Helicopter Aerodynamics - Aircraft Theory of Flight

The helicopter, as we know it today, falls under the classification known as rotorcraft. Rotorcraft is also known as rotary wing aircraft, because instead of their wing being fixed like it is on an airplane, the wing rotates. The rotating wing of a rotorcraft can be thought of as a lift producing device, like the wing of an airplane, or as a thrust producing device, like the propeller on a piston engine.

Helicopter Structures and Airfoils

The main parts that make up a helicopter are the cabin, landing gear, tail boom, power plant, transmission, main rotor, and tail rotor. [Figure 1]

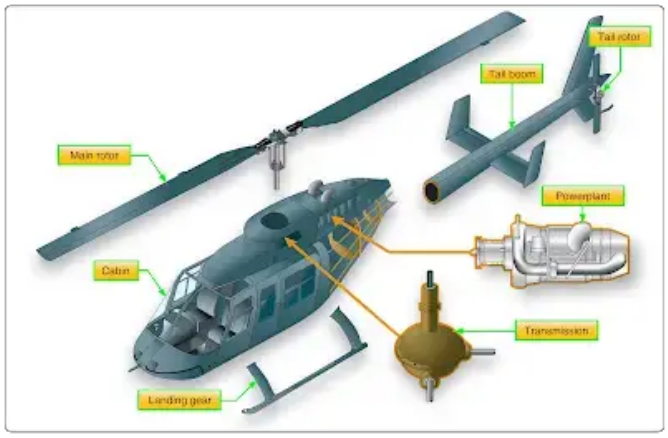

Figure 1. Main components of a helicopter

Main Rotor Systems

In the fully articulated rotor system, the blades are attached to the hub multiple times. The blades are hinged in a way that allows them to move up and down and fore and aft, and bearings provide for motion around the pitch change axis. Rotor systems using this type of arrangement typically have three or more blades. The hinge that allows the blades to move up and down is called the flap hinge, and movement around this hinge is called flap.

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The hinge that allows the blades to move fore and aft is called a drag or lag hinge. Movement around this hinge is called dragging, lead/lag, or hunting. These hinges and their associated movement are shown in Figure 2. The main rotor head of a Eurocopter model 725 is shown in Figure 3, with the drag hinge and pitch change rods visible. The semi-rigid rotor system is used with a two-blade main rotor. The blades are rigidly attached to the hub, with the hub and blades able to teeter like a seesaw. The teetering action allows the blades to flap, with one blade dropping down while the other blade rises. The blades are able to change pitch independently of each other. Figure 4 shows a Bell Jet Ranger helicopter in flight. This helicopter uses a semi-rigid rotor system, which is evident because of the way the rotor is tilted forward when the helicopter is in forward flight.

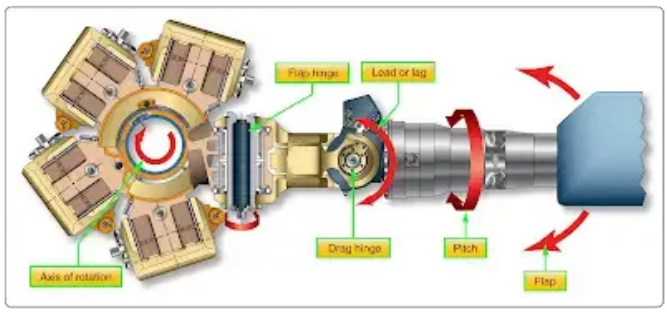

Figure 2. Fully articulated main rotor head

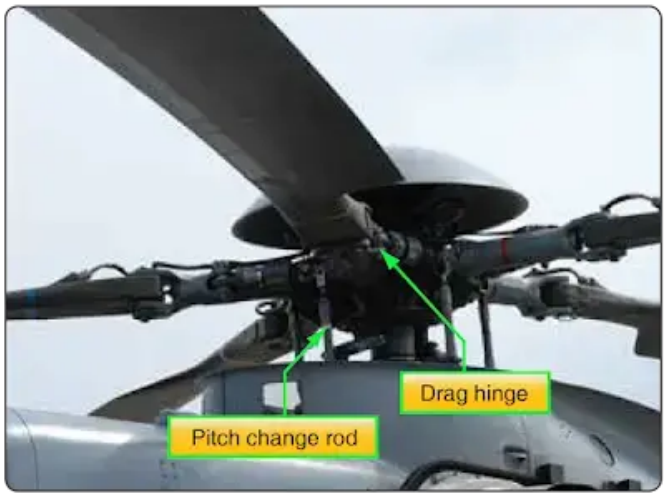

Figure 3. Eurocopter 725 main rotor head

Figure 4. Bell Jet Ranger with semi-rigid main rotor

With a rigid rotor system, the blades are not hinged for movement up and down, or flapping, or for movement fore and aft, or drag. The blades are able to move around the pitch change axis, with each blade being able to independently change its blade angle. The rigid rotor system uses blades that are very strong and yet flexible. They are flexible enough to bend when they need to, without the use of hinges or a teetering rotor, to compensate for the uneven lift that occurs in forward flight. The Eurocopter model 135 uses a rigid rotor system. [Figure 5]

Figure 5. Eurocopter Model 135 rigid rotor system

Anti-Torque Systems

Any time a force is applied to make an object rotate; there will be equal force acting in the opposite direction. If the helicopter's main rotor system rotates clockwise when viewed from the top, the helicopter will try to rotate counterclockwise. It was discovered that torque is what tries to make something rotate. For this reason, a helicopter uses what is called an anti-torque system to counteract the force trying to make it rotate.

One method that is used on a helicopter to counteract torque is to place a spinning set of blades at the end of the tail boom. These blades are called a tail rotor or anti-torque rotor, and their purpose is to create a force, or thrust that acts in the opposite direction of the way the helicopter is trying to rotate. The

tail rotor force, in pounds, multiplied by the distance from the tail rotor to the main rotor, in feet, creates a torque in pound-feet that counteracts the main rotor torque.

Figure 6. Aerospatiale helicopter tail rotor

Figure 6 shows a three-bladed tail rotor on an Aerospatiale AS-315B helicopter. This tail rotor has open tipped blades that are variable pitch, and the helicopter's anti-torque pedals that are positioned like rudder pedals on an airplane, control the amount of thrust they create. Some potential problems with this tail rotor system are as follows:

- The spinning blades are deadly if someone walks into them.
- When the helicopter is in forward flight and a vertical fin may be in use to counteract torque, the tail rotor robs engine power and creates drag.

An alternative to the tail rotor seen in Figure 6 is a type of anti-torque rotor known as a fenestron, or "fan-in-tail" design as seen in Figure 7. The rotating blades present less of a hazard to personnel on the ground and they create less drag in flight, because they are enclosed in a shroud.

Figure 7. Fenestron on a Eurocopter Model 135

A third method of counteracting the torque of the helicopter's main rotor is a technique called the "no tail rotor" system, or NOTAR. This system uses a high volume of air at low pressure, which comes from a fan driven by the helicopter's engine. The fan forces air into the tail boom, where a portion of it exits out of slots on the right side of the boom and, in conjunction with the main rotor downwash, creates a phenomenon called the "Coanda effect." The air coming out of the slots on the right side of the boom causes a higher velocity, and therefore lower pressure, on that side of the boom. The higher pressure on the left side of the boom creates the primary force that counteracts the torque of the main rotor. The remainder of the air travels back to a controllable rotating nozzle in the helicopter's tail. The air exits the nozzle at a high velocity, and creates an additional force, or thrust, that helps counteracts the torque of the main rotor. A NOTAR system is shown in Figures 8 and 9.

Figure 8. McDonnell Douglas 520 NOTAR

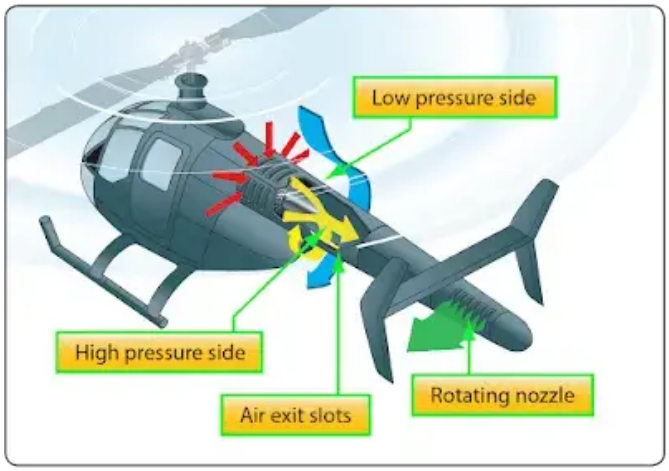

Figure 9. Airflow for a NOTAR

For helicopters with two main rotors, such as the Chinook that has a main rotor at each end, no anti-torque rotor is needed. For this type of helicopter, the two main rotors turn in opposite directions, and each one cancels out the torque of the other.

Helicopter Axes of Flight

Helicopters, like airplanes, have a vertical, lateral, and longitudinal axis that passes through the helicopter's center of gravity. Helicopters yaw around the vertical axis, pitch around the lateral axis, and rotate around the longitudinal axis. Figure 10 shows the three axes of a helicopter and how they relate to the helicopter's movement. All three axes will intersect at the helicopter's center of gravity, and the helicopter pivots around this point. Notice in the figure that the vertical axis passes almost through the center of the main rotor, because the helicopter's center of gravity needs to be very close to this point.

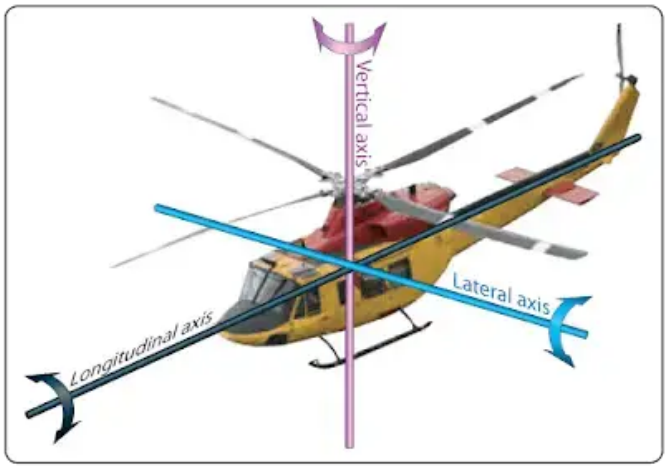

Figure 10. Three axes of rotation for a helicopter

Control Around the Vertical Axis

For a single main rotor helicopter, control around the vertical axis is handled by the anti-torque rotor, or tail rotor, or from the fan's airflow on a NOTAR type helicopter. Like in an airplane, rotation around this axis is known as yaw. The pilot controls yaw by pushing on the anti-torque pedals located on the cockpit floor, in the same way the airplane pilot controls yaw by pushing on the rudder pedals. To make the nose of the helicopter yaw to the right, the pilot pushes on the right anti-torque pedal. When viewed from the top, if the helicopter tries to spin in a counterclockwise direction because of the torque of the main rotor, the pilot will also push on the right anti-torque pedal to counteract the main rotor torque. By using the anti-torque pedals, the pilot can intentionally make the helicopter rotate in either direction around the vertical axis. The anti-torque pedals can be seen in Figure 11.

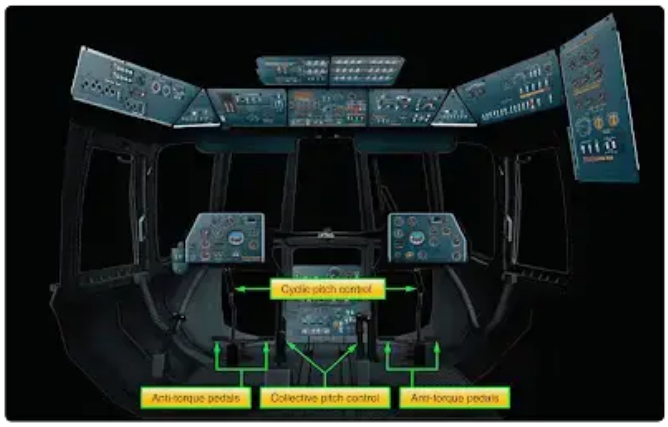

Figure 11. Helicopter cockpit controls

Some helicopters have a vertical stabilizer, such as those shown in Figures 10 and 12. In forward flight, the vertical stabilizer creates a force that helps counteract the torque of the main rotor, thereby reducing the power needed to drive the anti-torque system located at the end of the tail boom.

Figure 12. Agusta A-109 banking to the right

Control Around the Longitudinal and Lateral Axes

Movement around the longitudinal and lateral axes is handled by the helicopter's main rotor. In the cockpit, there are two levers that control the main rotor, known as the collective and cyclic pitch controls. The collective pitch lever is on the side of the pilot's seat, and the cyclic pitch lever is at the front of the seat in the middle. [Figure 11]

When the collective pitch control lever is raised, the blade angle of all the rotor blades increases uniformly and they create the lift that allows the helicopter to take off vertically. The grip on the end of the collective pitch control is the throttle for the engine, which is rotated to increase engine power as the lever is raised. On many helicopters, the throttle automatically rotates and increases engine power as the collective lever is raised. The collective pitch lever may have adjustable friction built into it, so the pilot does not have to hold upward pressure on it during flight.

The cyclic pitch control lever, like the yoke of an airplane, can be pulled back or pushed forward, and can be moved left and right. When the cyclic pitch lever is pushed forward, the rotor blades create more lift as they pass through the back half of their rotation and less lift as they pass through the front half. The difference in lift is caused by changing the blade angle, or pitch, of the rotor blades. The pitch change rods that were seen earlier, in Figures 2 and 3, are controlled by the cyclic pitch lever and they are what change the pitch of the rotor blades. The increased lift in the back either causes the main rotor to tilt forward, the nose of the helicopter to tilt downward, or both. The end result is the helicopter moves in the forward direction. If the cyclic pitch lever is pulled back, the rotor blade lift will be greater in the front and the helicopter will back up.

If the cyclic pitch lever is moved to the left or the right, the helicopter will bank left or bank right. For the helicopter to bank to the right, the main rotor blades must create more lift as they pass by the left side of the helicopter. Just the opposite is true if the helicopter is banking to the left. By creating more lift in the back than in the front, and more lift on the left than on the right, the helicopter can be in forward flight and banking to the right. In Figure 12, an Agusta A-109 can be seen in forward flight and banking to the right. The rotor blade in the rear and the one on the left are both in an upward raised position, meaning they have both experienced the condition called flap.

Some helicopters use a horizontal stabilizer, similar to what is seen on an airplane, to help provide additional stability around the lateral axis. A horizontal stabilizer can be seen on the Agusta A-109 in Figure 12.

Helicopters in Flight

Hovering

For a helicopter, hovering means that it is in flight at a constant altitude, with no forward, aft, or sideways movement. In order to hover, a helicopter must be producing enough lift in its main rotor blades to equal the weight of the aircraft. The engine of the helicopter must be producing enough power to drive the main rotor, and also to drive whatever type of anti-torque system is being used. The ability of a helicopter to hover is affected by many things, including whether or not it is in ground effect, the density altitude of the air, the available power from the engine, and how heavily loaded it is.

For a helicopter to experience ground effect, it typically needs to be no higher off the ground than one half of its main rotor system diameter. If a helicopter has a main rotor diameter of 40 ft., it will be in ground effect up to an altitude of approximately 20 ft. Being close to the ground affects the velocity of the air through the rotor blades, causing the effective angle of attack of the blades to increase and the lift to increase. So, if a helicopter is in ground effect, it can hover at a higher gross weight than it can when out of ground effect. On a windy day, the positive influence of ground effect is lessened, and at a forward speed of 5 to 10 mph the positive influence becomes less. In Figure 13, an Air Force CH-53 is seen in a hover, with all the rotor blades flapping up as a result of creating equal lift.

Figure 13. Air Force CH-53 in a hover

Forward Flight

In the early days of helicopter development, the ability to hover was mastered before there was success in attaining forward flight. The early attempts at forward flight resulted in the helicopter rolling over when it tried to depart from the hover and move in any direction. The cause of the rollover is what we now refer to as dissymmetry of lift.

When a helicopter is in a hover, all the rotor blades are experiencing the same velocity of airflow and the velocity of the airflow seen by the rotor blades changes when the helicopter starts to move. For helicopters built in the United States, the main rotor blades turn in a counterclockwise direction when viewed from the top. Viewed from the top, as the blades move around the right side of the helicopter, they are moving toward the nose; as they move around the left side of the helicopter, they are moving toward the tail. When the helicopter starts moving forward, the blade on the right side is moving toward the relative wind, and the blade on the left side is moving away from the relative wind. This causes the blade on the right side to create more lift and the blade on the left side to create less lift. Figure 14 shows how this occurs. In Figure 14, blade number 2 would be called the advancing blade, and blade number 1 would be called the retreating blade. The advancing blade is moving toward the relative wind, and therefore experiences a greater velocity of airflow. The increased lift created by the blade on the right side will try to roll the helicopter to the left. If this condition is allowed to exist, it will ultimately lead to the helicopter crashing.

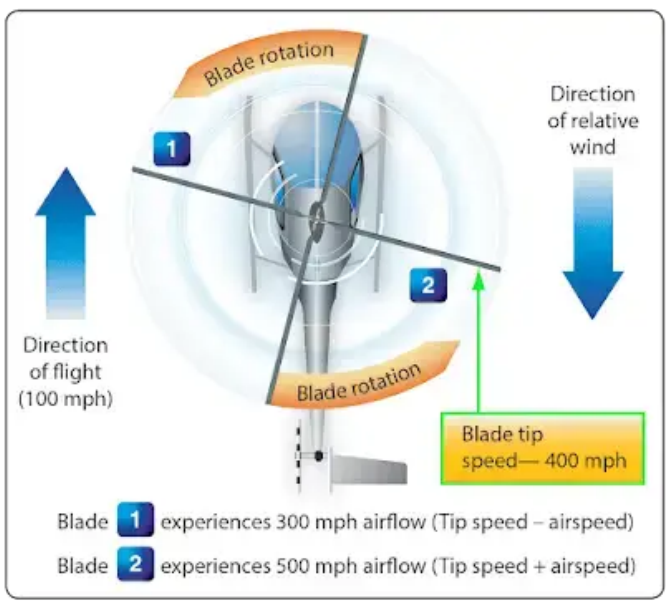

Figure 14. Dissymmetry of lift for rotor blades

Blade Flapping

To solve the problem of dissymmetry of lift, helicopter designers came up with a hinged design that allows the rotor blade to flap up when it experiences increased lift, and to flap down when it experiences decreased lift. When a rotor blade advances toward the front of the helicopter and experiences an increased velocity of airflow, the increase in lift causes the blade to flap up. This upward motion of the

blade changes the direction of the relative wind in relation to the chord line of the blade, and causes the angle of attack to decrease. The decrease in the angle of attack decreases the lift on the blade. The retreating blade experiences a reduced velocity of airflow and reduced lift, and flaps down. By flapping down, the retreating blade ends up with an increased angle of attack and an increase in lift. The end result is the lift on the blades is equalized, and the tendency for the helicopter to roll never materializes.

The semi-rigid and fully articulated rotor systems have flapping hinges that automatically allow the blades to move up or down with changes in lift. The rigid type of rotor system has blades that are flexible enough to bend up or down with changes in lift.

Advancing Blade and Retreating Blade Problems

The blade advancing toward the relative wind sees the airflow at an ever increasing velocity as a helicopter flies forward at higher and higher speeds. Eventually, the velocity of the air over the rotor blade will reach sonic velocity, much like the critical Mach number for the wing of an airplane. When this happens, a shock wave will form and the air will separate from the rotor blade, resulting in a high-speed stall.

As the helicopters forward speed increases, the relative wind over the retreating blade decreases, resulting in a loss of lift. The loss of lift causes the blade to flap down and the effective angle of attack to increase. At a high enough forward speed, the angle of attack will increase to a point that the rotor blade stalls. The tip of the blade stalls first, and then progresses in toward the blade root.

When approximately 25 percent of the rotor system is stalled, due to the problems with the advancing and retreating blades, control of the helicopter will be lost. Conditions that will lead to the rotor blades stalling include high forward speed, heavy gross weight, turbulent air, high-density altitude, and steep or abrupt turns.

Autorotation

The engine on a helicopter drives the main rotor system by way of a clutch and a transmission. The clutch allows the engine to be running and the rotor system not to be turning, while the helicopter is on the ground, and it also allows the rotor system to disconnect from the engine while in flight, if the engine fails. Having the rotor system disconnect from the engine in the event of an engine failure is necessary if the helicopter is to be capable of a flight condition called autorotation.

Autorotation is a flight condition where the main rotor blades are driven by the force of the relative wind passing through the blades, rather than by the engine. This flight condition is similar to an airplane gliding if its engine fails while in flight. As long as the helicopter maintains forward airspeed, while decreasing altitude and the pilot lowers the blade angle on the blades with the collective pitch, the rotor blades will continue to rotate. The altitude of the helicopter, which equals potential energy, is given up in order to have enough energy, which will then be kinetic energy, to keep the rotor blades turning. As the helicopter nears the ground, the cyclic pitch control is used to slow the forward speed and to flare the helicopter for

landing. With the airspeed bled off, and the helicopter now close to the ground, the final step is to use the collective pitch control to cushion the landing. The airflow through the rotor blades in normal forward flight and in an autorotation flight condition are shown in Figure 15. In Figure 16, a Bell Jet Ranger is shown approaching the ground in the final stage of an autorotation.

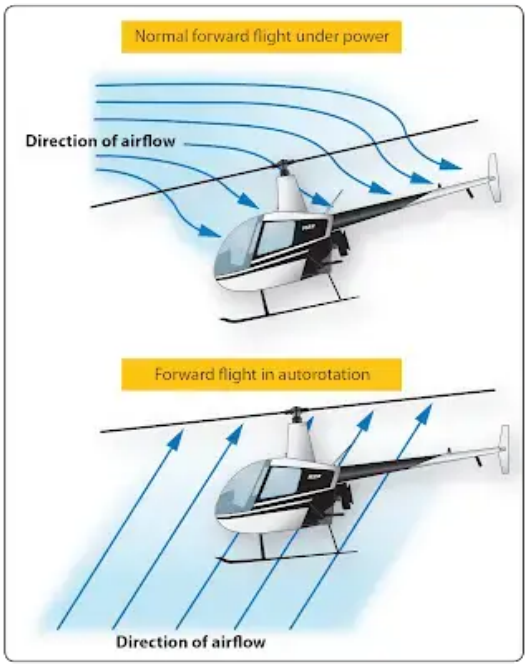

Figure 15. Rotor blade airflow during normal flight and during autorotation

Figure 16. Bell Jet Ranger in final stage of autorotation

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