Docket No.: SA-510
Exhibit No.: 9X-I

NATIONAL TRANSPORTATION SAFETY BOARD

Washington, D.C.

737 Directional Control System
Reprinted from Airliner* Oct-Dec 1995

* A quarterly publication of the Boeing Customer Services Division

737 Directional Control System

The Boeing 737. It is known as the "Three-Seven," the "Seven-Three," and the "Guppy." The 737 is the best-selling airplane in commercial aviation history, with:

- More than 2,600 airplanes in service.
- More than 53 million flights.
- More than 500 takeoffs and landings worldwide, every hour of every day.

The 737 has provided nearly 30 years of safe, reliable transportation service with a tremendous track record. Recently, Boeing has received a number of questions about the 737 directional control system. So after all these years, it is time to revisit some of the basics.

A Possible Scenario?

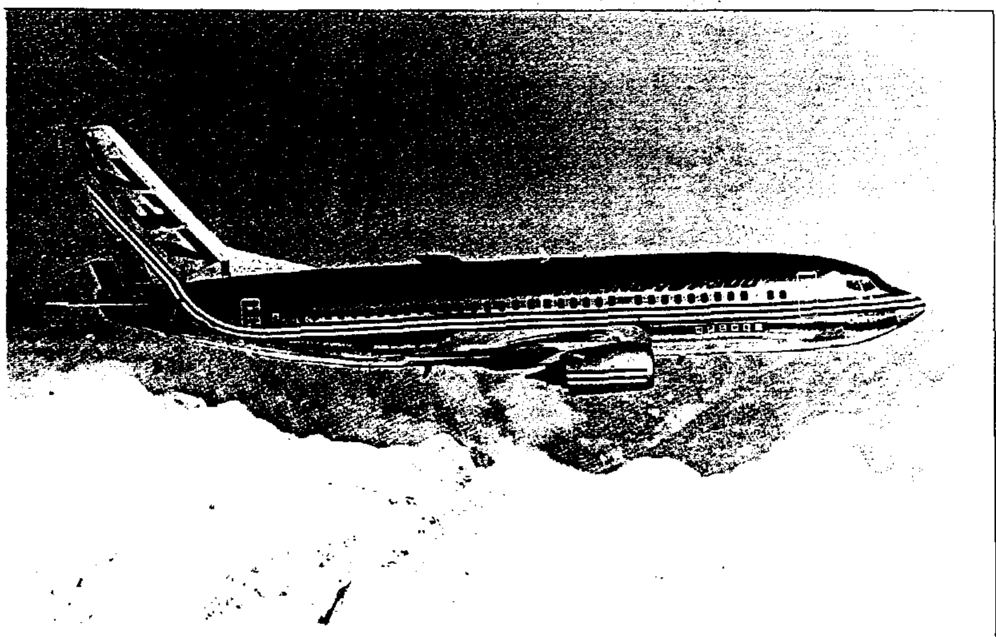
The 737 is in cruise at .74 Mach and FL350. It is the third leg of the third day of a three-day trip. Both pilots are content. The trip is going well. The last landing on this beautiful day will be a visual approach, much nicer than all their previous instrument approaches. It is the First Officer's leg, and the Captain is back a bit from the controls, making sure the maintenance log is complete. The autopilot is engaged in VNAV and LNAV, and the autothrottle is engaged. The First Officer turns to tune the nav radio.

Then something happens.

The First Officer immediately notices the airplane start to roll left. The Captain, his head down filling out the log, feels the airplane start to roll left — and sees the control wheel start to go right. The First Officer quickly grabs the wheel, believing he has to stop the roll. The Captain, with his seat back and books in his lap, is also quickly on the wheel, but can't reach the rudder pedals. Both crew members apply right wheel and the First Officer uses what he thinks is 1/4 right rudder. But the airplane control forces feel different. However, the airplane responds correctly: right wheel position results in a right roll. The airplane rolls back quickly to wings level. Then, they disengage the autopilot.

Seeing that the First Officer has the plane under control, the Captain releases the wheel and starts a scan to see what is going on. The pilots rapidly evaluate the situation in an effort to understand what caused the roll:

- *Engine failure? No. Both seem fine.*
- *Autopilot roll channel hardover? Maybe, except the plane rolled left, and the wheel went right.*
- *Something came off the airplane? Maybe, but there is no unusual buffeting or vibration.*
- *Wake turbulence? Maybe, but from what airplane?*



Mike Carriker
Senior Project Pilot
737 Engineering Test
Boeing Commercial Airplane Group

Marty Ingham
Aerodynamics Engineer
737 Stability and Control
Boeing Commercial Airplane Group

Al Nader
Technical Representative
737 Flight Training
Boeing Commercial Airplane Group

1

The First Officer notes that it takes right wheel to maintain the desired heading. About a minute later, he observes that less and less right wheel is required to maintain wings level. The pilots decide to leave the autopilot off and turn the yaw damper off as a precaution. When the yaw damper is disengaged, wheel is no longer required to maintain wings level. After an uneventful landing, they write a detailed report. The maintenance chief reads it and has his crew troubleshoot the yaw damper system.

Subsequent testing finds the yaw damper solenoid valve to have malfunctioned.

The above scenario is actually a combination of several in-service yaw damper events that have been reported by flight crews. In most cases, the incidents were reported to be more dramatic than the actual flight data recorder numbers showed. Crews' written reports have estimated bank angles in excess of 30 degrees, when flight data recorder data has shown bank angles of 9 to 11 degrees.

737 yaw damper malfunctions are infrequent — and the airplane is certified to handle them. Full yaw damper deflections have been successfully demonstrated during 737 certification. In all yaw damper failure modes, the airplane is easily controllable by the pilot.

How can the yaw damper system malfunction? How should the crew respond? Why does the crew's perception of an event differ dramatically from recorded flight data?

The answers exist in four parts:

- Aerodynamics.
- Flight Control System Design.
- Yaw Damper Malfunctions.
- Human Factors.

This article discusses each of these issues, and how they can affect 737 directional control. It also provides guidance to pilots on recognizing possible yaw damper failure modes and their effects, and reviews proper pilot procedures.

Aerodynamics

As you may remember from basic aerodynamics (Figure 1), the airplane's yaw axis and roll axis are strongly coupled to each other. What a pilot does in one axis will invariably affect the other.

Directional Stability. The primary control the 737 uses to maintain positive directional stability is the vertical stabilizer. Positive directional stability means it requires more and more rudder deflection to get higher and higher angles of sideslip. The pilot and selected airplane systems use the rudder to control side forces on the vertical stabilizer.

Lateral Stability. Unlike directional stability, there is no surface that, by itself, provides lateral stability. The closest thing to lateral stability is called spiral stability. The prime contributor to the 737's spiral stability characteristics is the wing's dihedral angle and its dihedral effect (roll-due-to-yaw angle). Equal lift on both wings will result in zero tendency to roll. Spiral stability is an airplane's tendency to roll back toward wings level (positive) or away from wings level (negative) when established in a shallow bank angle. In the 737, the spiral stability is essentially neutral; the airplane will generally stay where it is when at shallow bank angles.

Lateral-Directional Interaction. The lateral and directional axes constantly interact. Even a pure rolling moment will change the angle of attack on the vertical stabilizer, creating lift and force on the surface that is displaced above the airplane's center of gravity. One of the primary modes of interaction is defined as dynamic lateral directional stability. This is more commonly referred to as Dutch roll.

Dutch roll begins when the airplane experiences a yawing moment — either naturally (such as a wind gust), or inten-

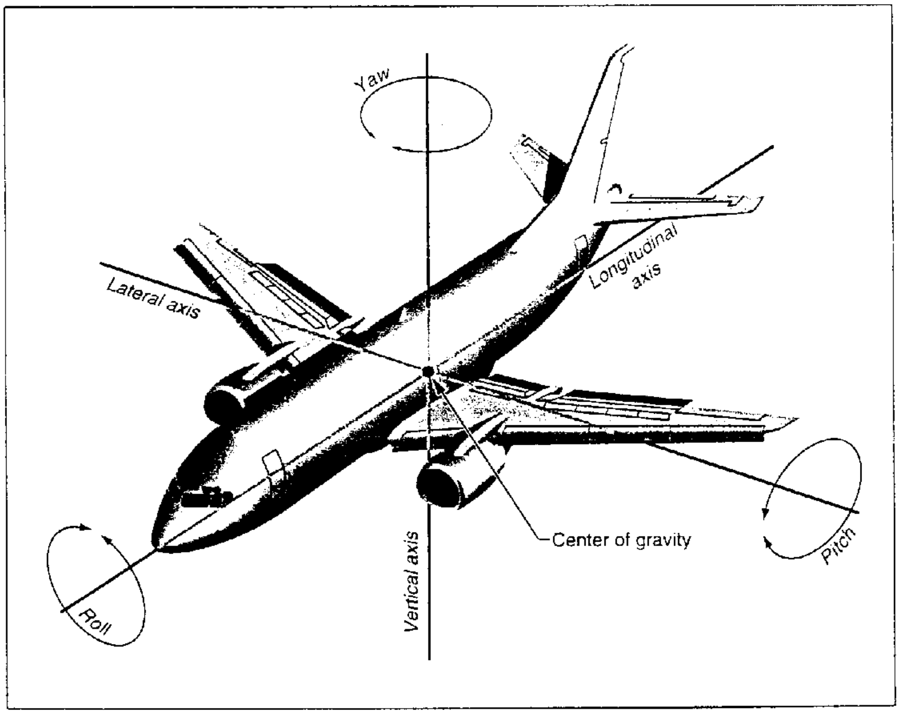


Figure 1. The six components of an airplane's motion are comprised of travel along — and rotation about — the longitudinal, lateral, and vertical axes.

2

tionally by a rudder input. Yawing moments can also be a result of wheel inputs, which can generate adverse yaw. Because the 737 has positive directional stability, the nose tends to realign into the wind when the temporary yawing moment is removed. The nose does not return to zero sideslip, but tends to overshoot, setting up the cyclic rolling/yawing motion of Dutch roll (the name comes from the swaying/bobbing motion of Dutch ice skaters).

As noted in FAR part 25.181(b): "Any combined lateral-directional oscillations (Dutch roll) occurring between 1.2 V_{stall} and maximum allowable speed appropriate to the configuration of the airplane must be positively damped with controls free." The 737 Dutch roll mode is positively damped (the motions get smaller each cycle) throughout the flight envelope, without an active Dutch roll damping system. It is only when an airplane does not have positively damped Dutch roll motions that an active yaw damper system is required for flight. Although not required for dispatch, a yaw damper system is installed on the 737 to improve ride quality by more quickly damping Dutch roll.

A historical note: The original 737-100 had a dual yaw damper system. From 707 and 727 experience, engineers originally believed that an operating yaw damper for the 737 would be required for dispatch. When flight test showed the natural Dutch roll mode to be positively damped in all flight conditions, it was determined to be unnecessary for dispatch. There was no reason to have two when none was required.

Flight Control System Design

The 737 uses a hydraulically powered conventional flight control system (Figure 2).

Lateral Control System. For roll control, the 737 utilizes a combination of ailerons and spoilers. Ailerons cause an increase in lift and drag. Spoilers cause a loss of lift and increase in drag. Together, they provide for greatly reduced yawing moments in rolling maneuvers. This balance of forces is what allows "feet-on-the-floor" turns.

Directional Control System. For directional control, the 737 uses a trimmable rudder on the vertical stabilizer (Figure 3). The rudder surface has a maximum deflection of 26 degrees, and it can be trimmed to 16 degrees of deflection. The yaw damper system can deflect the rudder two, three, or four degrees from its commanded position, depending on the model. All 737-300s, -400s, and -500s are limited to *three* degrees of travel. The yaw damper inputs are not fed back into the pedals. The only indication to the pilot is deflection of the yaw damper indicator needle. The system operates continuously, with response characteristics (gains) changed according to bank angle, localizer capture, and radio altitude.

The 737 rudder control system (Figure 4) is designed for a worst-case rudder requirement that includes:

- Low gross weight (slower speeds).
- Aft center of gravity (smaller moment arm).
- Engine failure at full thrust on rotation (maximum possible yawing moment).

This worst-case scenario can be controlled by the rudder/vertical stabilizer combination. The shorter 737s (-300 and -500) do not use higher-thrust engines because there would not be enough rudder control to handle the worst-case scenario.

The 737 rudder is normally controlled by the main rudder power control unit (PCU). It delivers power from the 'A' and 'B' hydraulic systems. A standby rudder PCU and standby hydraulic system will provide rudder control following a dual hydraulic system failure. In

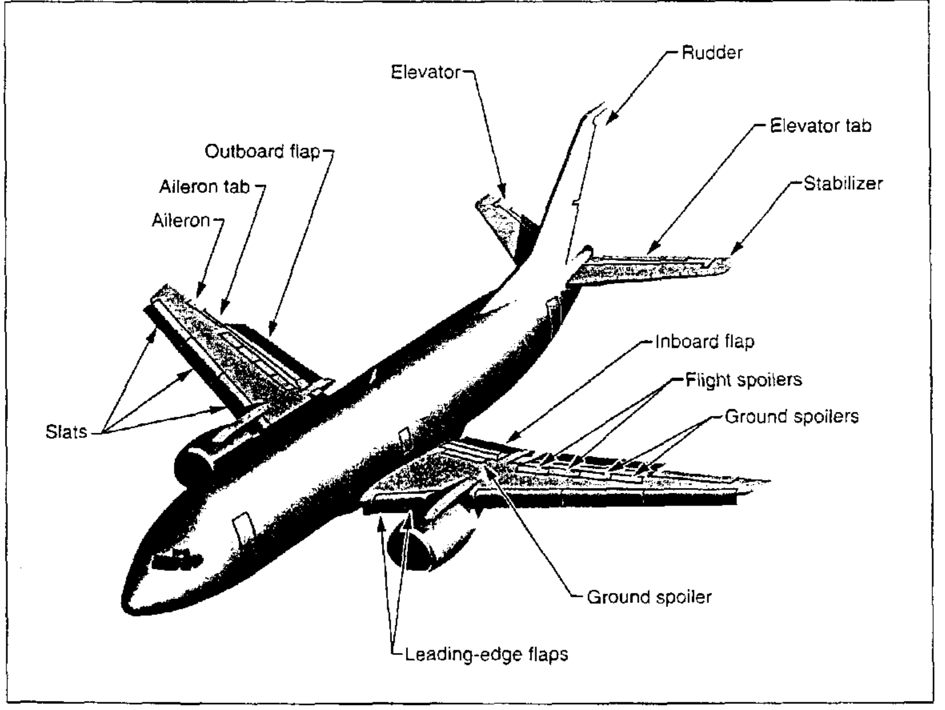


Figure 2. The conventional 737 flight control system allows pilots to fly feet-on-the-floor turns. This figure shows a 737-300.

3

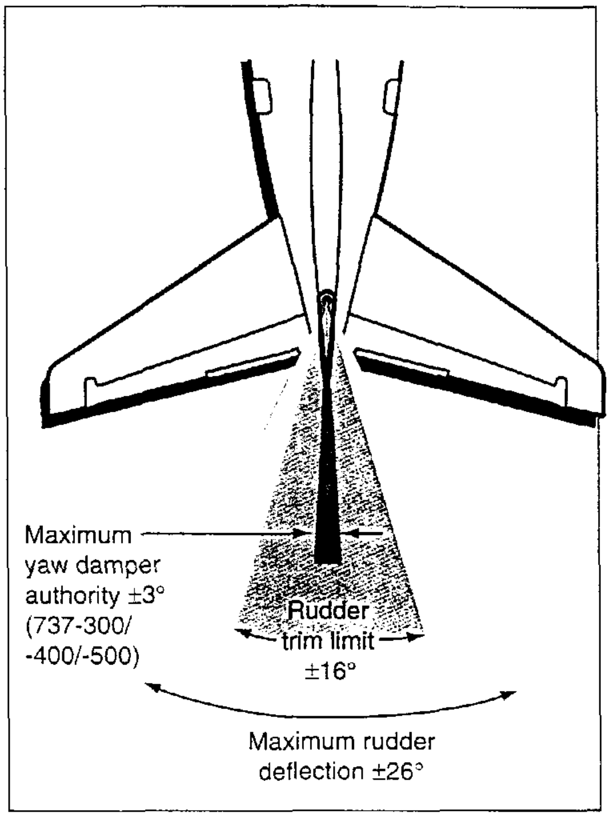


Figure 3. The maximum 737 rudder deflection that the yaw damper can command is only a small portion of the total rudder travel. Yaw damper limits for the 737-100 and -200 can be 2, 3, or 4 degrees, depending upon the installation.

the event of a single hydraulic system failure, the standby hydraulic system will come on automatically when the flaps are not in the up position.

The rudder PCU receives inputs from the rudder pedals, rudder trim actuator, and yaw damper. The yaw damper system's primary input is from a yaw rate gyro, which is located in the yaw damper coupler. The yaw damper coupler is located in the 737's electronic equipment bay. The rudder control system does not receive any commands from the autopilot. Therefore, engaging or disengaging the autopilot will have no effect on rudder or yaw damper operation.

The 737 directional control system is designed to be jam-tolerant to meet certification requirements for continued safe flight and landing. The 737 lateral control system (ailerons and spoilers) provides adequate roll control to overcome a rudder jammed in any position that would normally be used by the flight crew.

There is no rudder limiter or rudder pressure reducer on the 737. Instead, the 737 design takes advantage of an aerodynamic effect called "blowdown" to limit rudder travel. Blowdown is the point where the hydraulic power of the rudder control system has just enough force to overcome the aerodynamic force of the air pushing back on the rudder. As airspeed increases, the amount of available rudder decreases. For example, at taxi and takeoff speeds, full rudder (26 degrees) is available. But at 190 knots, the rudder will only travel about 14 degrees, even with a full rudder pedal input. At high speeds, blowdown limits the structural loads and limits the amount of yaw — and resulting roll created.

Yaw Damper Malfunctions

Statistically, the 737 yaw damper system malfunctions, on average, only once every 29,000 flight hours. The yaw damper system has three possible failure modes:

- A zero yaw damper command.
- An oscillatory or erratic yaw damper command.
- A full yaw damper command.

It is this third mode — a full yaw damper command — that causes the most concern for flight crews. The full yaw damper command may be sustained, or may slowly disappear with time, depending on the specific cause. This event can be easily controlled by the flight crew.

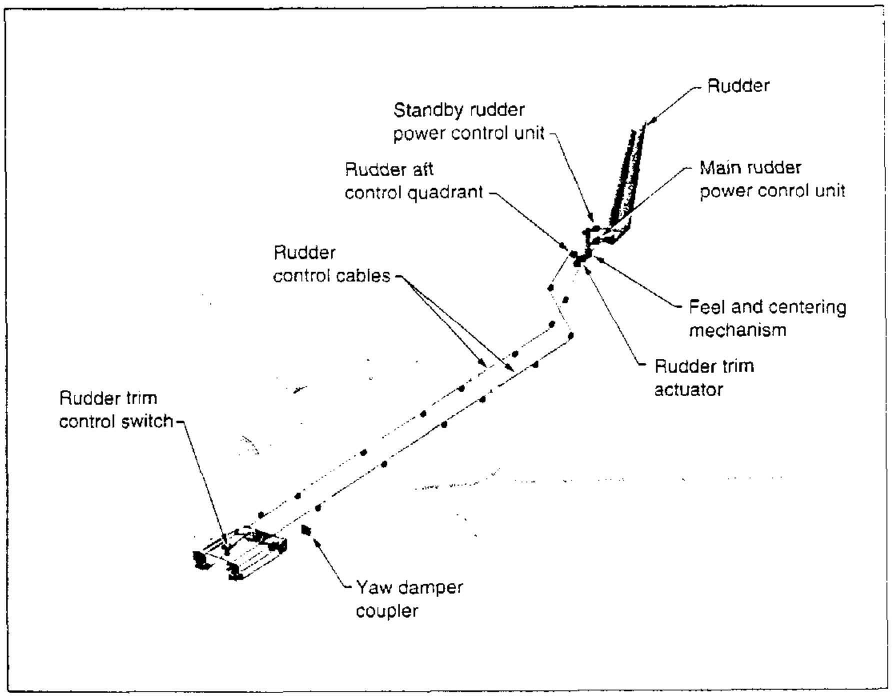


Figure 4. The 737 rudder control system is designed to handle the worst-case scenario: engine failure during takeoff rotation.

4

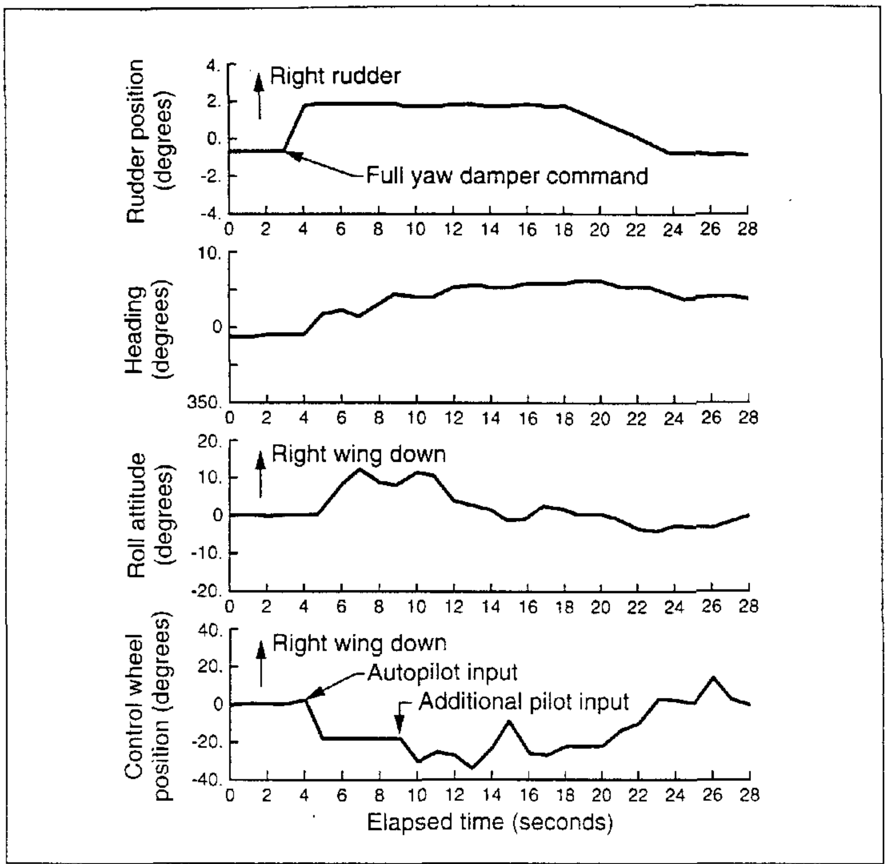


Figure 5. This actual 737 flight data recorder data shows how the airplane responds to a full authority yaw damper command. The airplane was in cruise with the autopilot on.

As you may remember from our basic aerodynamics discussion, rudder surface movement creates a yawing moment. In the flight deck, the yawing moment created by a full yaw damper command (which is less than one created by an engine failure) is more often felt than seen. The roll resulting from the yaw will typically be felt *and* seen by the flight crew.

Remember, the autopilot system has no input to the rudder control system. When engaged, the autopilot responds with lateral control inputs to the roll and heading changes generated by the yawing motion. The autopilot reacts differently depending upon the autopilot roll mode selected, and flap configuration. The autopilot can respond to a change in heading and/or roll with up to full autopilot lateral control authority. If the flaps are up, the control wheel limit is three units of rotation (18 degrees). If the flaps are not up, the limit is four units (24 degrees). Under certain flight conditions, this may be just enough roll authority to roll to wings level, but will most likely only slow the roll to an average rate of one to two degrees per second (Figure 5).

Human Factors

Frequently after an unexpected roll event, pilots report bank angle excursions two or three times as large as the actual recorded values on the flight data recorder. The accuracy of these pilot reports also appears to be a function of altitude; the lower the altitude, the more accurate the report. This is primarily because external visual cues are more prominent at lower altitudes.

Essentially, there are three major reasons why an experienced crew might perceive a bank angle to be higher than actual:

- Startle Factor.
- Acceleration.
- Flight Control Feedback due to Control Wheel Steering.

Startle Factor. For thousands of hours, flight crews sit in airplanes that are flying straight and level. The bank angle for course corrections seldom exceeds 25 degrees, and often is only 15 degrees or less. Every bank angle change is normally commanded by the pilot or easily explained by outside disturbances such as turbulence. Reports on crew fatigue, crew awareness, and crew interaction show that after thousands of hours of uneventful flying, crews become relaxed. That's why an unexpected event of a given magnitude in flight will cause a bigger pilot reaction than an event of larger magnitude in a simulator. This is due to lower pilot awareness and expectations of non-normal events during a routine two-hour flight than a pilot would experience in a two-hour simulator session, where something is expected to "go wrong."

Pilot reactions to an event vary depending upon the phase of flight. Reactions at FL350 are different than reactions at 35 feet. This reaction time differential is well-known and incorporated in the design and certification of transport category airplanes. During certification tests in cruise flight, recovery controls are not to be applied until four seconds after a malfunction has been inserted. When you would expect quicker pilot reactions to disturbances, such as in the approach and landing phase of flight, reaction times for certification purposes are reduced to one second.

Acceleration. When discussing the airplane's roll axis, three terms are commonly used:

- Bank angle (measured in degrees).
- Roll rate (the rate of change of bank angle, measured in degrees per second).

5

- Roll acceleration (the rate of change of roll rate, measured in degrees per second^2).

When pilots of large commercial transport airplanes manually maneuver the airplane to acquire and maintain a desired heading, they generally initiate a turn using a rather slow acceleration (two to three degrees per second^2) until they achieve a gentle roll rate (four to five degrees per second), so that it takes five to six seconds to roll to between 25 and 30 degrees of bank. The latest 737-300, -400, and -500 autopilot uses a variable roll rate during Heading Select as a function of the bank angle commanded, varying from 1.3 degrees per second to 4 degrees per second. Earlier 737 autopilots have fixed roll rate limits.

Although it can vary with the flight phase, pilots generally react very quickly to the roll acceleration. This is quite evident when landing in a gusting wind. Sometimes, almost full control authority will be used to stop a roll acceleration long before a significant rate can develop, and long before a large bank angle is reached. Here again, the startle factor comes in. Pilots train for events such as an engine failure at V_R or V_2; they react in milliseconds with proper controls, and the bank angle varies only a few degrees. Pilots also stop rolling motions during landings very quickly. They know that rapid accelerations can be present, and they realize that large roll rates and bank angles will result if they fail to react quickly. During cruise, pilots are accustomed to relatively small roll rates and roll accelerations. When an upset occurs in cruise, the roll acceleration may be perceived as being excessive, even though the acceleration is less than that experienced with an engine failure at V_R, or in a gusty crosswind. There is evidence that roll accelerations of 10 to 15 degrees per second^2, even if they are sustained for less than a second, cause concern for pilots.

Flight Control Feedback due to Control Wheel Steering (CWS). The interaction of the flight control feel, autopilot system, and human reaction may result in incorrect interpretation and response to CWS. When the autopilot is engaged in Heading Select or LNAV and a breakout force of 10 pounds is applied to the yoke, the control wheel moves and the autopilot reverts into CWS.

Apparent Uncommanded Yaw or Roll *Not* Caused by Yaw Damper Malfunction

In addition to the yaw damper malfunctions discussed in this article, other events might manifest themselves to the flight crew as an apparent uncommanded yaw or roll. These events can be either normal or non-normal.

Normal events may include autopilot attempts to maintain course guidance and airplane attitude during Flight Management Computer (FMC) position updates, and during autopilot approach course intercepts.

Non-normal events might include:

- Wake turbulence.
- Adverse weather.
- Flight control malfunctions.
- Split throttles.
- Engine power loss.
- Autopilot malfunctions.

In any of these events, pilot situational awareness, alerting and warning systems, as well as knowledge of procedures should dictate the appropriate response. The crew may not immediately recognize the reason the airplane enters a roll.

In any case, if the airplane yaws or rolls, and—in the pilot's judgment—there is no easily identifiable cause, then the crew should perform the "Uncommanded Yaw or Roll" procedure.

Uncommanded roll can be caused by a malfunction of the lateral axis of the autopilot. This malfunction is characterized by a control wheel deflection in the direction of the uncommanded roll with the autopilot engaged. In this case, the pilot should simultaneously disengage the autopilot and counter the roll input, bringing the airplane to wings level, and complete the "Uncommanded Yaw or Roll" procedure.

For uncommanded rolls not associated with an autopilot malfunction when the autopilot is engaged, the control wheel position will move opposite to the direction of the uncommanded roll. In this case, the autopilot is attempting to oppose the uncommanded roll. Allowing the control wheel to go to neutral after disengagement may allow the airplane to roll even farther in the uncommanded direction. Because of this, the pilot should grasp and hold the control wheel firmly, disengage the autopilot, make appropriate control wheel corrections to return to wings level, and complete the "Uncommanded Yaw or Roll" procedure.

6

In CWS, the autopilot response is based on the airplane's bank angle when the force on the control wheel is released. If the bank angle is:

- Five degrees or less, the autopilot will maintain the current heading.
- Between 5 and 30 degrees, the autopilot will maintain the existing bank angle.
- More than 30 degrees, the autopilot will roll back to and maintain 30 degrees of bank.

The autopilot uses available roll control to capture the desired bank angle. This wheel response may be unexpected by a pilot unfamiliar with CWS operation.

Normally in CWS, pilots use wheel input rates of 5 to 10 degrees per second. If the wheel is turned at a high rate (40 degrees per second, or more), then the force required to turn the wheel approximately triples. This happens because the autopilot actuators can not respond fast enough and are being forced by the pilot's input. So, for a very quick wheel motion, the lateral control forces can noticeably increase, but the corresponding roll rate doesn't.

In summary, three factors can result in pilot confusion about feedback due to control wheel steering:

- The breakout force.
- Autopilot capturing and maintaining the commanded CWS bank angle, as per design.
- The force to move the wheel increases as the wheel movement rate increases.

Pilot Actions

Pilot response to yaw damper malfunctions depends on the type of yaw damper event. Remember, the yaw damper system can only command a maximum of three degrees of rudder deflection for the 737-300, -400, and -500 (two, three, or four degrees for the 737-100 and -200, as installed). In all cases, this is easily controlled by the flight crew. Appropriate non-normal procedures are outlined in the Operations Manual and Quick Reference Handbook.

Response to Yaw Damper Malfunctions. First, the system may malfunction without any commands being made to deflect the rudder. Because there is no resulting movement in any airplane axis, there are no special techniques for this condition. If the yaw damper light on the overhead panel illuminates, perform the "Yaw Damper" procedure and turn the yaw damper off.

If the yaw damper malfunctions and gives commands that appear to the pilot as an oscillation or erratic motion about the yaw axis, then turn the yaw damper off in accordance with the "Uncommanded Yaw or Roll" procedure. The yaw damper light will not illuminate until the switch is turned off. Cross checking the yaw damper indicator is the best way to identify a yaw damper malfunction.

If the yaw damper malfunctions and commands a full yaw damper input, the airplane may respond with an initial yawing motion that the pilots may not notice. However, the yawing motion will be followed by a readily apparent rolling motion in the same direction as the rudder deflection. The roll rate and roll acceleration are quicker than a normal autopilot input. If engaged, the autopilot will respond with opposite wheel to counter the roll. At .74 Mach and at normal cruise altitudes, the autopilot may not be able to roll the airplane back to wings level, but will reduce the roll rate to an average of one to two degrees per second, allowing the pilot ample time to recover.

In this case, the pilot should perform the "Uncommanded Yaw or Roll" procedure:

- Grasp and hold the control wheel firmly.
- Disengage the autopilot.
- Make appropriate control wheel corrections to return to wings level.

If yaw and/or roll forces continue:

- Turn the yaw damper off.

Other Possible Causes of Apparent Uncommanded Yaw or Roll. Yaw damper system malfunctions are not the only possible causes of an apparent uncommanded yaw or roll. There are other events, normal and non-normal, that could manifest themselves as a yaw or roll (see page 29 sidebar, "Apparent Uncommanded Yaw or Roll Not Caused by Yaw Damper Malfunction").

Summary

Since its introduction in 1968, the 737 has carried more than four billion passengers and flown more than 20 billion miles in safety and comfort. Its aerodynamic characteristics are trusted and well-understood, and the flight control system has proven itself to be reliable and safe.

This article has discussed the 737 flight control system — particularly the rudder, yaw damper, and autopilot systems — and associated yaw damper failure modes. It has also reviewed the proper pilot actions in the event of uncommanded yaw or roll. Worst-case yaw damper system malfunctions are easily controllable.

Boeing is currently working to improve airline flight and maintenance crews' awareness of the 737 directional control system. These efforts focus on both current production airplanes (737-300, -400, and -500), as well as the 737-600, -700, and -800 series airplanes, which are scheduled to go into service in 1997.

It's all part of the Boeing commitment to building a quality product, and providing world-class support for the life of the airplane.

7