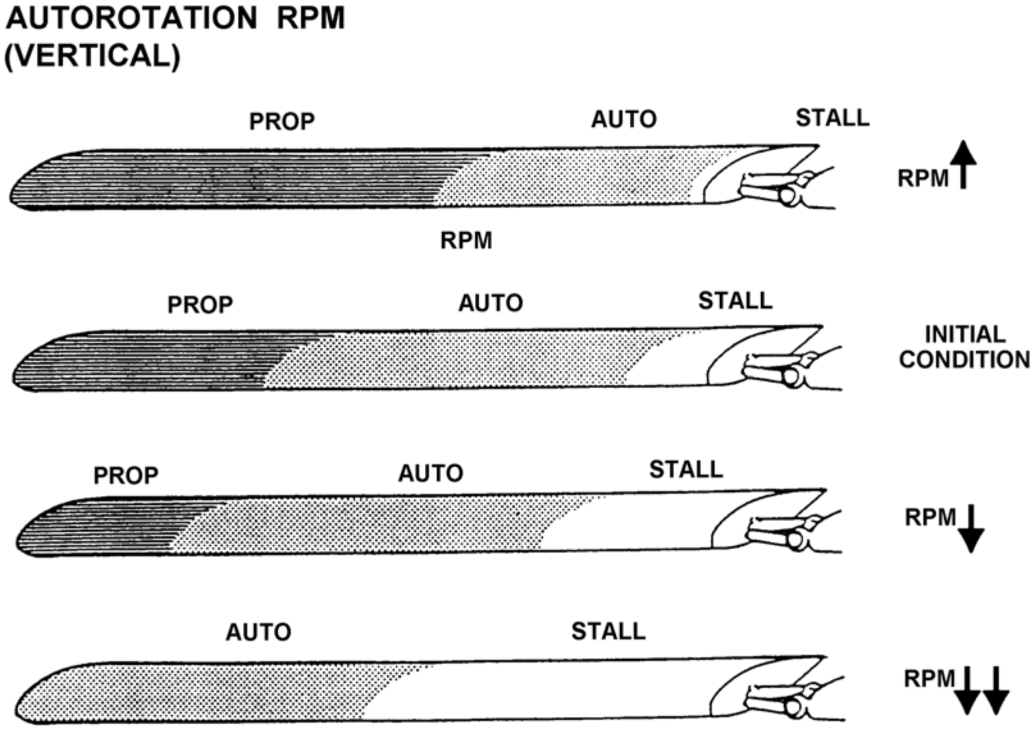

Figure 4-8

HEIGHT-VELOCITY DIAGRAM

No matter how well the pilot can execute an autorotation, there remain some combinations of initial altitudes and airspeeds from which a safe autorotational landing will be extremely difficult to perform. The diagram illustrating this is the Height-Velocity (H-V) Diagram, also known as the Deadman's Curve.

The purpose of an H-V diagram is to identify the portions of the flight envelope from which a safe landing can be made in the event of a sudden engine failure. The H-V diagram (figure 4-9) generally depicts two areas to be avoided: The low-airspeed/high-altitude region and the high-airspeed/low-altitude region.

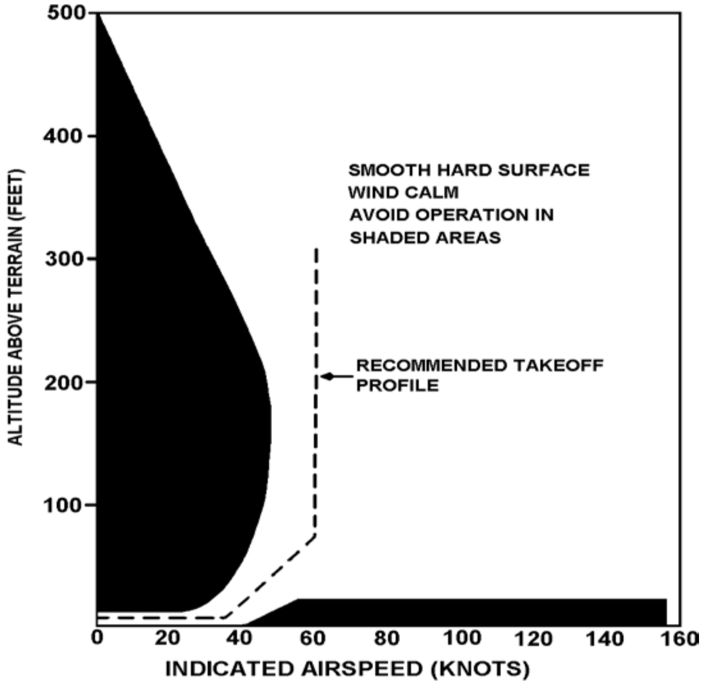

Figure 4-9

There are H-V diagrams for each type of helicopter. They are found in their respective NATOPS Manuals. Helicopter pilots should be familiar with these diagrams.

Taking a closer look at the H-V diagram, we see several definite points define the curve, the first being the low hover height. Up to this height, a pilot can handle a power failure by coming straight down, using collective increase to cushion the landing. Above that altitude in combination with low speed, the rotor blades will slow down and stall if collective setting remains constant, or the helicopter will impact the ground too hard if collective is lowered. Enough altitude does not exist to acquire enough forward airspeed by the time flare altitude is reached to successfully execute a flare. This height is a function of: 1) the power required to hover, 2) rotor inertia, 3) blade area and stall characteristics, and 4) the capability of the landing gear to absorb the landing forces without sustaining damage.

The unsafe hover area runs from the low hover height to the high hover height. Above this altitude, there is enough altitude to make a diving transition into forward flight autorotation and execute a normal flare.

Beyond the knee of the curve, a power failure is survivable at any altitude above the high-airspeed/low-altitude region. The three problems associated with the high-airspeed/low-altitude region are as follows: 1) pilot reaction time, 2) lack of time and altitude for the induced flow to reverse before ground impact, and 3) possibility of tail rotor stinger strike in response to cyclic flare to trade altitude for airspeed.

Skilled test pilots who try to make their reactions simulate those of the average reaction time of a pilot establish H-V diagrams. This is done by specifying a definite delay time following the engine failure before initiating control input. The military assumes their pilots may be distracted during an engine failure due to focused attention to assigned missions, allowing a two-second delay before response during any flight condition.

CHAPTER FOUR REVIEW QUESTIONS

1. ________________________is the self-sustaining rotation of the rotor blades in unpowered flight.

2. For unpowered flight, induced flow is perpendicular/parallel to the tip-path-plane and comes from above/below the rotor disk.

3. Pro-autorotative force is the vertical/horizontal component of lift/profile drag.

4. What is the anti-autorotative force in the rotor system?____________________________

5. The three conditions required to enter an autorotation are____________, ____________, and ______________.

6. How does the flare in an autorotational descent affect the aircraft?____________________ ____

7. Minimum rate of descent in unpowered flight is achieved by_________________________ ______________________________.

8. The unshaded areas of the H-V diagram identify the portions of the flight envelope from which a ____________________can be accomplished in the event of a____________________.

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CHAPTER FOUR REVIEW ANSWERS

1. autorotation
2. perpendicular . . . below
3. horizontal . . . lift
4. in-plane drag
5. lower collective, reverse airflow, control Nr
6. reduce rate of descent, reduce forward airspeed, increase Nr
7. flying at max endurance/loiter airspeed with minimum rate of descent rotor speed
8. safe landing . . . loss of engine power

CHAPTER FIVE

TERMINAL OBJECTIVE

5.0 Upon completion of this chapter, the student will be able to identify undesirable flight phenomena and state the solutions to the problems associated with these flight conditions.

ENABLING OBJECTIVES

5.1 Define retreating blade stall by stating its cause and the effects on helicopter flight.

 5.1.1 State the solution to retreating blade stall.

5.2 Define compressibility effect by stating its cause and the effects on helicopter flight.

 5.2.1 State the solution to compressibility effect.

5.3 Define the vortex ring state by stating its cause and the effects on helicopter flight.

 5.3.1 State the recovery techniques for the vortex ring state.

5.4 Define power required exceeds power available by stating its cause and the effects on helicopter flight.

 5.4.1 State the recovery technique for power required exceeds power available.

5.5 Define ground resonance by stating its cause and the effects on helicopter flight.

 5.5.1 State the techniques to cease ground resonance.

5.6 Define dynamic rollover by stating the two essential elements required for rollover to occur.

5.7 Define mast bumping by stating its cause and the effect on the helicopter.

 5.7.1 State the major and minor causes of mast bumping.
 5.7.2 State the indications of mast bumping.
 5.7.3 State the recovery technique for mast bumping.

5.8 State the three categories of helicopter vibrations.

 5.8.1 State the cockpit indications of each category.
 5.8.2 State the possible sources for each category.

RETREATING BLADE STALL

A tendency for the retreating blade to stall in forward flight is inherent in all present-day helicopters, and a major factor in limiting their forward speed. Just as the stall of an airplane wing limits the low speed possibilities of an airplane, the stall of a rotor blade limits the high speed potential of a helicopter (figure 5-1).

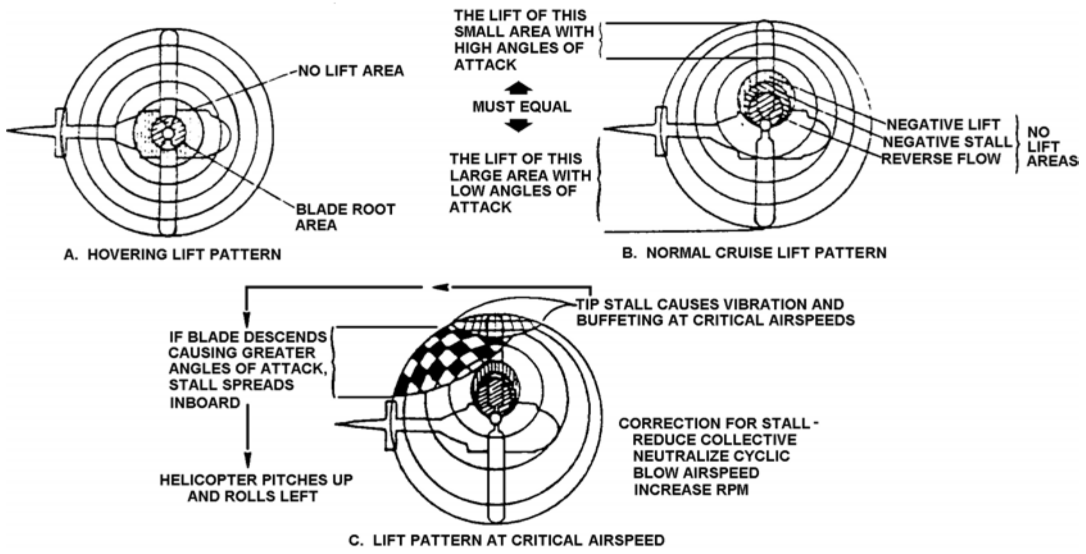


Figure 5-1

The airspeed of the retreating blade (the blade moving away from the direction of flight) slows down as forward speed increases. The retreating blade must still produce an amount of lift equal to that of the advancing blade. Therefore, as the airspeed of the retreating blade decreases with forward speed, the blade AOA must be increased to equalize lift throughout the rotor disk. As this AOA increase continues, the retreating blade will stall before the advancing blade at some high forward speed.

As forward airspeed increases, the "no lift" area moves further left of center of the disk, covering more of the retreating blade sector. This places a demand for greater lift from the outer area of the retreating side. In the area of reversed flow, the rotational velocity of the airfoil is slower than the aircraft airspeed; therefore, the air flows from the trailing edge to the leading edge of the airfoil. In the negative stall area, the rotational velocity of the airfoil is faster than the aircraft airspeed, allowing air to flow from the leading to the trailing edge. However, due to the relative arm and induced flow, blade flapping is not sufficient to produce a positive AOA. Blade flapping and rotational velocity in the negative lift area are sufficient to produce a positive AOA, but not to a degree which produces appreciable lift.

Figure 5-2 shows a rotor disk that reached a stall condition on the retreating side. It is assumed the stall AOA for this rotor system is 14°. Distribution of AOA along the blade is shown at eight positions in the rotor disk. Although the blades are twisted and have less pitch at the tip than at the root, AOA is higher at the tip because of less induced flow or flow coming from below due to flapping.

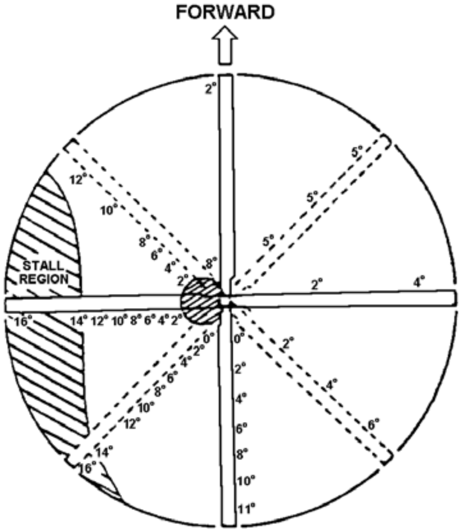


Figure 5-2

Upon entry into blade stall, the first effect is generally a noticeable progressive vibration of the helicopter. The vibration will be a two-to-one beat (2 vibrations per 1 revolution). This will terminate in a loss of longitudinal control and severe feedback in the cyclic control. The nose of the helicopter will oscillate up and down violently, independent of cyclic position. Corrective action can be taken before stall becomes severe. Onset of blade stall varies with the following:

1. Airspeed
2. Gross weight
3. Density altitude
4. G loading (including high AOB turns and turbulence)
5. Rotor rpm

If blade stall is encountered, the pilot should initiate one or more of the following actions:

1. Decrease the severity of the maneuver (reduces G loading).
2. Decrease collective pitch (reduces AOA).
3. Reduce airspeed (reduces power required, thus reducing pitch and AOA).
4. Descend to lower altitude (decreases power required).
5. Increase rotor rpm (increases rotational velocity).

COMPRESSIBILITY EFFECT

Another factor, which limits forward speed in helicopters, is the compressibility effect on the advancing blade. The airspeed the advancing blade "sees" increases as forward helicopter speed increases. At low speeds, air compression is not a problem because the air experiences relatively small changes in pressure with only negligible changes in density. At high speeds, the pressure changes taking place are larger and result in significant air density changes.

The dominant factor in high speed airflow is the speed of sound. Speed of sound is found at the point where pressure disturbances are no longer propagated through the air, and this propagation speed is a function of air temperature. As altitude increases and temperature decreases, the speed of sound decreases.

If the airflow is traveling at some speed above the speed of sound, the airflow ahead of it will not be influenced by the pressure field, because pressure disturbances cannot be propagated ahead of the airfoil. As the speed nears the speed of sound, a compression wave forms at the leading edge of the blade and all changes in velocity and pressure take place sharply and suddenly. The airflow ahead of the airfoil is not influenced until the air particles are suddenly forced out of the way by the concentrated pressure wave formed by the airfoil. Typical supersonic airflow is shown in figure 5-3.

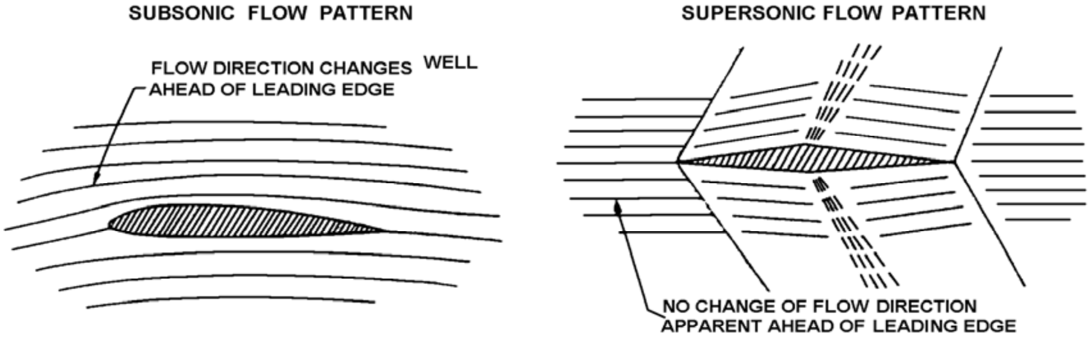


Figure 5-3

The principal effects of compressibility on the advancing blade are: 1) a large increase in blade drag and 2) rearward shift of the airfoil aerodynamic center. This increases power required to maintain rotor rpm, vibrations, cyclic feedback, and an undesirable high twisting moment on the blade.

Compressibility effects become more severe at higher lift coefficients (higher AOA) and higher speeds. The following operating conditions represent the most adverse compressibility conditions:

1. High airspeed
2. High rotor rpm
3. High gross weight

4. High density altitude
5. Low temperature
6. Turbulent air

Compressibility effects will vanish if blade pitch is decreased. There are similarities in critical conditions for retreating blade stall and compressibility, but one difference must be appreciated. Compressibility occurs at high rotor rpm, while blade stall occurs at low rotor rpm. Recovery technique is similar for both, with the exception of rpm control.

VORTEX RING STATE

Vortex ring state (power settling) is an uncontrolled rate of descent caused by the helicopter rotor encountering disturbed air as it settles into its own downwash. This condition is based on the pilot's observation that even though the aircraft may have plenty of engine power, the aircraft continues to sink rapidly. This condition may occur in powered descending flight at low airspeeds while out of ground effect.

The vortex ring state is encountered when the rate of descent approaches or equals the induced flow rate (figure 5-4).

Based on wind tunnel and flight tests, flight in the vortex ring state begins at ¼ induced velocity, peaks at ¾ induced velocity, and disappears at 1¼ times the induced velocity.

Depending on their disk loading, various helicopters enter this phenomenon at a descent rate of 300 to 600 feet per minute and must exceed 1500 to 3000 feet per minute to get clear of it. Staying in this state for any length of time depends on maintaining a nearly vertical flight path. There is some evidence a glide slope of about 70° is worse than a true 90° descent. Approaches with glide slopes less than about 50° with forward speeds between 15 and 30 knots will introduce enough fresh air into the rotor system to blow the tip vortices away from the rotor and free it from the clutches of vortex ring state.

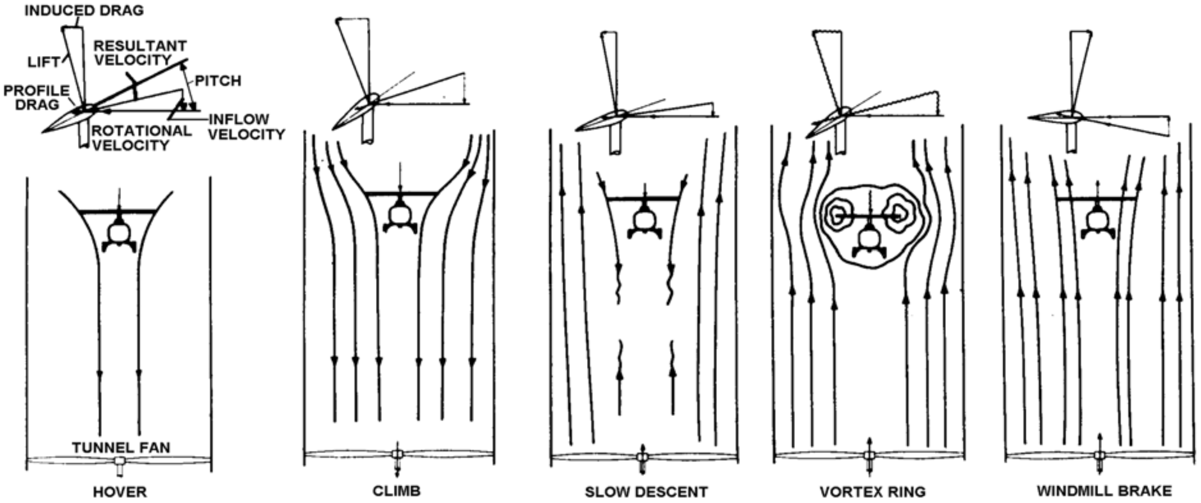


Figure 5-4

The unsteadiness of the flow has been seen during wind-tunnel tests of model rotors using smoke for flow visualization. Figure 5-5 shows a sequence of events based upon interpretation of the smoke patterns. According to this model, the rotor is continually pumping air into a big bubble under the rotor. This bubble fills up and bursts every second or two, causing large-scale disturbances in the surrounding flow field. The bubble appears to erupt from one side and then another, causing the rotor thrust to vary and the rotor to flap erratically in pitch and roll, requiring prompt reaction. This is what causes the loss of control effectiveness. Recovery includes lowering the collective and forward cyclic to fly out of the condition. Increasing the collective only serves to aggravate the situation.

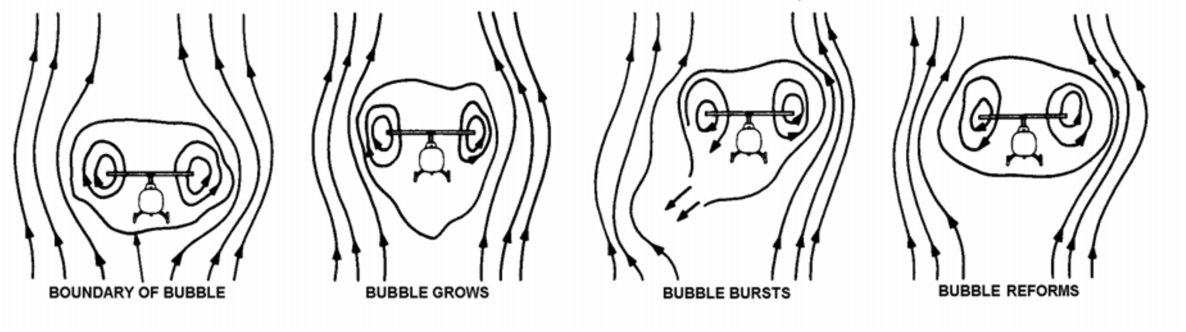


Figure 5-5

Figure 5-6 shows the power and pitch settings required to maintain constant rotor thrust in vertical descent for a typical helicopter. Notice the increase in rate of descent with collective increase during vortex ring state conditions.

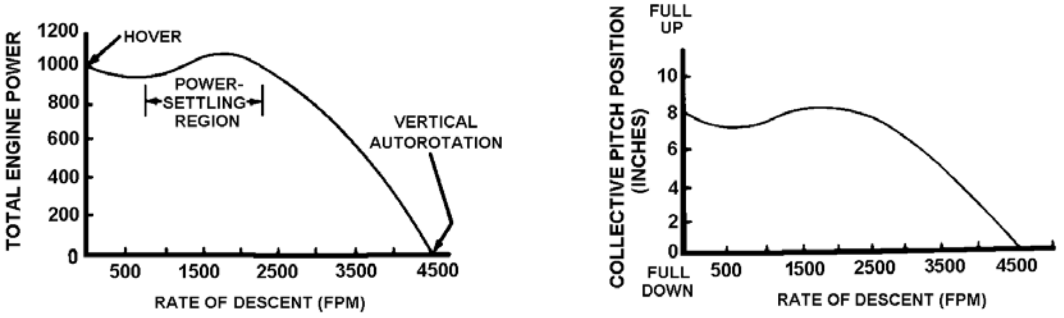


Figure 5-6

After a helicopter is descending fast enough to pass through the worst of the unsteadiness in vortex ring state, it will achieve vertical autorotation. Usually there is still a little induced downflow through portions of the rotor disk, but most of the flow will be upwards. This mixed-flow condition technically qualifies the rotor to be in the vortex ring state, but the difference in collective setting differentiates the states. You can see entering unpowered descent and flight will get one out of vortex ring state, but due to the usual proximity to the ground, combined with the high rate of descent associated with this phenomenon, catastrophic results are likely. The hazards of operation in the vortex ring state were first discovered in main rotor systems, but tail rotors may encounter vortex ring state in conditions such as right hovering turns and left sideward flight (for helicopters with main rotors which turn counterclockwise when viewed from above). Not all helicopters experience these troubles, but for those, which are susceptible, a common symptom is a sudden increase in rate of turn.

POWER REQUIRED GREATER THAN POWER AVAILABLE

The name of this state defines itself. Indications of this state include:

1. Uncommanded descent with associated maximum torque and/or rotor rpm droop.
2. Decrease in tail rotor effectiveness.

Factors which can cause or aggravate this situation include:

1. High G loading.
2. High gross weight.
3. Rapid maneuvering.
4. Engine spool up time from low to high power settings.
5. Loss of wind effect.
6. Change of wind direction.
7. Loss of ground effect.

This condition is especially dangerous when operating in close proximity to obstructions where enough altitude/maneuvering space is unavailable to allow for safe recovery from the situation. Recover by:

1. Nr -- Maintain.
2. Rpm switch -- FULL INCREASE
3. Airspeed -- INCREASE/DECREASE TO 50 KIAS (min power required airspeed).
4. Angle of bank -- LEVEL WINGS.
5. Jettison stores -- as required.
   If impact is imminent:
6. Level aircraft to conform to terrain.
7. Cushion the landing.

Pilots can easily avoid this situation through proper preflight planning and using sound judgment when considering entry into a high power required flight regime.

GROUND RESONANCE

Ground resonance is normally associated with fully-articulated rotor systems. In order for this to occur, at least one landing gear or skid must be in contact with the deck. A destructive oscillation may be encountered if the blades move excessively about their lead-lag hinges to the point where their combined center of gravity is displaced from the center. In most flight conditions, this situation will rapidly right itself as the individual blades sort themselves out. In this process, each blade leads and lags in such a way as to spiral the CG toward the mast where it belongs.

The problem exists if the aircraft is not airborne. A gust of wind, sudden control movement or hard landing can displace the blades. The resulting motion due to the offset centrifugal force may be just at the right frequency to rock the airframe on its landing gear.

Figure 5-7 illustrates this situation. Once this occurs, these two motions get in step, causing the CG to spiral outward violently, producing a rotating force at the rotor hub, which can shake the aircraft to pieces almost immediately.

Despite this dire possibility, ground resonance does not happen every time it has an opportunity; just often enough to scare everyone concerned. The first recorded instance was in the 1930's, when a Kellett autogyro apparently hit a rock while taxiing. This accident attracted the attention of scientists, who eventually produced a mathematical and physical understanding of the phenomenon. They found ground resonance can be prevented with damping, but the damping must be used in the rotor around the lead/lag hinges and the landing gear.

As far as the pilot is concerned, prevention consists of making sure all dampers are operational during the preflight inspection. If an oscillation is detected and the aircraft is up to flying rpm, the primary recovery method is to lift off. An alternate method is to land, secure the engine, and apply the rotor brake. These actions should bring the rotor system back into balance.

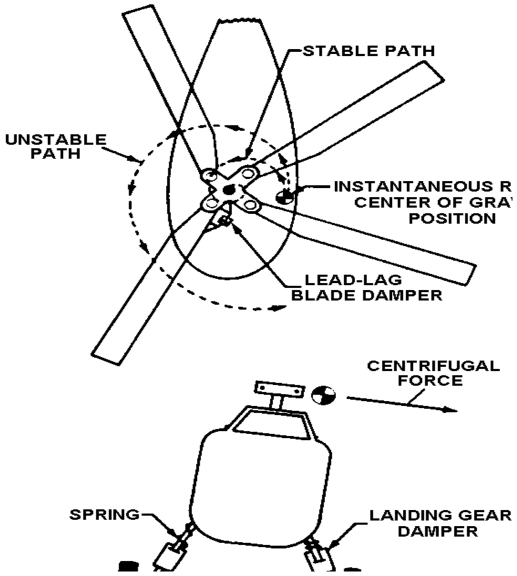
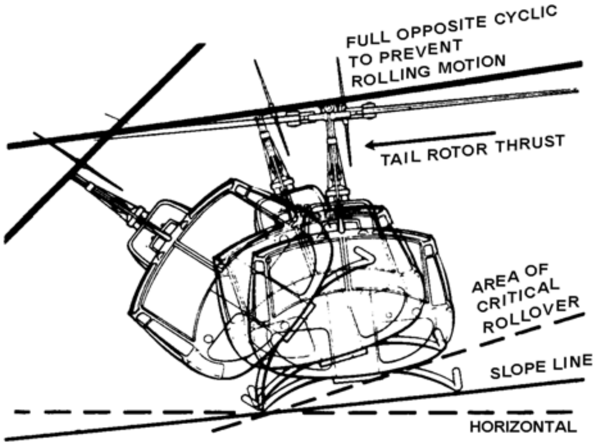


Figure 5-7

DYNAMIC ROLLOVER

During slope or crosswind landing or takeoff maneuvers, the helicopter is susceptible to a lateral rolling tendency called **dynamic rollover**. Each helicopter has a critical rollover angle beyond which recovery is impossible. If the critical rollover angle is exceeded, the helicopter will roll over on its side regardless of cyclic input. The rate of rolling motion is also critical. As the roll rate increases, it reduces the critical rollover angle from which recovery is still possible. Depending on the helicopter, the critical rollover angle may change, depending on which skid or wheel is in contact with the ground, the crosswind component, a lateral offset in CG, and amount of left pedal input for antitorque corrections.

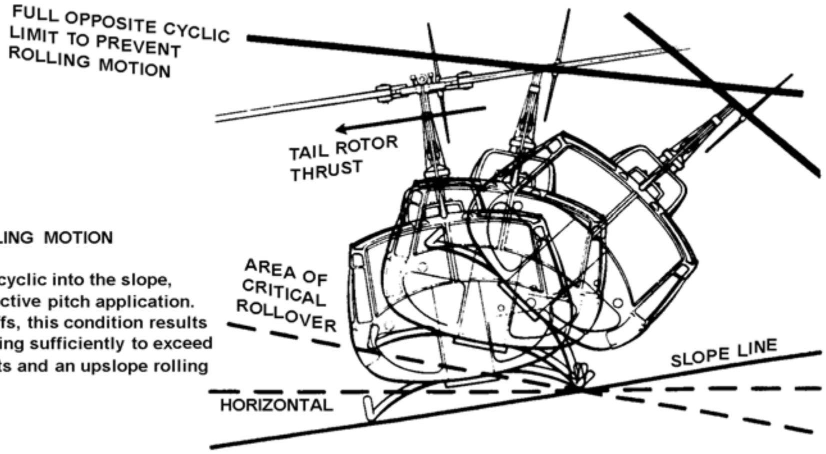
Dynamic rollover begins when the helicopter has only one skid or wheel on the ground and that gear becomes a pivot point for lateral roll (figure 5-8). When this happens, lateral cyclic control response is more sluggish and less effective than for a free-hovering helicopter. The gear may become a pivot point due to an uneven deck surface or poor takeoff/landing technique.



DOWNSLOPE ROLLING MOTION

Excessive application of collective pitch in coordination with cyclic application into the slope. When the downslope skid is on the slope, excessive application of collective may result in the upslope skid rising sufficiently to exceed lateral cyclic limits and induce a downslope rolling motion.

DOWNSLOPE ROLLING MOTION



UPSLOPE ROLLING MOTION

Excessive application of cyclic into the slope, in coordination with collective pitch application. During landings or takeoffs, this condition results in the downslope skid rising sufficiently to exceed lateral cyclic control limits and an upslope rolling motion occurs.

UPSLOPE ROLLING MOTION

Figure 5-8

Application of collective pitch is more effective than lateral cyclic in controlling the rolling motion because it changes main rotor thrust. A smooth, moderate collective reduction may be the most effective way to stop a rolling motion. Collective must not be reduced so fast as to cause the rotor blades to flap excessively and impact the fuselage or ground. Also, an excessive collective reduction rate may create a high roll rate in the opposite direction.

A sudden increase of collective pitch in an attempt to become airborne may be ineffective in stopping dynamic rollover. If the skid acting as a pivot point, does not break free of the ground as collective is increased, the rollover tendency will become more likely. If the skid does break free, a rolling motion in the opposite direction may occur as the mechanical axis attempts to align itself with the virtual axis.

When performing maneuvers with one skid in contact with the ground, like slope takeoffs and landings, care must be taken to keep the helicopter trimmed laterally. Control can be maintained if the pilot does not allow lateral roll rates to accelerate, and if the pilot keeps the bank angle from exceeding the critical rollover angle. The pilot must fly the aircraft into the air smoothly with gradual changes and corrections in pitch, roll, and yaw.

MAST BUMPING

The mechanical design of the semi-rigid rotor system dictates downward flapping of the blades must have some physical limit. **Mast bumping** is the result of excessive rotor flapping. Each rotor system design has a maximum flapping angle. If flapping exceeds the design value, the static stop will contact the mast. It is the violent contact between the static stop and the mast during flight that causes mast damage or separation. This contact must be avoided at all costs.

Mast bumping is directly related to how much the blade system flaps. In straight and level flight, blade flapping is minimal, perhaps 2° under usual flight conditions. Flapping angles increase slightly with high forward speeds, at low rotor rpm, at high-density altitudes at high gross weights, and when encountering turbulence. Maneuvering the aircraft in a sideslip or during low-speed flight at extreme CG positions can induce larger flapping angles.

The causes of mast bumping can be divided into most influential and less influential causes. The most influential causes of mast bumping are as follows:

1. Low G maneuvers.
2. Rapid, large cyclic motion (especially forward).
3. Flight near longitudinal/lateral CG limits.
4. High-slope landings.

Less influential causes include sideward/rearward flight, sideslip, and blade stall.

Excessive flapping is most probable when pilots allow the aircraft to approach low G conditions. Common maneuvers leading to low G flight include crossing a ridgeline during high- speed terrain flight, masking and unmasking, acquiring or staying on a target, and recovery from a pullup. Each of these maneuvers has in common an application of forward cyclic and/or a reduction of collective pitch which unloads thrust from the rotor head. Absence of main rotor thrust makes lateral cyclic control inputs ineffective.

In normal flight, the rotor head is loaded and all forces are in balance. If abrupt forward cyclic is applied, the main rotor is unloaded, significantly reducing thrust. The aircraft rolls right, due to the thrust of the tail rotor, which produces a rolling moment above the longitudinal axis of the helicopter. To counter this right roll, the pilot may apply left cyclic, causing excessive lateral flapping and mast bumping.

How should the pilot recover from this situation? Smoothly apply aft cyclic to restore thrust on the rotor head, then center the cyclic laterally. The pilot can resume normal inputs to bring the aircraft to a level flight attitude.

Mast bumping can result from incorrect pilot reaction to engine failure. Let's begin with a helicopter flying in normal cruise. The rotor disk and fuselage are tilted slightly forward. Viewed from the rear, the rotor disk is tilted slightly toward the left to counter the right tail rotor thrust. The aircraft roll axis is located slightly below the tail rotor thrust axis. All forces are balanced.

As the engine fails, rotor rpm, altitude, and airspeed will start to decay. Because the engine is no longer driving the main rotor, torque is diminishing. The tail rotor thrust produces a left yaw and right roll. The left yaw exposes the right side of the fuselage, aggravating the yaw.

The pilot sees a new aircraft attitude--nose down and left yaw. The aircraft appears to be in a roll to the right. Normal pilot reaction is to apply right pedal and left aft cyclic. The cyclic input tilts the rotor disk left and aft, creating larger flapping angles and possible mast bumping. The problem is the pilot reacted to the roll and not the engine failure. The correct response is to lower collective to maintain Nr and right pedal to return the aircraft to balanced flight, then maneuver the aircraft to a landing zone.

Another possible cause of mast bumping is tail rotor failure in forward flight. At the instant of failure, antitorque thrust goes to zero, and the aircraft yaws right. The aircraft rolls left, due to the left tilt of the main rotor system which counteracted the right thrust of the tail rotor above the roll axis.

The pilot sees an abrupt right yaw and left roll and counters with right/aft cyclic and left pedal. These inputs tilt the rotor disk toward the fuselage, dramatically increasing blade flapping. Mast bumping becomes a strong possibility. Correct pilot reaction for this failure is immediate reduction in power to reduce torque. This will reduce the yaw and allow time to correct for the roll tendency.

The last possible causes of mast bumping we will look at are slope landings and takeoffs.

When a helicopter rests on a slope, the mast is perpendicular to the slope, while the rotor disk remains parallel to "level" ground. Cyclic control stops, static stops, or mast bumping limits the cyclic control available for rotor tilt. These limits are reached sooner with a downslope wind condition. Extreme lateral CG loading on the upslope side of the aircraft will further restrict the amount of controllability.

VIBRATIONS

The final phenomenon we will discuss deals with helicopter vibrations. Vibrations of low magnitude are inherent in helicopters. It is important one have the ability to identify the type of vibration should it become excessive. It is important to note sources of vibrations can only be from rotating or moving parts. Other parts may vibrate sympathetically with these rotating or moving parts, but may not be a source.

Helicopter vibrations are classified into three categories: low, medium, and high frequencies.

Low frequency vibrations are the most common and originate from the main rotor. The frequency beat can be either one or two frequency beats per revolution. “One per” revolution vibrations can be classified as vertical or lateral. The source of one per vertical vibrations is the main rotor in an out-of-track condition. This occurs when one blade develops more lift than the other blade at the same point of rotation in the rotor disk. These vibrations are felt through the airframe as a vertical bounce and can be corrected by maintenance personnel.

Lateral one per vibrations are also caused by the main rotor system due to an imbalance in the main rotor from either a difference of weight between the blades (spanwise imbalance) or a misalignment of the blades (chordwise imbalance).

Rigidly controlled manufacturing processes nearly eliminate differences between the blades. These minor differences do affect the vibration level and are correctable by adjusting the trim tabs, blade pitch settings or small balance adjustments. Imbalances can also occur in the rotor hub.

Two-to-one vibrations are inherent in two-bladed rotor systems. A slight two-to-one vibration will be felt in the TH-57 during normal flight operations. A noticeable increase in vibration is an indication of a worn rotating control part.

Medium frequency vibrations have a frequency of 4 to 6 beats per revolution and are also inherent in helicopters. An increase in normal medium frequency vibrations can be caused by a change in the aircraft's ability to absorb normal vibrations, or by a loose aircraft component vibrating sympathetically with the rotor system. A rattling in the aircraft structure indicates these vibrations.

High frequency vibrations are characterized by a frequency too fast to count and are felt as a “buzz”. High frequency vibrations are always present and sometimes difficult to determine when they become abnormal.

Sources of high frequency vibrations can be anything rotating or vibrating at a speed equal to or greater than that of the tail rotor. Common sources are the tail rotor, engine, drive shaft, and barbell shaft, but the tail rotor is most commonly the culprit. Common tail rotor problems are an out-of-track condition, out-of-balance condition, or worn tail rotor components. These vibrations may be indicated by a buzz in the pedals. Vibration-sensing equipment can isolate the source of high frequency vibrations by matching the vibrating frequency to the frequency of dynamic components.

CHAPTER FIVE REVIEW QUESTIONS

1. Two factors which limit a helicopter's forward speed are_____________________and ___________________________.

2. As forward speed increases, the "no lift" areas of the rotor system move_______________.

3. List the indications of retreating blade stall.
____
____

4. High gross weight and low rotor rpm increase the likelihood of retreating blade stall._____. (True/False)

5. The proper procedure when encountering blade stall is to apply forward cyclic and full up collective.____________(True/False)

6. Vortex ring state usually occurs during_______________, _______________flight at__________airspeed while out of________________.

7. The tail rotor can experience vortex ring state.____________(True/False)

8. Ground resonance is a destructive phenomenon particular to hingeless rotor systems operating near the San Andreas fault.____________(True/False)

9. ________________and________________are the essential elements of dynamic rollover.

10. When a dynamic rollover situation is suspected, the best course of action is to_________.

11. A low-G maneuver may cause mast bumping.____________(True/False)

12. What other conditions are conducive to mast bumping?____________________________
____

13. When mast bumping occurs, the correct response is to apply________________cyclic.

14. The most common normal vibrations associated with helicopters are________________vibrations.

15. A buzz felt on the pedals is most likely associated with vibration originating from the ________________.

16. Loose external stores may cause________________vibrations.

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CHAPTER FIVE REVIEW ANSWERS

1. retreating blade stall and compressibility
2. left of center
3. vibration, loss of longitudinal control, cyclic feedback, violent pitch oscillation.
4. True
5. False
6. powered . . . descending . . . low . . . ground effect
7. True
8. False
9. Sideward force . . . ground pivot point
10. smoothly lower the collective
11. True
12. Engine and tail rotor failures in forward flight
13. aft
14. low frequency
15. tail rotor
16. medium frequency