ATTACHMENT V

Excerpts from the Boeing/Airbus Training Aid

(10 pages)

Pilot Guide to Airplane Upset Recovery

2.0 Introduction

The "Pilot Guide to Airplane Upset Recovery" is one part of the *Airplane Upset Recovery Training Aid*. The other parts include an "Overview for Management" (Sec. 1), "Example Airplane Upset Recovery Training Program" (Sec. 3), "References for Additional Information" (Sec. 4), and a two-part video.

The goal of this training aid is to increase the ability of pilots to *recognize and avoid* situations that can lead to airplane upsets and to improve their ability to recover control of an airplane that has exceeded the normal flight regime. This will be accomplished by increasing awareness of potential upset situations and knowledge of aerodynamics and by application of this knowledge during simulator training scenarios.

The education material and the recommendations provided in the *Airplane Upset Recovery Training Aid* were developed through an extensive review process to achieve a consensus of the air transport industry.

2.1 Objectives

The objectives of the "Pilot Guide to Airplane Upset Recovery" are to provide pilots with

- Knowledge to recognize situations that may lead to airplane upsets so that they may be prevented.
- Basic airplane aerodynamic information.
- Airplane flight maneuvering information and techniques for recovering airplanes that have been upset.

It is intended that this information be provided to pilots during academic training and that it be retained for future use.

2.2 Definition of Airplane Upset

Research and discussions within the commercial aviation industry indicated that it was necessary to establish a descriptive term and definition in order to develop this training aid. Terms such as "unusual attitude," "advanced maneuver," "selected event," "loss of control," "airplane upset," and others are terms used within the industry. The team decided that "airplane upset" was appropriate for this training aid. An airplane upset is defined as an airplane in flight unintentionally exceeding the parameters normally experienced in line operations or training.

While specific values may vary among airplane models, the following unintentional conditions generally describe an airplane upset:

- Pitch attitude greater than 25 deg, nose up.
- Pitch attitude greater than 10 deg, nose down.
- Bank angle greater than 45 deg.
- Within the above parameters, but flying at airspeeds inappropriate for the conditions.

2.4.1.1.5 Microbursts

Identification of concentrated, more powerful downdrafts—known as microbursts—has resulted from the investigation of windshear accidents and from meteorological research. Microbursts can occur anywhere convective weather conditions occur. Observations suggest that approximately 5% of all thunderstorms produce a microburst. Downdrafts associated with microbursts are typically only a few hundred to 3000 ft across. When a downdraft reaches the ground, it spreads out horizontally and may form one or more horizontal vortex rings around the downdraft (Fig. 6). Microburst outflows are not always symmetric. Therefore, a significant airspeed increase may not occur upon entering outflows, or it may be much less than the subsequent airspeed loss experienced when exiting the microburst. Windspeeds intensify for about 5 min after a microburst initially contacts the ground and typically dissipate within 10 to 20 min after ground contact.

It is vital to recognize that some microbursts cannot be successfully escaped with any known techniques.

2.4.1.2 Wake Turbulence

Wake turbulence is the leading cause of airplane upsets that are induced by the environment. The phenomenon that creates wake turbulence results from the forces that lift the airplane. High-pressure air from the lower surface of the wings flows around the wingtips to the lower pressure region above the wings. A pair of counter-rotating vorti-

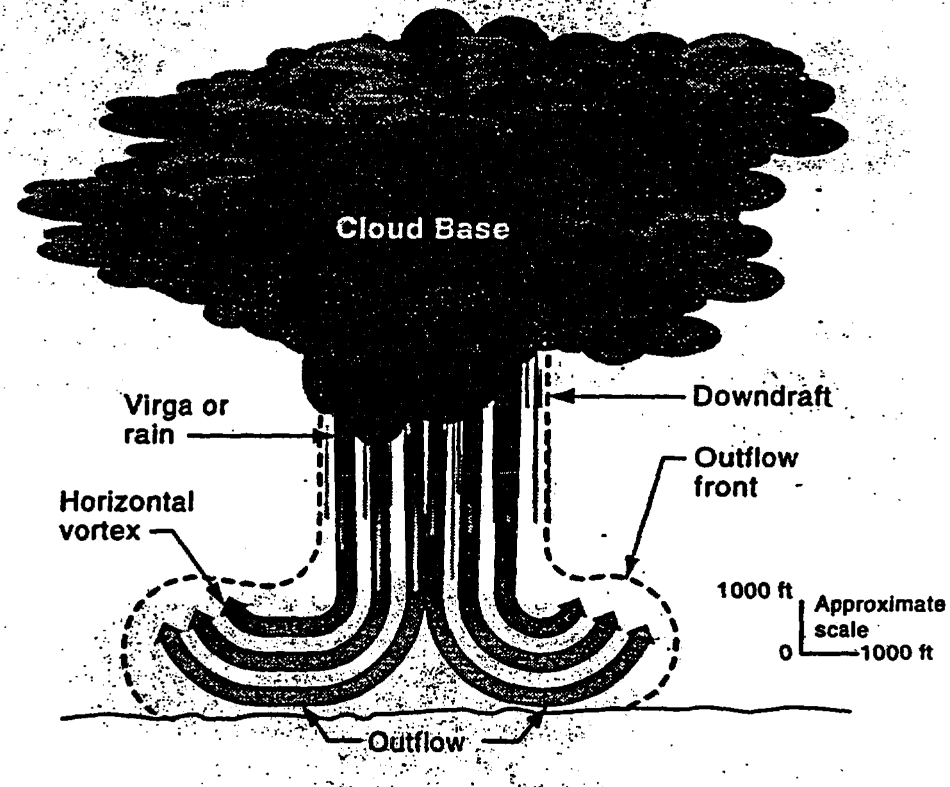


***Figure 6** Symmetric Microburst—An airplane transiting the microburst would experience equal headwinds and tailwinds.*

ces are thus shed from the wings: the right wing vortex rotates counterclockwise, and the left wing vortex rotates clockwise (Fig. 7). The region of rotating air behind the airplane is where wake turbulence occurs. The strength of the turbulence is determined predominantly by the weight, wingspan, and speed of the airplane. Generally, vortices descend at an initial rate of about 300 to 500 ft/min for about 30 sec. The descent rate decreases and eventually approaches zero at between 500 and 900 ft below the flight path. Flying at or above the flight path provides the best method for avoidance. Maintaining a vertical separation of at least 1000 ft when crossing below the preceding aircraft may be considered safe. This vertical motion is illustrated in Figure 8. Refer to the *Wake Turbulence Training Aid* for comprehensive information on how to avoid wake turbulence. This aid is available from the National Technical Information Service or The Boeing Company.

An encounter with wake turbulence usually results in induced rolling or pitch moments; however, in rare instances an encounter could cause structural damage to the airplane. In more than one instance, pilots have described an encounter to be like "hitting a wall." The dynamic forces of the vortex can exceed the roll or pitch capability of the airplane to overcome these forces. During test programs, the wake was approached from all directions to evaluate the effect of encounter direction on response. One item was common to all encounters: without a concerted effort by the pilot to reenter the wake, the airplane would be expelled from the wake and an airplane upset could occur.

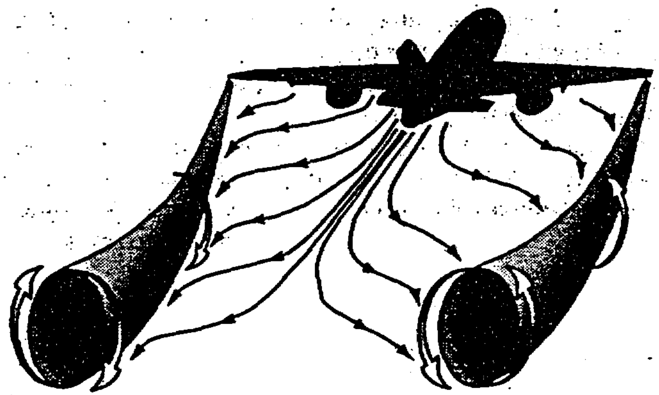


Figure 7 Wake Turbulence Formation

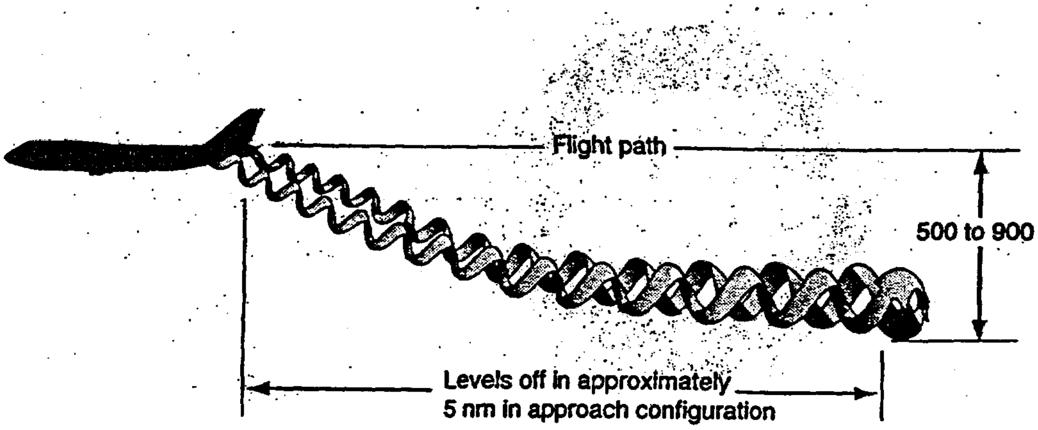


Figure 8 Vertical Motion Out of Ground Effect

Counter-control is usually effective and induced roll is minimal in cases where the wingspan and ailerons of the encountering airplane extend beyond the rotational flowfield of the vortex (Fig. 9). It is more difficult for airplanes with short wingspan (relative to the generating airplane) to counter the imposed roll induced by the vortex flow.

Avoiding wake turbulence is the key to avoiding many airplane upsets. Pilot and air traffic control procedures and standards are designed to accomplish this goal, but as the aviation industry expands, the probability of an encounter also increases.

2.4.1.3 Airplane Icing

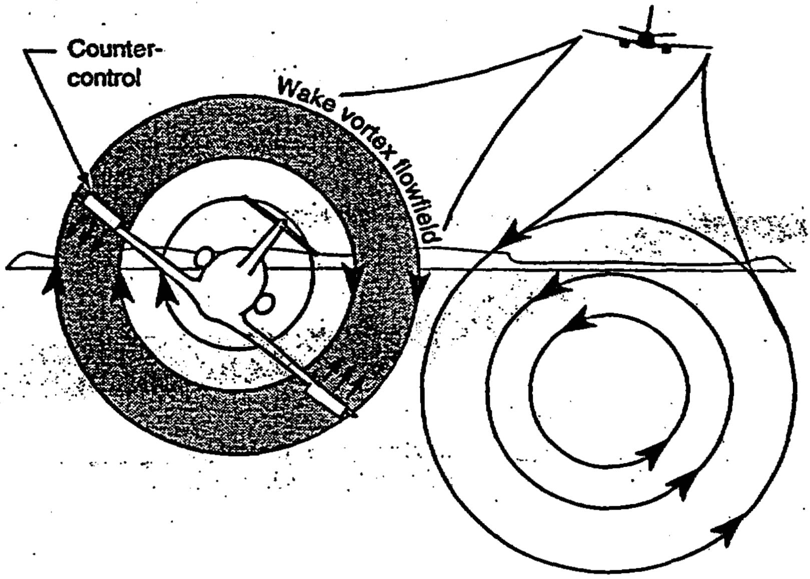
Technical literature is rich with data showing the adverse aerodynamic effects of airfoil contamination. Large degradation of airplane performance can result from the surface roughness of an extremely small amount of contamination. These detrimental effects vary with the location and roughness, and they produce unexpected airplane handling characteristics, including degradation of maximum lift capability, increased drag, and possibly unanticipated changes in stability and control. Therefore, the axiom of "Keep it clean" for critical airplane surfaces continues to be a universal requirement.

2.4.2 Systems-Anomalies-Induced Airplane Upsets

Airplane designs, equipment reliability, and flight crew training have all improved since the Wright brothers' first powered flight. Airplane certification processes and oversight are rigorous. Airlines and manufacturers closely monitor equipment failure rates for possible redesign of airplane parts or modification of maintenance procedures. Dissemination of information is rapid if problems are detected. Improvement in airplane designs and equipment components has always been a major focus in the aviation industry. In spite of this continuing effort, there are still failures. Some of these failures can lead to an airplane upset. That is why flight crews are trained to overcome or mitigate the impact of the failures. Most failures are survivable if correct responses are made by the flight crew.

An airplane was approaching an airfield and appeared to break off to the right for a left downwind to the opposite runway. On downwind at approximately 1500 ft, the airplane pitched up to nearly 60 deg and climbed to an altitude of nearly 4500 ft, with the airspeed deteriorating to almost 0 kn. The airplane then tail-slid, pitched down, and seemingly recovered. However, it continued into another steep pitchup of 70 deg. This time as it

Figure 9
Induced Roll



in such a way as to get the aerodynamics of the tab to hold the elevator in the desired position. The airplane is then in trim (because the required load on the tail has been achieved) and the column force trim condition is met as well (because the tab holds the elevator in the desired position). One side effect of this configuration is that when trimmed near one end of the deflection range, there is not much more control available for maneuvering in that direction (Fig. 24).

In the case of the all-flying tail, the entire stabilizer moves as one unit in response to column commands. This changing of the angle of attack of the stabilizer adjusts the tail lift as required to balance the moments. The tail is then held in the desired position by an irreversible flight control system (usually hydraulic). This configuration requires a very powerful and fast-acting control system to move the entire tail in response to pilot inputs, but it has been used quite successfully on commercial jet transport airplanes.

In the case of the trimmable stabilizer, the proper pitching moment is achieved by deflecting the elevator and generating the required lift on the tail. The stabilizer is then moved (changing its angle of attack) until the required tail lift is generated by the stabilizer with the elevator essentially at zero deflection. A side effect of this configuration is that from the trimmed condition, full elevator deflection is available in either direction, allowing a much larger range of maneuvering capability. This is the configuration found on most high-performance airplanes that must operate through a very wide speed range and that use very powerful high-lift devices (flaps) on the wing.

Knowing that in the trimmed condition the elevator is nearly faired or at zero deflection, the pilot instantly knows how much control power is available in either direction. This is a powerful tactile cue, and it gives the pilot freedom to maneuver without the danger of becoming too close to surface stops.

2.5.5.4 Lateral and Directional Aerodynamic Considerations

Aerodynamically, anti-symmetric flight, or flight in sideslip can be quite complex. The forces and moments generated by the sideslip can affect motion in all three axes of the airplane. As will be seen, sideslip can generate strong aerodynamic rolling moments as well as yawing moments. In particular the magnitude of the coupled roll-due-to-sideslip is determined by several factors.

2.5.5.4.1 Angle of Sideslip

Just as airplane angle of attack is the angle between the longitudinal axis of the airplane and the relative wind as seen in a profile view, the sideslip angle is the angle between the longitudinal axis of the airplane and the relative wind, seen this time in the plan view (Fig. 25). It is a measure of whether the airplane is flying straight into the relative wind.

With the exception of crosswind landing considerations requiring pilot-commanded sideslip, commercial transport airplanes are typically flown at or very near zero sideslip. This usually results in the lowest cruise drag and is most comfortable for passengers, as the sideways forces are minimized.

For those cases in which the pilot commands a sideslip, the aerodynamic picture becomes a bit more complex. Figure 25 depicts an airplane in a

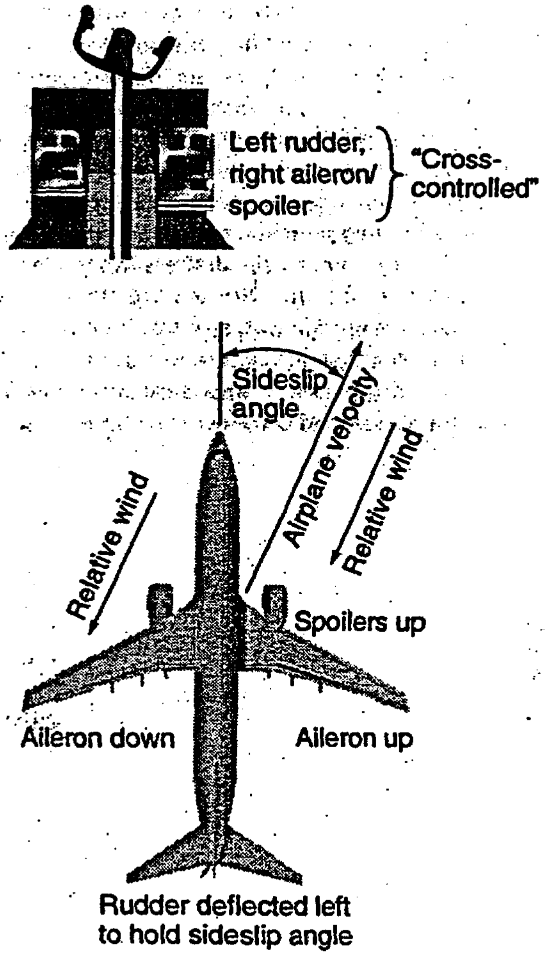


Figure 25
Angle of Sideslip

commanded nose-left sideslip. That is, the velocity vector is not aligned with the longitudinal axis of the airplane, and the relative wind is coming from the pilot's right.

One purpose of the vertical tail is to keep the nose of the airplane "pointed into the wind," or make the tail follow the nose. When a sideslip angle is developed, the vertical tail is at an angle of attack and generates "lift" that points sideways, tending to return the airplane to zero sideslip. Commercial jet transport airplanes are certificated to exhibit static directional stability that tends to return the airplane to zero sideslip when controls are released or returned to a neutral position. In order to hold a sideslip condition, the pilot must hold the rudder in a deflected position (assuming symmetrical thrust).

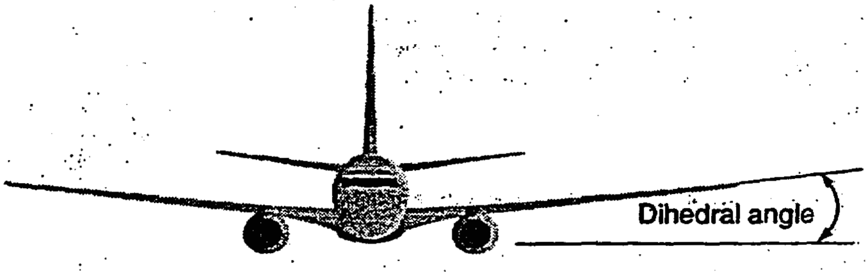
2.5.5.4.2 Wing Dihedral Effects

Dihedral is the positive angle formed between the lateral axis of an airplane and a line that passes through the center of the wing, as depicted in Figure 26. Dihedral contributes to the lateral stability of an airplane, and commercial jet transport airplanes are certificated to exhibit static lateral stability. A wing with dihedral will develop stable rolling moments with sideslip. If the relative wind comes from the side, the wing into the wind is subject to an increase in lift. The wing away from the wind is subject to a decrease in angle of attack and develops a decrease in lift. The changes in lift effect a rolling moment, tending to raise the windward wing; hence, dihedral contributes a stable roll due to sideslip. Since wing dihedral is so powerful in producing lateral stability, it is used as a "common denominator term" of the lateral stability contribution of other airplane components, such as rudder and wing sweep. In other words, the term "dihedral effect" is used when describing the effects of wing sweep and rudder on lateral stability and control.

A swept-wing design used on jet transport airplanes is beneficial for high-speed flight, since higher flight speeds may be obtained before components of speed perpendicular to the leading edge produce critical conditions on the wing. In other words, wing sweep will delay the onset of compressibility effects. This wing sweep also contributes to the dihedral effect. When the swept-wing airplane is placed in a sideslip, the wing into the wind experiences an increase in lift, since the effective sweep is less, and the wing away from the wind produces less lift, since the effective sweep is greater (Fig. 25). The amount of contribution, or dihedral effect, depends on the amount of sweepback and lift coefficient of the wing. The effect becomes greater with increasing lift coefficient and wing sweep. The lift coefficient will increase with increasing angle of attack up to the critical angle. This means that any sideslip results in more rolling moment on a swept-wing airplane than on a straight-wing airplane. Lateral controls on swept-wing airplanes are powerful enough to control large sideslip angles at operational speeds.

Rudder input produces sideslip and contributes to the dihedral effect. The effect is proportional to the angle of sideslip. (That is, roll increases with sideslip angle; therefore, roll increases with increasing rudder input.) When an airplane is at a high angle of attack, aileron and spoiler roll controls become less effective. At the stall angle of attack, the rudder is still effective; therefore, it can produce large sideslip angles, which in turn produces roll because of the dihedral effect.

Figure 26
Wing Dihedral Angle



2.5.5.4.3 Pilot-Commanded Sideslip

It is important to keep in mind that the rudders on modern jet transport airplanes are usually sized to counter the yawing moment associated with an engine failure at very low takeoff speeds. This very powerful rudder is also capable of generating large sideslips (when an engine is not failed). The large sideslip angles generate large rolling moments that require significant lateral control input to stop the airplane from rolling. In maneuvering the airplane, if a crosswind takeoff or landing is not involved and an engine is not failed, keeping the sideslip as close to zero as possible ensures that the maximum amount of lateral control is available for maneuvering. This requires coordinated use of both aileron/spoilers and rudder in all maneuvering.

One way to determine the sideslip state of the airplane is to "feel" the lateral acceleration; it feels as if the pilot is being pushed out of the seat sideways. Another way is to examine the slip-skid indicator and keep the ball in the center. Pilots should develop a feel for the particular airplanes they fly and understand how to minimize sideslip angle through coordinated use of flight controls.

Crossover speed is a recently coined term that describes the lateral controllability of an airplane with the rudder at a fixed (up to maximum) deflection. It is the minimum speed (weight and configuration dependent) in a 1-g flight, where maximum aileron/spoiler input (against the stops) is reached and the wings are still level or at an angle to maintain directional control. Any additional rudder input or decrease in speed will result in an unstoppable roll into the direction of the deflected rudder or in an inability to maintain desired heading. Crossover speed is very similar in concept to Vmca, except that instead of being Vmc due to a thrust asymmetry, it is Vmc due to full rudder input. This crossover speed is weight and configuration dependent. However, it is also sensitive to angle of attack. With weight and configuration held constant, the crossover speed will increase with increased angle of attack and will decrease with decreased angle of attack. Thus, in an airplane upset due to rudder deflection with large and increasing bank angle and the nose rapidly falling below the horizon, the input of additional nose-up elevator with already maximum input of aileron/spoilers will only aggravate the situation. The correct action in this case is to unload the airplane to reduce the angle of attack, which will regain aileron/spoiler effectiveness and allow recovery This action may not be intuitive and will result in a loss of altitude.

Note: The previous discussion refers to the aerodynamic effects associated with rudder input; however, similar aerodynamic effects are associated with other surfaces.

2.5.5.5 High-Speed, High-Altitude Characteristics

Modern commercial jet transport airplanes are designed to fly at altitudes from sea level to more than 40,000 ft. There are considerable changes in atmospheric characteristics that take place over that altitude range, and the airplane must accommodate those changes.

One item of interest to pilots is the air temperature as altitude changes. Up to the tropopause (36,089 ft in a standard atmosphere), the standard temperature decreases with altitude. Above the tropopause, the standard temperature remains relatively constant. This is important to pilots because the speed of sound in air is a function only of air temperature. Aerodynamic characteristics of lifting surfaces and entire airplanes are significantly affected by the ratio of the airspeed to the speed of sound. That ratio is Mach number. At high altitudes, large Mach numbers exist at relatively low calibrated airspeeds.

As Mach number increases, airflow over parts of the airplane begins to exceed the speed of sound. Shock waves associated with this local supersonic flow can interfere with the normally smooth flow over the lifting surfaces, causing local flow separation. Depending on the airplane, as this separation grows in magnitude with increasing Mach number, characteristics such as pitchup, pitchdown, or aerodynamic buffeting may occur. Transport category airplanes are certificated to be free from characteristics that would interfere with normal piloting in the normal flight envelope and to be safely controllable during inadvertent exceedances of the normal envelope, as discussed in Section 2.5.4, "Aerodynamic Flight Envelope."

The point at which buffeting would be expected to occur is documented in the Approved Flight Manual. The Buffet Boundary or Cruise Maneuver come curved and the airplane will accelerate toward the earth quite rapidly. In this case, the pilot must find a way to orient the lift vector away from gravity. In all cases, the pilot should ensure that the angle of attack is below the stall angle and roll to upright as rapidly as possible.

2.5.5.10 Directional Maneuvering

Motion about the vertical axis is called "yaw" (Fig. 36). The character of the motion about the vertical axis is determined by the balance of moments about the axis (around the center of gravity). The principal controller of aerodynamic moments about the vertical axis is the rudder, but it is not the only one. Moments about the vertical axis can be generated or affected by asymmetric thrust, or by asymmetric drag (generated by ailerons, spoilers, asymmetric flaps, and the like). These asymmetric moments may be desired (designed in) or undesired (perhaps the result of some failure).

Generally, the rudder is used to control yaw in a way that minimizes the angle of sideslip, that is, the angle between the airplane's longitudinal axis and the relative wind. For example, when an engine fails on takeoff, the object is to keep the airplane aligned with the runway by using rudder.

On modern jet transports with powerful engines located away from the centerline, an engine failure can result in very large yawing moments, and rudders are generally sized to be able to control those moments down to very low speeds. This means that the rudder is very powerful and has the capability to generate very large yawing moments. ***When the rest of the airplane is symmetric, for example, in a condition of no engine failure, very large yawing moments would result in very large sideslip angles and large structural loads, should the pilot input full rudder when it is not needed.*** Pilots need to be aware of just how powerful the rudder is and the effect it can have when the rest of the airplane is symmetric. Many modern airplanes limit the rudder authority in parts of the flight envelope in which large deflections are not required, for example, at high speeds. In this way, the supporting structure can be made lighter. Pilots also need to be aware of such "rudder limiting" systems and how they operate on airplanes.

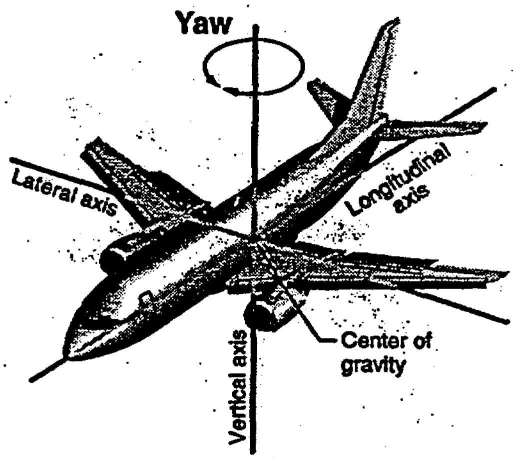


Figure 36
Yaw Axis

There are a few cases, however, when it is necessary to generate sideslip. One of the most common is the crosswind landing. In the slip-to-a-landing technique, simultaneous use of rudder and aileron/spoiler aligns the airplane with the runway centerline and at the same time keeps the airplane from drifting downwind. The airplane is flying "sideways" and the pilot feels the lateral acceleration.

Static stability in the directional axis tends to drive the sideslip angle toward zero. The vertical fin and rudder help to do this. The number of times the airplane oscillates as it returns to zero sideslip depends on its dynamic stability. Most of the dynamic stability on a modern transport comes, not from the natural aerodynamics, but from an active stability augmentation system: the yaw damper. If disturbed with the yaw damper off, the inertial and aerodynamic characteristics of a modern jet transport will result in a rolling and yawing motion referred to as "dutch roll." The yaw damper moves the rudder to oppose this motion and damp it out very effectively. Transport airplanes are certificated to demonstrate positively damped dutch-roll oscillations.

The installed systems that can drive the rudder surface are typically designed in a hierarchical manner. For example, the yaw damper typically has authority to move the rudder in only a limited deflection range. Rudder trim, selectable by the pilot, has authority to command much larger rudder deflections that may be needed for engine failure. In most cases, the pilot, with manual control over rudder deflection, is the most powerful element in the system. The pilot can command deflection to the limits of the system, which may be surface stops, actuator force limits, or any others that may be installed (e.g., rudder ratio changers).

The pilot must overcome the surprise and quickly shift into analysis of what the airplane is doing and then implement the proper recovery. ***Gain control of the airplane and then determine and eliminate the cause of the upset.***

2.6.2.2 Negative G Force

Airline pilots are normally uncomfortable with aggressively unloading the g forces on a large passenger airplane. They habitually work hard at being very smooth with the controls and keeping a positive 1-g force to ensure flight attendant and passenger comfort and safety. Therefore, they must overcome this inhibition when faced with having to quickly and sometimes aggressively unload the airplane to less than 1 g by pushing down elevator.

Note: It should not normally be necessary to obtain less than 0 g.

While flight simulators can replicate normal flight profiles, most simulators cannot replicate sustained negative-g forces. Pilots must anticipate a significantly different cockpit environment during less-than-1-g situations. They may be floating up against the seat belts and shoulder harnesses. It may be difficult to reach or use rudder pedals if they are not properly adjusted. Unsecured items such as flight kits, approach plates, or lunch trays may be flying around the cockpit. These are things that the pilot must be prepared for when recovering from an upset that involves forces less than 1-g flight.

2.6.2.3 Use of Full Control Inputs

Flight control forces become less effective when the airplane is at or near its critical angle of attack or stall. Therefore, pilots must be prepared to use full control authority, when necessary. The tendency is for pilots not to use full control authority because they rarely are required to do this. This habit must be overcome when recovering from severe upsets.

2.6.2.4 Counter-Intuitive Factors

Pilots are routinely trained to recover from *approach* to stalls. The recovery usually requires an increase in thrust and a relatively small reduction in pitch attitude. Therefore, it may be counterintuitive to use greater unloading control forces or to reduce thrust when recovering from a high angle of attack, especially at lower altitudes. If the airplane is stalled while already in a nose-down attitude, the pilot must still push the nose down in order to reduce the angle of attack. Altitude cannot be maintained and should be of secondary importance.

2.6.2.5 Previous Training in Nonsimilar Airplanes

Aerodynamic principles do not change, but airplane design creates different flight characteristics. Therefore, training and experience gained in one model or type of airplane may or may not be transferable to another. For example, the handling characteristics of a fighter-type airplane cannot be assumed to be similar to those of a large, commercial, swept-wing airplane.

2.6.2.6 Potential Effects on Engines

Some extreme airplane upset situation may affect engine performance. Large angles of attack can reduce the flow of air into the engine and result in engine surges or compressor stalls. Additionally, large and rapid changes in sideslip angles can create excessive internal engine side loads, which may damage an engine.

APPENDIX

3-D

Flight Simulator Information

General Information

The ability of the simulators in existence today to adequately replicate the maneuvers being proposed for airplane upset recovery training is an important consideration. Concerns raised about simulators during the creation of the *Airplane Upset Recovery Training Aid* include the adequacy of the hardware, the equations of motion, and the aerodynamic modeling to provide realistic cues to the flight crew during training at unusual attitudes.

It is possible that some simulators in existence today may have flight instruments, visual systems or other hardware that will not replicate the full six-degree-of-freedom movement of the airplane that may be required during unusual attitude training. It is important that the capabilities of each simulator be evaluated before attempting airplane upset training and that simulator hardware and software be confirmed as compatible with the training proposed.

Properly implemented equations of motion in modern simulators are generally valid through the full six-degree-of-freedom range of pitch, roll, and yaw angles. However, it is possible that some existing simulators may have equations of motion that have unacceptable singularities at 90, 180, 270, or 360 deg of roll or pitch angle. Each simulator to be used for airplane upset training must be confirmed to use equations of motion and math models (and associated data tables) that are valid for the full range of maneuvers required. This confirmation may require coordination with the airplane and simulator manufacturer.

Operators must also understand that simulators cannot fully replicate all flight characteristics. For example, motion systems cannot replicate sustained linear and rotational accelerations. This is true of pitch, roll, and yaw accelerations, and longitudinal and side accelerations, as well as normal load factor, "g's." This means that a pilot cannot rely on all sensory feedback that would be available in an actual airplane. However, a properly programmed simulator should provide accurate control force feedback and the motion system should provide airframe buffet consistent with the aerodynamic characteristics of the airplane which could result from control input during certain recovery situations.

The importance of providing feedback to a pilot when control inputs would have exceeded airframe, physiological, or simulator model limits must be recognized and addressed. Some simulator operators have effectively used a simulator's "crash" mode to indicate limits have been exceeded. Others have chosen to turn the visual system red when given parameters have been exceeded. Simulator operators should work closely with training departments in selecting the most productive feedback method when selected parameters are exceeded.

The simulation typically is updated and validated by the airplane manufacturer using flight data acquired during the flight test program. Before a simulator is approved for any crew training, it must be evaluated and qualified by a national regulatory authority. This process includes a quantitative comparison of simulation results to actual flight data for certain test conditions such as those specified in the ICAO *Manual of Criteria for the Qualification of Flight Simulators*. These flight conditions represent airplane operation within the normal operating envelope.

The simulation may be extended to represent regions outside the typical operating envelope using wind tunnel data or other predictive methods. However, flight data are not typically available for conditions where flight testing would be very hazardous. From an aerodynamic standpoint, the regimes of flight that are usually not fully validated with flight data are the stall region and the region of high angle of attack with high sideslip angle where there may be separated airflow over the wing or empennage surfaces. While numerous approaches to stall or stalls are flown on each model (available test data are normally matched on the simulator), the flight controls are not fully exercised during an approach to stall or during a full stall, because of safety concerns. Also, roll and yaw rates and sideslip angle are carefully controlled during stall maneuvers to be near zero; therefore, validation of derivatives involving these