The way a helicopter rotor flaps is the most important factor in both stability and control. Stability is the tendency for a system to remain as is — and differences in the level of stability are illustrated by the increasing skill required to master a tricycle, a bicycle, and a unicycle. Control, on the other hand, is primarily a measure of the accelerations a system can generate. For example, imagine the increasing difficulty in docking a rowboat, a cabin cruiser, and an aircraft carrier.

When considered in the light of these definitions, blade flapping can contribute to both the stability and the control of a helicopter. If flapping occurs as a result of changes in flight conditions while the pilot holds his controls fixed, then it is a stability characteristic. But, if it results from pilot action, then it is a control characteristic. In both cases, the effect is primarily felt as a moment about the aircraft's center of gravity.

The two factors that contribute to this moment are shown in Figure 13-1. They are the tilt of the thrust vector — normally perpendicular to the tip-path plane — and the hub moment due to flapping-hinge offset. Rotors without a flapping-hinge offset obtain all of the effect of flapping from the tilt of the thrust vector. These rotors are generally placed high above the CG to maximize this effect for control purposes.

Hub moment from offset flapping hinges can be visualized (as in the illustration) as a couple generated by centrifugal forces on the blades on opposite sides of the rotor. The hinge offset allows the rotor to be located close to the fuselage. These rotors also have the advantage of being able to produce control moments even at very low values of rotor thrust— such as in zero-G maneuvers.

They have a disadvantage, however, in that any adverse stability characteristic due to flapping is magnified. For very large offsets, care must be taken to avoid tipping over on the ground with inadvertent control motions.

Stability characteristics due to flapping are those associated with changes in shaft attitude with respect to the initial flight path, rates of pitch or roll, and changes in velocities. Flapping characteristics can be explained on the basis that at the flapping hinges (or at the effective
Shaft Tilted in Hover

Effects of Rotor Flapping

hinge in the case of a hingeless rotor), the summation of moments produced by aerodynamic, inertial, and centrifugal forces must be zero.

Both stability and control characteristics are essential to the pilot’s perception of the overall handling qualities of his helicopter, so we will now look at how these factors affect the machine under various conditions.

Shaft Tilted in Hover

If the rotor shaft is tilted while the aircraft is in hover, aerodynamic forces will be generated forcing the tip-path plane to align itself perpendicular to the shaft. The sequence of steps leading to this is shown in Figure 13-2.

First, there is the tilt of the shaft alone as the rotor disc acts as a gyroscope and remains in its original plane. However, since blade feathering is referenced to the shaft, the angle of attack of the right-hand blade is increased and that of the left-hand blade decreased by the same amount.

This causes the rotor to flap until it is perpendicular to the shaft, where it will again be in equilibrium with a constant angle of attack around the azimuth and the moments will be balanced. This alignment is very rapid, usually taking less than one revolution following a sudden tilt. Because of this, the flapping motion in hover has practically no effect on the stability of the helicopter in terms of holding a given attitude.

Shaft Tilted in Forward Flight

If the shaft is tilted laterally (rolled) in forward flight, the effect is the same as it is in hover—the tip-path follows the shaft and the flapping with respect to the shaft remains unchanged. However, if the shaft is tilted longitudinally (pitched), the non-uniformity of velocity distribution produces a different situation.

Figure 13-3 illustrates this with a rotor that, for simplicity’s sake, starts from a condition of zero lift on the advancing and retreating blades. Following a, sudden nose-up tilt, the immediate result is the same as in hovering: the advancing blade receives an increase in angle of attack and the retreating blade receives a decrease—producing an unbalanced lift that causes the tip-path plane to flap nose up. In forward flight, however, when the blade flaps up until it is perpendicular with the shaft, the forces are not yet balanced.

This unbalance is due to the forward-flight velocity vector. The airflow coming at the machine as a result of its forward motion modifies both the local velocity and
the local angle of attack on the advancing and retreating blades. Both blades have positive angles of attack, with the angle on the retreating blade actually being greater than on the advancing side, as you see in Figure 13-3C. The aerodynamic lift on the retreating blade is less than on the advancing blade, because the lift of a blade is proportional to the product of the angle of attack and the square of the resultant velocity. This causes the rotor to flap past the perpendicular to the shaft to a more nose-up position where the forces are in balance, as shown in Figure 13-3D. The magnitude of the excessive flapping is approximately proportional to the square of the forward speed. The result is negative rotor angle-of-attack stability, since the aft flapping generates a nose-up pitching moment about the CG that tends to cause a further increase in the shaft's angle of attack.

### Horizontal Stabilizer

To compensate for this undesirable characteristic, the helicopter designer follows the airplane designer and adds a horizontal stabilizer. Since the effectiveness of the stabilizer is proportional to the square of the forward speed, it will correct for the rotor instability at all speeds, once it is sized for a given flight condition.

A stabilizer is not an absolute necessity, however, and most pilots can cope with an unstable aircraft—just as they can learn to ride a unicycle. Many helicopters designed before 1960 had inadequate or no stabilizers but they were considered successful. Actually, they were following a trail blazed by the Wright Flyer—an unstable but controllable aircraft.

Pilots, of course, prefer their aircraft to be both stable and controllable but given the choice between high stability and high controllability they will choose the latter, since it allows them to escape tight situations that even a stable aircraft occasionally encounters.

Another effect of a longitudinal shaft tilt in forward flight is an increase in lateral flapping along with the change in rotor coning. For the nose-up tilt just described, the rotor thrust increases and with it the coning and the lateral flapping. This change in lateral flapping is also proportional to the square of the forward speed but is somewhat less than the change in longitudinal flapping. The resultant rolling moment is a source of cross-coupling, where a change in pitch results in a roll. This particular cross-coupling effect doesn’t work both ways, since a change in roll angle will not result in pitch. Airplanes are largely free from this problem, with the exception of some high-powered propeller-driven models.

### Shaft with angular velocity

If the helicopter is pitching or rolling due to a wind gust or a pilot’s control pulse, the rotor will flap such as to reduce the rate of pitch or roll. That is, it will act as a damper. This damping is very helpful to the pilot in mollifying the effects of gusts or overenthusiastic control motions.
The damping is produced because the tilt of the tip-path plane lags behind the motion of the shaft by an amount proportional to the rate of pitch or roll. Figure 13-4 illustrates this effect by using a helicopter mounted on a trunnion. If we force the model to pitch up at a steady rate, the rotor disc will follow the shaft — since it has an equilibrium position to achieve once the pitching motion stops.

The flapping angle by which the rotor lags the shaft produces flapping velocities on the left and right sides. These, in turn, generate unbalanced aerodynamic moments that precess the rotor disc as a gyroscope. (That is, they have their maximum effect 90° later.) The faster the rate of pitch, the more the rotor must lag to produce a sufficient precessional moment. Similarly, a rotor with a high inertia will lag more than one with a low inertia. The resulting blade flapping produces a nose-down pitching moment on the helicopter that resists the forced pitching motion and is, therefore, a damping moment. The flapping that produces the damping effect is also accompanied by some flapping cross-coupling in the other axis. For example, during a nose-up pitching motion, the blades over the nose and over the tail initially have different angles of attack caused by the vertical velocity associated with the pitch rate. This difference in angle of attack is automatically compensated for by the blade flapping down on the left side and up on the right side enough to produce flapping velocities at these two blade positions equal and opposite the velocities due to the pitch rate.

The production of both a lateral and a longitudinal flapping by a pure pitch rate is another source of cross-coupling. This effect is a two-way street, since either pitch or roll rates will produce flapping in the other axis. For most rotors, the cross-coupling flapping is approximately half the primary damping flapping.

**Change in Forward Speed**

The flapping caused by a change in forward speed was explained in our discussion of de la Cierva’s rattan-sparred autogyro model. The amount of this flapping is approximately proportional to the product of forward speed and rotor thrust. If the individual blades have no lift to start with, the increase in forward speed will produce no flapping.

The rearward tilt of the rotor produces a nose-up pitching moment with respect to the helicopter’s center of gravity as shown in Figure 13-5. This change in pitching moment due to a change in forward speed is known as speed stability or static longitudinal stability and is one of the most important differences between a helicopter and an airplane. The airplane has no corresponding change in pitching moment with respect to speed.

This difference can be illustrated with an airplane model mounted in a low-speed wind tunnel. If an adjustable elevator is used to trim the pitching moment to zero at one tunnel speed and fixed angle of attack, the moment will remain zero for any other tunnel speed. A helicopter
model in a similar test, however, will generate a pitching moment due to rotor flapping as the tunnel speed is changed.

In free flight, the change in longitudinal flapping with increasing speed is stabilizing since it produces a nose-up moment causing the helicopter to pitch up and slow down to its original speed. A manifestation of positive speed stability is the requirement for the pilot to move the cyclic stick forward to keep the helicopter trimmed as he increases speed.

In some cases, the effect of a horizontal stabilizer carrying positive lift (or the interference effects of the front rotor on the rear rotor of a tandem helicopter) can overpower the natural speed stability of the rotor and produce negative stability. This happens when an increase in speed with the controls held fixed produces a nose-down pitching moment, causing the helicopter to go into a dive as the speed and nose-down moment increase. With negative speed stability, the pilot will push the stick forward to accelerate to a new speed but when he finally trims at that speed, the stick will be further aft than when he started. This characteristic is undesirable from a flying-qualities standpoint but pilots who can learn to ride unicycles can learn to handle such problems.

Since the flapping due to a change in speed is actually generated by a change in the asymmetry of the velocity distribution at the blades, the effect can also be produced by holding forward speed constant and changing rotor speed.

Normally, helicopters fly with almost constant rotor speed but in case of a sudden engine failure, the rotor speed initially decreases while the forward speed remains about the same. The result is an increase in the asymmetry of the velocity distribution with corresponding nose-up flapping. This helps the pilot make the safe transition to an autorotative condition where air must be coming up from below the rotor disc rather than from above as in normal flight.

**Change in sideslip angle**

In addition to the flapping effects due to changes in forward speed, the rotor also responds to changes in sideslip angle, since blade flapping is produced by conditions referenced to the flight path rather than to whatever orientation the fuselage might have at the time.

Imagine a helicopter in forward flight with no sideslip and the rotor trimmed so that the tip-path plane is perpendicular to the shaft. If the flight direction is suddenly changed (Figure 13-6) so that the helicopter is flying directly to the right without changing the fuselage heading or control settings, the blade over the tail becomes the advancing blade and the one over the nose the retreating blade. Since the cyclic pitch no longer corresponds to trim conditions, the rotor will flap down on the helicopter's left side because of the asymmetrical velocity distribution — thus producing a rolling moment to the left.

![Figure 13-6 Effect of Sideslip on Rotor Flapping](http://www.ACTechbooks.com)
In practice, sideslip angles are less than the 90° used for illustration, but the trend is the same — the helicopter tends to roll away from the sideward velocity. This is the same characteristic found on airplanes with dihedral (both wings slanted up) and is known as the positive dihedral effect.

It is a desirable characteristic that helps the pilot. With negative dihedral, a sideslip would tend to roll the aircraft into an ever-tightening spiral dive. Positive dihedral manifests itself during flight as a lateral stick displacement required in the direction of the sideslip to stabilize the aircraft.

The rolling moment due to dihedral is also accompanied by a pitching moment. Again going back to the case of the helicopter flying directly to the right, the blade pointing in the direction of flight was originally the advancing blade and had a low pitch in the zero-sideslip trim condition. It still has a low pitch and thus will cause the rotor to flap down over the nose, producing a nose-down pitching moment.

Similarly, during flight to the left, the blade pointing in the direction of flight has a high pitch and will cause the rotor to flap up over the tail — also producing a nose-down pitching moment. Thus, steady sideslip in either direction requires aft stick displacement, an effect that does not exist on an airplane.

Somewhat surprisingly, if the same analysis is made on a rotor turning clockwise when viewed from above, the pitching moment direction is unchanged — nose-down for sideslip in either direction. This pitching effect is not always observable in flight, since other pitching moments may be generated by changes in airflow conditions on the horizontal stabilizer and tail boom as they move out from behind the fuselage during sideslip.

**Cyclic Pitch Change**

For a rotor with blades hinged at the center of rotation, a 1° change in cyclic pitch in hover will result in a 1° change in flapping a quarter of a revolution later. This is because the rotor's stable condition is with no cyclic-pitch variations in respect to the tip-path plane without regard to the relative position between the shaft and the tip-path plane. Thus, the rotor flaps just enough to cancel out the initial cyclic input and return, to its initial configuration with respect to the tip-path plane. This is one result of the equivalence between flapping and feathering.

If the rotor has a flapping-hinge offset, the maximum flapping will be at somewhat less than 90°. This phasing means that the helicopter will be subjected to some roll motion during a maneuver when the pilot is calling for only pitching motion by moving his stick straight fore and aft. This is known as acceleration cross-coupling, since it occurs while the pilot is attempting to generate an angular acceleration in either pitch or roll. Because the phasing is constant for a given rotor, it is sometimes