Aerodynamic Principles of Large-Airplane Upsets

To our readers:

Loss of airplane control in flight is a leading cause of fatalities in the commercial aviation industry. A variety of reasons exist for airplane upsets, but none is statistically significant. Reducing the number of reasons for upsets is a continual training process, and eliminating one reason will not necessarily reduce the number of loss-of-control accidents and fatalities. Additionally, many reasons for upsets are associated with the environment, in which case avoidance is the best solution, but is not always possible. Therefore, pilots must have the necessary knowledge and skills to recover an upset airplane.

Aerodynamic principles of large, swept-wing commercial jet airplanes are similar among all manufacturers. In the interest of safety, and the desire to acknowledge the commonality in recovery techniques, this article was written jointly by Airbus, Boeing Commercial Airplane Group, and Douglas Products Division. The article focuses on Airbus and Boeing airplanes that do not have electronic flight controls, commonly known as fly-by-wire. However, when a fly-by-wire airplane is in a degraded control law (mode), the recovery techniques are appropriate. Additionally, certain conditions can upset any airplane and the basic principles of recognition and recovery still apply regardless of the flight control architecture.

Pilots can be exposed to an infinite number of slightly different situations. For this reason, it is not possible to develop specific recovery procedures for each. Operators should address procedural application of techniques within their fleet structures. Pilots who are knowledgeable about aerodynamics and who possess the skills to apply basic recovery techniques can return an upset airplane to normal flight parameters. Airbus and Boeing are dedicating many resources and actively working with an industry team to develop an airplane upset recovery training aid. When it is completed we will make it available to our customers at no charge.

Airline flight crews constantly strive to provide passengers with a smooth ride while ensuring an extremely high degree of safety. Pilots in line operation seldom experience the excessive pitch or bank angles associated with an airplane upset. However, with a greater understanding of the fundamental principles of aerodynamics, pilots will be better equipped to successfully maneuver the airplane back to straight-and-level flight in the unlikely event they experience an airplane upset.

Aerodynamic principles applied to large, swept-wing commercial jet airplanes are similar among all manufacturers, and the recommended techniques for recovering from an upset in an airplane subject to these principles are also compatible. Pilots who understand the conditions of an upset, though such an event is unlikely, will be better prepared to recover from it. The four conditions that generally describe an airplane upset (figure 1) are **unintentional**:

- Pitch attitude more than 25 degrees nose up.
- Pitch attitude more than 10 degrees nose down.
- Bank angle more than 45 degrees.

- Flight within these parameters at airspeeds inappropriate for the conditions.

In order to avoid an upset, or to recover from one, pilots must understand the following:

- 1. Aerodynamic fundamentals applied to large airplanes.
- 2. Application of aerodynamic fundamentals to airplane upsets.
- 3. Recovery techniques.

Aerodynamic Fundamentals Applied to Large Airplanes
Airline pilots are thoroughly familiar with airplane handling qualities under normal flight conditions. In general, if pitch is increased (the result of pulling back on the controls), altitude increases; in level flight, if thrust is increased, airspeed increases.

However, when an airplane is taken to the edges of the flight envelope, different situations result. It is possible, for example, to encounter flight conditions where an increase in thrust is needed to maintain a slower airspeed, and where an increase in pitch will decrease altitude. While airline pilots may have received training on how to use flight controls to recover from airplane upsets, they rarely, if ever, experience these conditions in line operations.

In the context of aerodynamics, the following three basic concepts should be understood:

- Energy management.
- Pitch control.
- Lateral and directional control.

ENERGY MANAGEMENT.
Three sources of energy are available to generate aerodynamic forces and thus maneuver the airplane: kinetic, which increases with increasing airspeed; potential, which is proportional to altitude; and chemical, which is from the fuel in the airplane's tanks. The term "energy state" describes how much of each kind of energy the airplane has available at any given time. The critical element to realize is that pilots who understand the airplane energy state will be in a position to know what options are available to maneuver the airplane.

The airplane is continuously expending energy in flight because of drag. Drag is usually offset by using some of the stored chemical energy -- that is, by burning fuel in the engines. (At landing, the reverse is the case when wheel brakes [friction] and thrust reversers dissipate energy.)

During maneuvering, the three types of energy can be traded, or exchanged, usually at the cost of additional drag. This process of consciously manipulating the energy state of the airplane is referred to as energy management. Airspeed (kinetic energy) can be traded for altitude (potential energy). Altitude therefore can be traded for airspeed, as in a dive. This trading of energy, however, must be balanced with the final desired energy state in mind. For example, when a pilot trades altitude for airspeed by descending the airplane, the descent angle must be selected carefully in order to capture the final desired energy state with the introduction of the necessary chemical energy.

This becomes especially important when the pilot wants to generate aerodynamic forces and moments to maneuver the airplane. Kinetic energy can be traded for potential energy (climb). Potential energy can be converted to kinetic energy. Chemical energy can be converted by engines to either potential or kinetic energy, but only at specified rates. These relationships are shown in figure 2.

The objective of maneuvering the airplane is to manage energy so that kinetic energy stays between limits (stall and placards), potential energy stays within limits (terrain-to-buffet altitude), and chemical energy stays above certain thresholds (fuel in tanks). These concepts are especially important to understanding recovery from an airplane upset.

In managing these energy states and trading between the sources of energy, the pilot does not directly control the energy. The pilot controls the direction and magnitude of the forces acting on the airplane. These forces result in accelerations applied to the airplane. The result of these accelerations is a change in the orientation of the airplane and a change in the direction, magnitude, or both, of the flight path vector. Ultimately, velocity and altitude define the energy state.

This process of controlling forces to change accelerations and produce a new energy state takes time. The amount of time required is a function of the mass of the airplane and the magnitude of the applied forces, and is governed by Newton's laws. Airplanes of larger mass generally take longer to change orientation than do smaller ones. This longer time requires the pilot to plan ahead in a large-mass airplane to ensure that the actions taken will result in the final desired energy state.

Thrust, weight, lift, and drag are the forces that act upon an airplane (figure 3). Maneuvering is accomplished by variations of these forces and is controlled by the throttles and flight controls.

The lift force in pounds or kilograms generated by a surface is a result of the angle of attack, the dynamic pressure of the air moving around it (which is a function of the airspeed and density), and the size and shape of the surface. Lift varies with angle of attack for constant speed and air density. As angle of attack is increased, the lift increases proportionally, and this increase in lift is normally linear. At a specific angle of attack, however, the resulting lift due to angle of attack behaves differently. Instead of increasing, it decreases. At this critical angle of attack, the air moving over the upper wing surface can no longer remain attached to the surface, the flow breaks down, and the surface is considered stalled. The breakdown of the flow and consequent loss of lift is dependent only upon the angle of attack of the surface. This is true regardless of airplane speed or attitude. An airplane stall is characterized by any one (or a combination) of the following conditions:

- Buffeting.
- Lack of pitch authority.
- Lack of roll control.
- Inability to arrest descent rate.

These conditions are usually accompanied by a continuous stall warning. A stall must not be confused with the stall warning that alerts the pilot to an approaching stall. Recovery from an approach to stall is not the same as a recovery from an actual stall. An approach to stall is a controlled flight maneuver; a stall is an out-of-control, but recoverable, condition.

Flight controls give the pilot the ability to manage the forces acting on the airplane in order to maneuver; that is, to change the flight path of the airplane (figure 4).

PITCH CONTROL.
Movement around the lateral axis of an airplane is called pitch (figure 5), and is usually controlled by the elevator. Given any specific combination of airplane configuration, weight, center of gravity, and speed, all forces will be balanced at one elevator position. In flight, the two elements most easily changed are speed and elevator position; as speed changes, the elevator position must be adjusted to balance the aerodynamic forces. Control forces required for this

new position can be neutralized by adjusting the pitch trim mechanism. Typically, the pitch trim mechanism adjusts the position of the horizontal stabilizer.

An important concept for pilots to understand is that if the airplane is at a balanced, "in-trim" angle of attack in flight, it will generally seek to return to the trimmed angle of attack if upset by external forces or momentary pilot input. This is due to the longitudinal stability designed into that airplane.

Changes in airplane configuration also affect pitch control. For example, flap extension usually creates a nose-down pitching moment; flap retraction usually creates a nose-up pitch. When extended, wing-mounted speed brakes usually produce a nose-up pitching moment.

Pitch attitude can also change with thrust (figure 5). With underwing engines, reducing thrust creates a nose-down pitching moment; increasing thrust creates a nose-up pitching moment. The combination of elevator and stabilizer positions also affects pitch. In normal maneuvering, the pilot displaces the elevator by applying an elevator control force. The pilot then trims the stabilizer by driving it to a new position to remove the elevator control force. This new stabilizer position is faired with the elevator. If they are not faired (one is down and the other is up), one cancels out the other. This condition limits the airplane's ability to overcome other pitching moments from configuration changes or thrust.

LATERAL AND DIRECTIONAL CONTROL.
Similar to how feathers on the back of an arrow make it fly straight, airplanes have a vertical stabilizer to keep the nose into the wind. The rudder is attached to the vertical stabilizer, and movement of the rudder into the airflow creates a force and a resulting rotation about the vertical axis. This motion is called yaw (figure 5). The vertical stabilizer and the rudder are sized to meet two objectives: to control asymmetric thrust from an engine failure at the most demanding flight condition (greater than V_1), and to generate sufficient sideslip for crosswind landings. To achieve these objectives, the vertical stabilizer and rudder must be capable of generating powerful yawing moments and large sideslip angles.

Motion about the longitudinal axis is called roll (figure 5). Control inputs cause the ailerons and spoilers to control the airplane's roll rate. The aileron and spoiler movement changes the local angle of attack of the wing, changing the amount of lift and causing rotation about the longitudinal axis.

During an airplane upset, unusually large amounts of aileron or spoiler input may be required to recover the airplane. After input of full roll control, it may be necessary to use rudder in the direction of the desired roll. The amount of rudder required to coordinate the maneuver will depend on the airplane type and associated systems. An uncoordinated rudder movement results in a nose movement (yaw) in the direction of the rudder input. The yaw creates sideslip, which causes a roll in the same direction as the rudder input. The roll due to sideslip is referred to as dihedral effect.

When encountering an angle of attack associated with the onset of stick shaker, ailerons and spoilers are still effective at controlling roll. However, as the angle of attack continues to increase beyond the angle associated with stick shaker onset, the airflow over the wing separates and airplane buffet generally begins. Without decreasing the angle of attack, the combination of ailerons and spoilers in this separated airflow may not always generate a significant force; therefore, little rotation about the longitudinal axis occurs on some models. Since the vertical stabilizer/rudder is rarely aerodynamically stalled, it is still possible to generate a force and a nose rotation with associated roll rate.

However, at a high angle of attack, pilots must be extremely careful when using the rudder for assisting lateral control. Excessive rudder can cause excessive sideslip which could lead to departure from controlled flight.

Asymmetric thrust creates a yawing and a rolling moment. An engine failure creates an undesired yaw and roll. Conversely, an intentional engine throttle up or down could create a desired yawing moment followed by a desired rolling moment. Using asymmetric thrust to control roll is not precise because of the lag time associated with engine spool-up or spool-down and should be avoided unless no other means of roll control are available. Generally, the pilot should attempt to restore symmetric thrust conditions during an upset recovery.

Applying Aerodynamic Fundamentals to Airplane Upsets
Though airline pilots in line operation will rarely, if ever, encounter an upset situation, understanding how to apply aerodynamic fundamentals in such a situation will help them control the airplane. Several techniques are available for recovering from an upset. In most situations, if a technique is effective, it is not recommended that pilots use additional techniques. Several of these techniques are discussed in the example scenarios below:

- Stall recovery.
- Nose high, wings level.
- Nose low, wings level.
- High bank angles.

STALL RECOVERY.
In all upset situations, it is necessary to recover from a stall before applying any other recovery actions. To recover from the stall, angle of attack must be reduced below the stalling angle. Nose-down pitch control must be applied and maintained until the wings are unstalled. Under certain conditions, on airplanes with underwing-mounted engines, it may be necessary to reduce some thrust in order to prevent the angle of attack from continuing to increase. Once unstalled, upset recovery actions may be taken and thrust reapplied as needed.

NOSE HIGH, WINGS LEVEL.
In a situation where the airplane pitch attitude is unintentionally more than 25 degrees nose high and increasing, the kinetic energy (airspeed) is decreasing rapidly. According to the energy management discussed earlier, the energy is actually being stored as potential energy. As airspeed decreases, the pilot's ability to maneuver the airplane also decreases. If the stabilizer trim setting is nose up, as for slow-speed flight, it partially reduces the nose-down authority of the elevator. Further complicating this situation, as the airspeed decreases, the pilot could intuitively make a large thrust increase. This will cause an additional pitch up for underwing-mounted engines. At full thrust settings and very low airspeeds, the elevator -- working in opposition to the stabilizer -- will have limited control to reduce the pitch attitude.

In this situation the pilot should trade the potential energy of altitude for airspeed, and would have to maneuver the airplane's flight path back toward the horizon. This is accomplished by the input of up to full nose-down elevator and the use of some nose-down stabilizer trim. These actions should provide sufficient elevator control power to produce a nose-down pitch rate. It may be difficult to know how much stabilizer trim to use, and care must be taken to avoid using too much trim. Pilots should not fly the airplane using stabilizer trim, and should stop trimming nose down when they feel the g force on the airplane lessen or the required elevator force lessen. This use of stabilizer trim may correct an out-of-trim airplane and solve a less-critical problem before the pilot must apply further recovery measures. Because a large nose-down pitch rate will result in a condition of less than 1 g, at this point the pitch rate should be controlled by modifying control inputs to maintain between 0 to 1 g. If altitude permits, flight tests have determined that an effective way to achieve a nose-down pitch rate is to reduce some thrust on airplanes with underwing-mounted engines. The use of this technique is not intuitive and must be considered by each operator for their specific fleet types.

If normal pitch control inputs do not stop an increasing pitch rate, rolling the airplane to a bank angle that starts the nose down should work. Bank angles of about 45 degrees, up to a maximum of 60 degrees, could be needed. Unloading the wing by maintaining continuous nose-down elevator pressure will keep the wing angle of attack as low as possible, making the normal roll controls as effective as possible. With airspeed as low as stick shaker onset, normal roll controls -- up to full deflection of ailerons and spoilers -- may be used. The rolling maneuver changes the pitch rate into a turning maneuver, allowing the pitch to decrease. Finally, if normal pitch control then roll control is ineffective, careful rudder input in the direction of the desired roll may be required to induce a rolling maneuver for recovery.

Only a small amount of rudder is needed. Too much rudder applied too quickly or held too long may result in loss of lateral and directional control. Because of the lowenergy condition, pilots should exercise caution when applying rudder.

The reduced pitch attitude will allow airspeed to increase, thereby improving elevator and aileron control effectiveness. After the pitch attitude and airspeed return to a desired range the pilot can reduce angle of bank with normal lateral flight controls and return the airplane to normal flight.

NOSE LOW, WINGS LEVEL.
In a situation where the airplane pitch attitude is unintentionally more than 10 degrees nose low and going lower, the kinetic energy (airspeed) is increasing rapidly. A pilot would likely reduce thrust and extend the speed brakes. The thrust reduction will cause an additional nose-down pitching moment. The speed brake extension will cause a nose-up pitching moment, an increase in drag, and a decrease in lift for the same angle of attack. At airspeeds well above V_{MO}/M_{MO}, the ability to command a nose-up pitch rate with elevator may be reduced because of the extreme aero-dynamic loads on the elevator.

Again, it is necessary to maneuver the airplane's flight path back toward the horizon. At moderate pitch attitudes, applying nose-up elevator -- and reducing thrust and extending speed brakes, if necessary -- will change the pitch attitude to a desired range. At extremely low pitch attitudes and high airspeeds (well above V_{MO}/M_{MO}), nose-up elevator and nose-up trim may be required to establish a nose-up pitch rate.

HIGH BANK ANGLES.
A high bank angle is one beyond that necessary for normal flight. Though the bank angle for an upset has been defined as unintentionally more than 45 degrees, it is possible to experience bank angles greater than 90 degrees.

Any time the airplane is not in "zero-angle-of-bank" flight, lift created by the wings is not being fully applied against gravity, and more than 1 g will be required for level flight (figure 6). At bank angles greater than 67 degrees, level flight cannot be maintained within flight manual limits for a 2.5 g load factor (figure 7). In high bank angle increasing airspeed situations, the primary objective is to maneuver the lift of the airplane to directly oppose the force of gravity by rolling to wings level. Applying nose-up elevator at bank angles above 60 degrees causes no appreciable change in pitch attitude and may exceed normal structure load limits as well as the wing angle of attack for stall. The closer the lift vector is to vertical (wings level), the more effective the applied g is in recovering the airplane.

A smooth application of up to full lateral control should provide enough roll control power to establish a very positive recovery roll rate. If full roll control application is not satisfactory, it may even be necessary to apply some rudder in the direction of the desired roll.

Only a small amount of rudder is needed. Too much rudder applied too quickly or held too long may result in loss of lateral and directional control or structural failure.

NOSE HIGH, HIGH BANK ANGLES.
A nose-high, high-angle-of-bank upset requires deliberate flight control inputs. A large bank angle is helpful in reducing excessively high pitch attitudes. The pilot must apply nose-down elevator and adjust the bank angle to achieve the desired rate of pitch reduction while considering energy management. Once the pitch attitude has been reduced to the desired level, it is necessary only to reduce the bank angle, ensure that sufficient airspeed has been achieved, and return the airplane to level flight.

NOSE LOW, HIGH BANK ANGLES.
The nose-low, high-angle-of-bank upset requires prompt action by the pilot as potential energy (altitude) is rapidly being exchanged for kinetic energy (airspeed). Even if the airplane is at a high enough altitude that ground impact is not an immediate concern, airspeed can rapidly increase beyond airplane design limits. Simultaneous application of roll and adjustment of thrust may be necessary. It may be necessary to apply nose-down elevator to limit the amount of lift, which will be acting toward the ground if the bank angle exceeds 90 degrees. This will also reduce wing angle of attack to improve roll capability. Full aileron and spoiler input should be used if necessary to smoothly establish a recovery roll rate toward the nearest horizon. It is important to not increase g force or use nose-up elevator or stabilizer until approaching wings level. The pilot should also extend the speed brakes as necessary.

Recovery Techniques
It is possible to consolidate and incorporate recovery techniques into two basic scenarios -- nose-high and nose-low -- and to acknowledge the potential for high bank angles in each scenario described above. Other crew actions such as recognizing the upset, reducing automation, and completing the recovery are included in these techniques. Boeing and Airbus believe the recommended techniques provide a logical progression for recovering an airplane. The techniques assume that the airplane is not stalled. If it is, recovery from the stall must be accomplished first.

NOSE-HIGH RECOVERY

- Recognize and confirm the situation.
- Disengage autopilot and autothrottle.
- Apply as much as full nose-down elevator.
- Apply appropriate nose-down stabilizer trim.
- Reduce thrust (for underwing-mounted engines).
- Roll (adjust bank angle) to obtain a nose-down pitch rate.
- Complete the recovery:
  ÐWhen approaching the horizon, roll to wings level.
  ÐCheck airspeed and adjust thrust.
  ÐEstablish pitch attitude.

NOSE-LOW RECOVERY

- Recognize and confirm the situation.
- Disengage autopilot and autothrottle.
- Recover from stall, if necessary.
- Roll in the shortest direction to wings level (unload and roll if bank angle is more than 90 degrees).
- Recover to level flight:
  Ð Apply nose-up elevator.
  Ð Apply stabilizer trim, if necessary.
  Ð Adjust thrust and drag as necessary.

Summary

Airplanes are subject to the laws of aerodynamics and physics. With a clear understanding of how airplanes react when obeying these laws, pilots will be better equipped to safely deal with an airplane upset in the rare event that one occurs. Each upset event may result from different causes, but the concepts for recovery are similar.

- Assess the energy situation.
- Understand where the ground is.
- Use whatever authority is required of the flight controls.
- Maneuver the airplane to return to normal bank and pitch.

These recovery concepts are central to any upset training. To help pilots develop a greater understanding of upset recovery procedures, the commercial aviation industry is developing an upset recovery training program. A training aid representing an industry consensus on a core training program was scheduled to be completed in second-quarter 1998 and delivered to operators of Airbus and Boeing airplanes beginning in third-quarter 1998. It is anticipated that this training aid will be an important factor in enhancing aviation safety by reducing loss-of-control events and the accidents that may result from them.

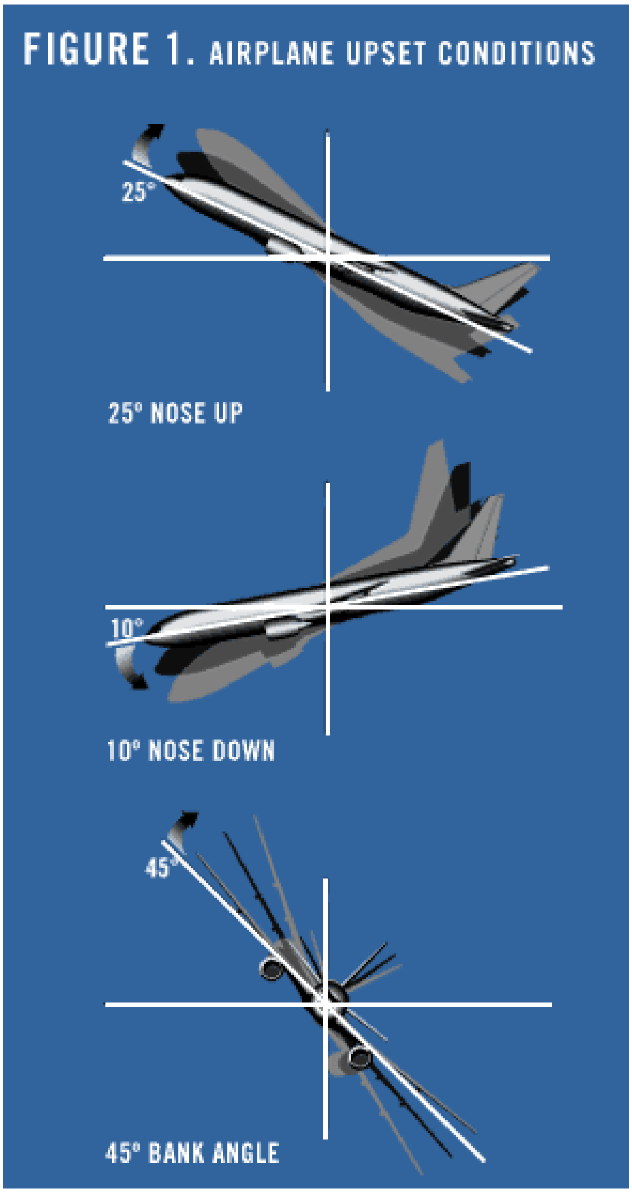


FIGURE 1. AIRPLANE UPSET CONDITIONS
25°
25° NOSE UP
10°
10° NOSE DOWN
45°
45° BANK ANGLE

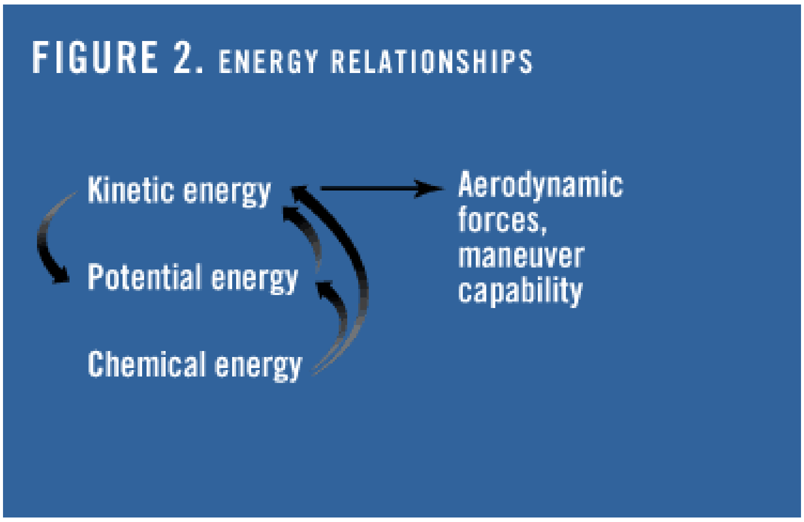


FIGURE 2. ENERGY RELATIONSHIPS
Kinetic energy
Potential energy
Chemical energy
Aerodynamic forces, maneuver capability

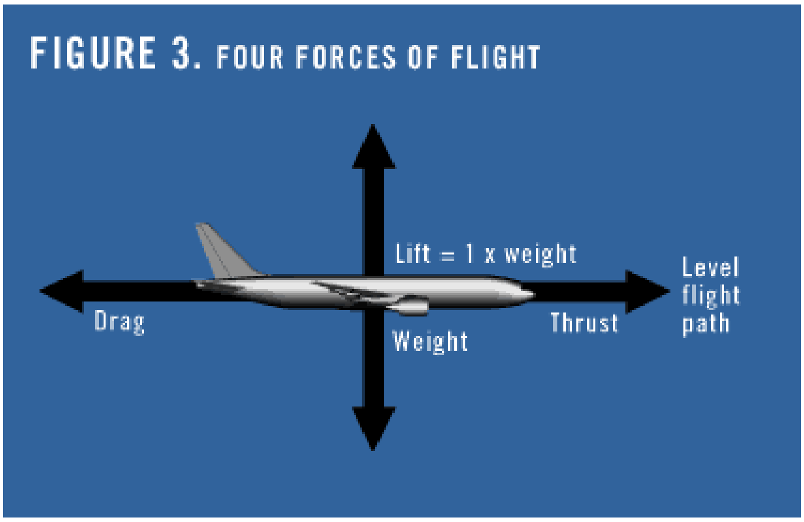


FIGURE 3. FOUR FORCES OF FLIGHT
Lift = 1 x weight
Level flight path
Drag
Thrust
Weight

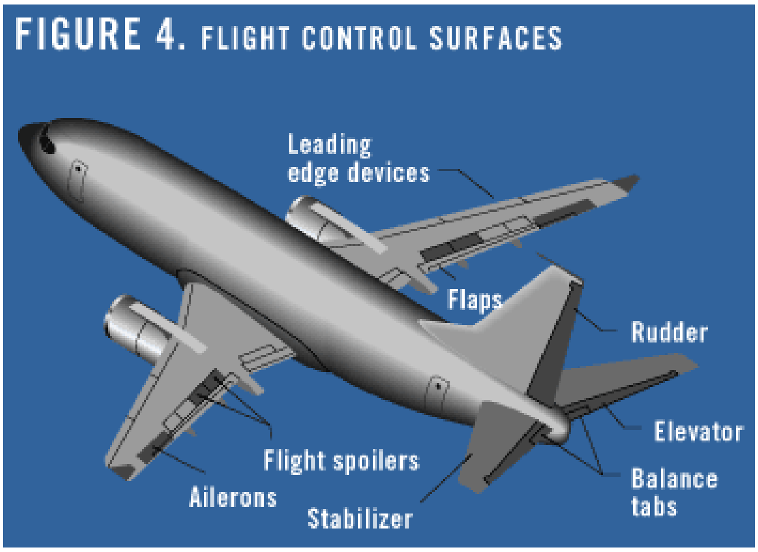


FIGURE 4. FLIGHT CONTROL SURFACES
Leading edge devices
Flaps
Rudder
Elevator
Flight spoilers
Ailerons
Stabilizer
Balance tabs

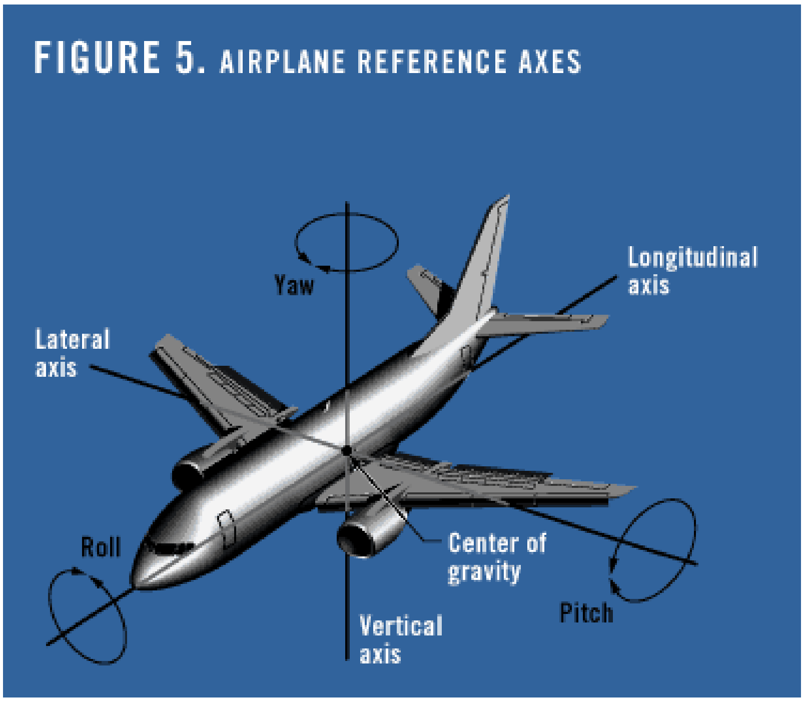
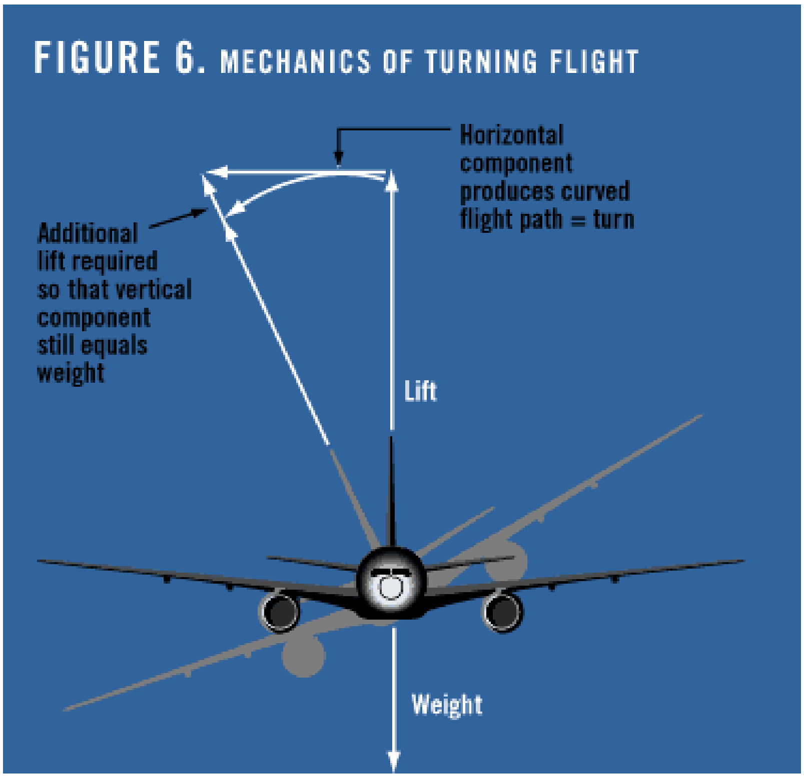
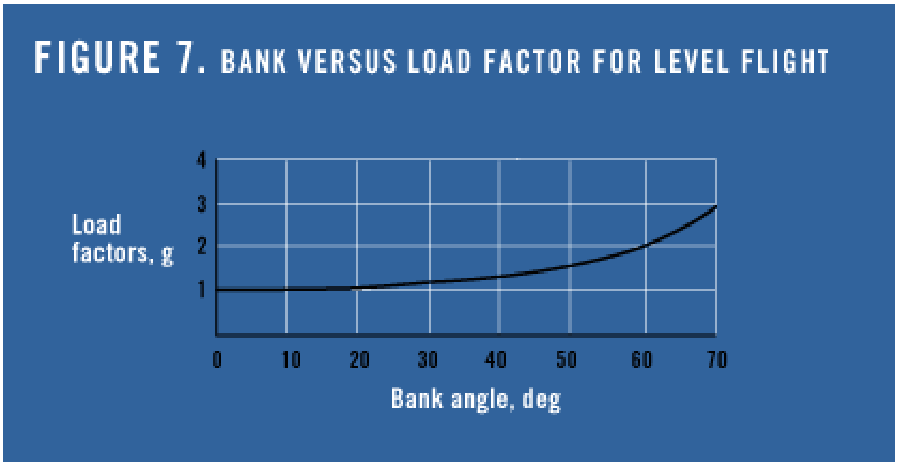


FIGURE 5. AIRPLANE REFERENCE AXES
Yaw
Longitudinal axis
Lateral axis
Roll
Center of gravity
Pitch
Vertical axis





Airplane Upset Recovery Training Aid

In recent years the commercial aviation industry has responded to flight crew training issues by developing several training aids. Examples of these aids, which were created by industry teams of representatives from airplane manufacturers, airlines, pilot groups, government and regulatory agencies, and others, include the following:

- Controlled flight into terrain.
- Takeoff safety.
- Turbulence.
- Turbulence avoidance.
- Windshear.

The industry has now identified the potential benefits of such a training aid to help pilots recover an airplane that has been upset. The goal of this airplane upset recovery training aid is to increase the pilot's ability to recognize and avoid situations that can lead to airplane upsets, and to improve the pilot's ability to recover control of an airplane to normal flight parameters if it has been upset. To support this goal the industry:

- Established an industrywide consensus on a variety of effective methods to train pilots to recover from airplane upsets.
- Developed appropriate educational material.
- Developed an example training program as a basis for tailored programs that individual operators may wish to develop.

The new training aid package consists of a document and a two-part video. Both the document and video will also be available in CD-ROM format. The document contains four sections:

1. A management overview that identifies the safety concern and encourages operators to establish an upset recovery training program.

2. A pilot guide that briefly reviews the causes of airplane upsets, fundamental aerodynamics of flight for large, swept-wing airplanes, and the application of techniques for recovering an airplane that has been upset. The guide is a highly readable, concise treatment for pilot issues written by pilots for pilots. It is intended for self-study or classroom use.

3. The example airplane upset training program, a stand-alone resource designed to serve the needs of a training department. An example academic and simulator training program are both included. The academic program provides the pilots with the requisite knowledge, and the simulator training scenarios are designed to help pilots improve their skills in recovering from an upset.

4. References for additional reading on subjects associated with airplane upsets and recovery.

Airbus and Boeing encourage all operators to endorse the training recommendations and include airplane upset recovery training in their overall pilot training programs.

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