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Rudder Malfunction Causes Loss of Control of Boeing 737

All 132 occupants were killed when the airplane struck terrain near Pittsburgh, Pennsylvania, U.S. The investigation report said that, following an encounter with wake turbulence, the airplane's rudder moved to the limit of its travel, in a direction opposite to that commanded by the flight crew. The report said that the rudder-control anomaly most likely was caused by a malfunction of the rudder's main power control unit.

FSF Editorial Staff

About 1903 local time on Sept. 8, 1994, USAir Flight 427, a Boeing 737-300, entered an uncontrolled descent during approach to Pittsburgh (Pennsylvania, U.S.) International Airport (PIT) and struck terrain near Aliquippa, Pennsylvania. All 132 occupants were killed. The airplane was destroyed.

The U.S. National Transportation Safety Board (NTSB), in its final report, said, "The probable cause of the USAir Flight 427 accident was a loss of control of the airplane resulting from the movement of the rudder surface to its blowdown limit.[1]

"The rudder surface most likely deflected in a direction opposite to that commanded by the pilots as a result of a jam of the main rudder power control unit [PCU] servo valve secondary slide to the servo valve housing offset from its neutral position and overtravel of the primary slide."

The airplane was on a scheduled flight from Chicago, Illinois. The flight crew was on the third day of a three-day flight schedule. They had begun duty at 1215 in Jacksonville, Florida, and had flown to Charlotte, North Carolina, and then to Chicago.

The captain, 45, had an airline transport pilot (ATP) certificate and approximately 12,000 flight hours, including 3,269 flight hours as a Boeing 737 (B-737) captain and 795 flight hours as a B-737 first officer.

"The captain's initial flight experience was in general aviation, and he obtained a private pilot certificate in August 1969," the report said. He joined the U.S. Air National Guard and in 1973 completed U.S. Air Force pilot training. His early military records were destroyed, but Air Force records from September 1975 through March 1979 show that he had 227 training hours and 667 flight hours in the Cessna O-2 (military version of the Cessna 337).

The captain flew for Braniff Airways from 1977 to 1980. He was hired by USAir (now US Airways) in 1981.

"USAir records indicated that the captain was on extended sick leave from Jan. 25 to April 28, 1994, because of back surgery," the report said. The surgery was performed in March 1994 to remove a ruptured disk. The captain's wife said that he did not complain of back pain after he returned to flight duty and that he took no medication other than allergy injections.

"Several check airmen, instructors and first officers who were acquainted with the captain and his piloting abilities indicated that the captain was meticulous, very proficient, very

Boeing 737-300

The Boeing Co. in 1965 announced the decision to build a short-range, twin-turbofan transport. The aircraft, designated the 737, was designed to use many components and assemblies from the tri-engine B-727. The first B-737 flew in April 1967, and deliveries of the first production model, the B-737-200, began before the end of 1967.

Boeing in 1980 announced plans to build the B-737-300, a larger version that would accommodate more passengers and baggage, and have quieter and more fuel-efficient engines. Fuselage plugs were installed forward of the wing and aft of the wing carry-through structure to increase length by 8.7 feet (2.7 meters). The airplane can accommodate 128 passengers to 149 passengers and 1,068 cubic feet (30.2 cubic meters) of freight, compared with accommodations in the B-737-200 for 115 passengers to 130 passengers and 875 cubic feet (24.8 cubic meters) of freight.

The Pratt & Whitney JT8D-9A engines, each producing 14,500 pounds thrust (64.5 kilonewtons), on the B-737-200 were replaced with CFM International CFM56-B engines, each producing 20,000 pounds thrust (88.97 kilonewtons) on the B-737-300.

The prototype made its first flight in February 1984, and deliveries of production B-737-300s began in November 1984. Maximum standard takeoff weight is 124,500 pounds (56,473 kilograms). Maximum landing weight is 114,000 pounds (51,710 kilograms).

Maximum operating speed is Mach 0.84. Maximum cruising speed at an average cruise weight of 100,000 pounds (45,360 kilograms) at 33,000 feet is 462 knots (856 kilometers per hour [kph]). Economy cruising speed at 33,000 feet is Mach 0.73. Stalling speed in landing configuration at 103,000 pounds (46,720 kilograms) is 102 knots (189 kph).

Source: *Jane's All the World's Aircraft*

professional and attentive to detail, and that he flew 'by the book,'" the report said. "They also reported that the captain was well liked and exhibited excellent [crew resource management] skills."

The captain's civilian flight records and post-1975 military records showed no aerobatic flight experience. The report said that Air Force initial pilot training included aerobatic training in jet trainers, but the captain's Air Force initial pilot training records were not available.

The first officer, 38, had an ATP certificate and 9,119 flight hours, including 3,644 flight hours as a B-737 first officer.

The first officer's initial flight experience was in general aviation. He was hired in 1987 by Piedmont Airlines and flew as a Fokker F28 first officer until 1989, when he transitioned to the B-737 as a first officer. He became an employee of USAir when the airline acquired Piedmont in 1989.

"Check airmen, instructors and captains who were acquainted with the first officer and his piloting abilities indicated that the first officer was friendly, very well qualified and an outstanding first officer who exhibited exceptional piloting skills," the report said. "One captain who had flown with the first officer described an in-flight hydraulic system emergency that occurred during one of their flights. He stated that the first officer remained very calm during the emergency situation."

There was no record that the first officer had training or experience in aerobatic flight. "However, his flight logbooks indicated that he had performed spin recoveries in 1973 in a Piper J-3 'Cub' airplane when he had total flight times between 77 [hours] and 93 hours."

The accident airplane was manufactured and delivered to USAir in 1987. At the time of the accident, the airplane had accumulated approximately 23,846 flight hours and 14,489 cycles.

The estimated flight time from Chicago to Pittsburgh was 55 minutes. Visual meteorological conditions prevailed along the route. The first officer was the pilot flying. The airplane's autoflight system[2] was engaged.

At 1845 — about 35 minutes after departing from Chicago — the crew was told by Cleveland Air Route Traffic Control Center (Cleveland Center) to descend from Flight Level (FL) 290 to FL 240. The captain, the pilot not flying, acknowledged the clearance.

At 1850, Cleveland Center told the crew to cross CUTTA intersection — an arrival fix approximately 30 nautical miles (56 kilometers) northwest of PIT — at 10,000 feet. The captain acknowledged the clearance and then listened to the PIT automatic terminal information service (ATIS) report.

The reported weather conditions included scattered clouds at 25,000 feet, 15 statute miles (24 kilometers) visibility, temperature 75 degrees Fahrenheit (F; 24 degrees Celsius [C]), dew point 51 degrees F (11 degrees C) and surface winds from 270 degrees at 10 knots. The ATIS report said that instrument landing system (ILS) approaches were being conducted to Runway 32 and Runway 28R.

At 1853, a flight attendant asked the flight crew if they had received connecting-flight information and gate information. The captain said that they had not received the information. The flight attendant then asked if the pilots wanted anything to drink, and both pilots requested juice.

At 1854, Cleveland Center told the crew to reduce airspeed to 250 knots.

"At that time, Delta Air Lines Flight 1083, a Boeing 727 [B-727] that had been sequenced to precede USAir Flight 427 on the approach to PIT from the northwest, was in level flight at 10,000 feet with an assigned airspeed of 210 knots and an assigned heading of 160 degrees," the report said. "Delta Flight 1083 was in communication with Pittsburgh Terminal Radar Approach Control [Pittsburgh Approach] personnel."

At 1856, Cleveland Center told the crew of Flight 427 to reduce airspeed to 210 knots and said that the airspeed reduction had been requested by Pittsburgh Approach. The controller then told the crew to descend at pilot's discretion to 10,000 feet and to contact Pittsburgh Approach.

At 1857:07, the flight attendant returned to the cockpit with juice for the pilots; she left the cockpit about one minute later.

At 1857:23, Pittsburgh Approach said, "USAir four twenty-seven, … heading one six zero, vector [for] ILS runway two eight right final approach course. Speed, two one zero." The captain acknowledged.

At 1858:03, the controller told the crew of Delta Flight 1083 to descend to 6,000 feet. At 1858:33, the controller told the crew of USAir Flight 427 to descend to 6,000 feet.

"The [USAir captain] acknowledged the descent instructions and, about 1859:04, [the crew] started to accomplish the preliminary landing checklist (altimeters/flight instruments, landing data, shoulder harnesses and approach briefing)," said the report.

At 1900:08, Pittsburgh Approach told the crew of Delta Flight 1083 to turn left to a heading of 130 degrees and to reduce airspeed to 190 knots. The controller then told the crew of USAir Flight 427 to fly a heading of 140 degrees and to reduce airspeed to 190 knots.

At 1900:24, the cockpit voice recorder (CVR) recorded the sound of the flap handle being moved.

"According to USAir personnel, the standard configuration for a [B-]737-300 airplane operating at an airspeed of 190 knots

Cockpit Voice Recorder Transcript, USAir Flight 427, Boeing 737-300, Near Aliquippa, Pennsylvania, U.S., Sept. 8, 1994

(FSF editorial note: The following transcript begins as the aircraft is descending to 6,000 feet on approach to Pittsburgh [Pennsylvania, U.S.] International Airport. The transcript is as it appears in the U.S. National Transportation Safety Board accident report, except for minor column rearrangement and addition of notes defining some terms that may be unfamiliar to the reader. Times are local.)

Time	Source	Content
1859:04	**HOT-2**	I guess we ought to do a preliminary Pete.
1859:06	**HOT-1**	altimeters and flight instruments thirty eleven?
1859:08	**HOT-2**	my side.
1859:11	**HOT-1**	aah, where are we … landing data is …
1859:12	**285LM**	Pit, two eight five Lima Mike is thirteen for uhh, ten with Allegheny's Hotel.
1859:14	**HOT-2**	posted on my side for a hundred and nine.
1859:15	**APR**	November two eight five Lima Mike, Pittsburgh approach. direct Montour vector ILS runway two eight final approach course.
1859:16	**HOT-1**	thirty three, forty three an two hundred.
1859:21	**285LM**	Montour on the vectors, Lima Mike …
1859:22	**HOT-1**	shoulder harness?
1859:24	**APR**	USAir fourteen sixty two, descend and maintain six thousand.
1859:25	**HOT-2**	on.
1859:28	**CAM**	[sound of clicks similar to shoulder harness being fastened]
1859:28	**HOT-1**	approach brief?
1859:30	**APR**	USAir three seventy four, contact approach one two three point niner five, good day.
1859:31	**HOT-2**	plan two eight right. two seventy nine inbound, one eleven seven.
1859:36	**HOT-2**	[sound similar to deep inhale and exhale]
1859:41	**APR**	USAir three zero nine, Pittsburgh approach, heading zero five zero vector ILS runway three two final approach course.
1859:54	**HOT-1**	ah, don't do this to me.
1859:56	**HOT-2**	[sound of chuckle] froze up did it?

during an approach to land would be flaps 1, which provides for partial extension of the wing leading-edge slats and full extension of the Krueger (wing leading-edge) flaps, and one degree of extension of the wing trailing-edge flaps," said the report.

At 1900:44, the first officer made a routine public-address (PA) announcement to the passengers and asked the flight attendants to prepare the cabin for arrival.

"The CVR indicated that, while the first officer was making the PA announcement … , [Pittsburgh Approach] instructed Delta Flight 1083 to turn left to a heading of 100 degrees," the report said. "Also during the first officer's PA announcement, the captain of USAir Flight 427 asked [Pittsburgh Approach], 'Did you say [runway] two eight left for USAir four twenty-seven?'"

At 1901:06, Pittsburgh Approach said, "Uh, USAir four twenty-seven, it will be two eight right."

At 1902:24, Pittsburgh Approach said, "USAir four twenty-seven, turn left [to] heading one zero zero. Traffic will be [at your] one [o'clock] to two o'clock [position], six miles [distant]. [The traffic is a British Aerospace] Jetstream climbing out of thirty-three [hundred feet] for five thousand [feet]."

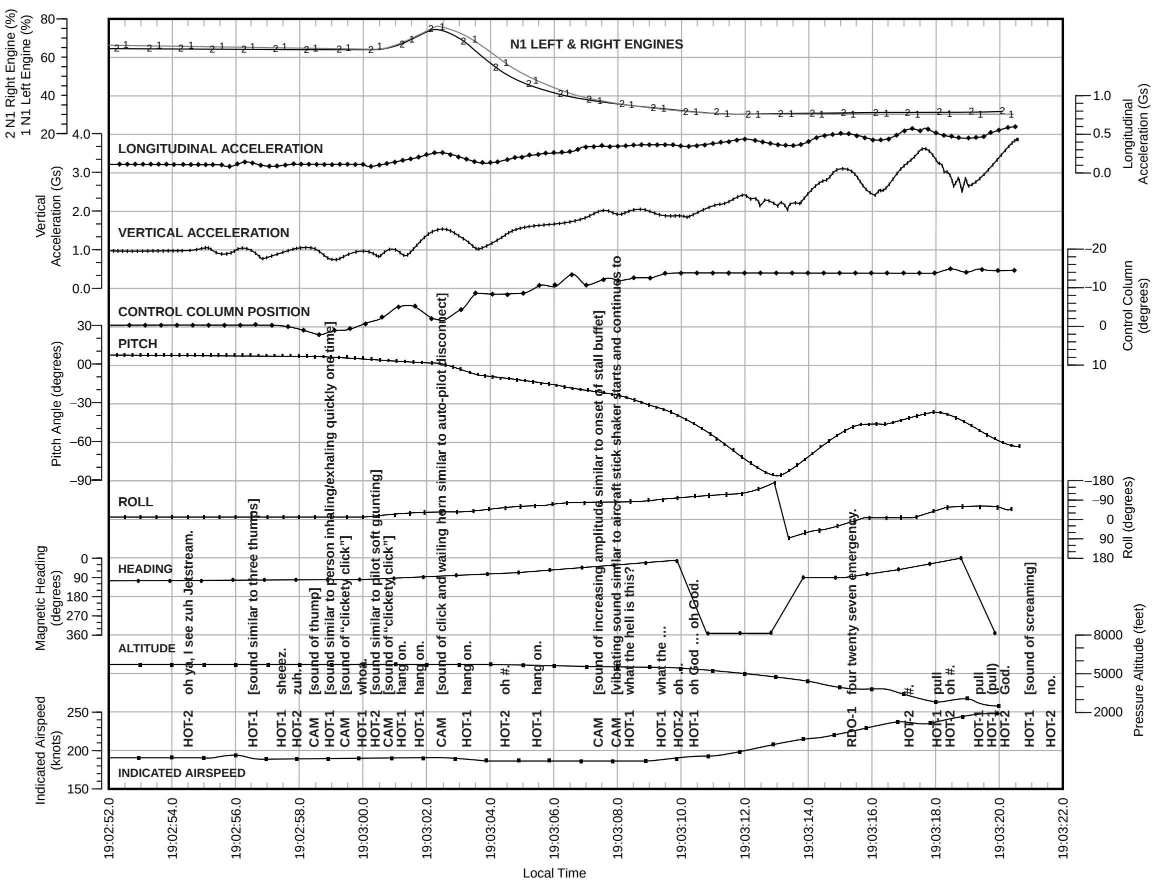
The captain said, "We're looking for the traffic [and] turning to one zero zero, USAir four twenty-seven."

Flight data recorder (FDR) data showed that, at 1902:53, the airplane was in a seven-degree left bank, rolling out of the left turn to the assigned heading of 100 degrees, at 6,000 feet and 190 knots. (Figure 1 shows FDR data recorded during the final 30 seconds of the flight.)

At 1902:54.3, the first officer told the captain, "Oh, ya, I see zuh Jetstream." The report said that the Jetstream would have been visible through the lower part of the first officer's middle window.

"As the first officer finished this statement (at about 1902:57), the CVR recorded a sound similar to three thumps in one second, the captain stating 'sheeez' (at 1902:57.3) and the first officer stating 'zuh' (at 1902:57.5)," the report said.

Flight Data Recorder Data, USAir Flight 427, Boeing 737-300, Near Aliquippa, Pennsylvania, U.S., Sept. 8, 1994



Source: U.S. National Transportation Safety Board

Figure 1

"Between about 1902:57 and about 1902:58, FDR data indicated that USAir Flight 427's airspeed fluctuated from about 190 knots to about 193 knots and then decreased to about 191 knots for the next four seconds.

"Between about 1902:57 and about 1902:59, FDR data indicated that the airplane's left bank steepened from slightly less than eight degrees to slightly more than 20 degrees."

The CVR recorded the sound of a thump and two "clickety click" sounds.

"About 1902:59, the left roll was arrested, and the airplane began to briefly roll right toward a wings-level attitude," the report said. "FDR data show that, between about 1902:59 and about 1903, the airplane's left bank had decreased to about 15 degrees."

The airplane yawed rapidly left through the assigned heading of 100 degrees. The captain said "whoa," and the first officer grunted softly.

"By just after 1903, the airplane had begun to roll rapidly back to the left again; its airspeed remained about 191 knots," the report said. "FDR heading data indicated that, by 1903:01, the airplane's heading had moved left through about 089 degrees and continued to move left at a rate of at least five degrees per second."

The captain told the first officer to "hang on," and the first officer grunted loudly. The captain repeated "hang on" three more times.

The airplane's left bank angle increased to approximately 43 degrees, and the airplane began to descend from 6,000 feet. The control column began to move aft, and airspeed began to decrease below 190 knots.

"The CVR recorded the sound of the autopilot disconnect horn [at 1903:02.1]," the report said. "During the next five seconds, the FDR recorded increasing left roll, aft control column, decreasing altitude and a decreasing airspeed to about 186 knots."

At 1903:07.5, the CVR recorded a sound similar to the onset of stall buffet and then a sound similar to activation of the stick shaker, which is part of the airplane's stall-warning system.

The captain said, "What the hell is this?" The sound similar to stick-shaker activation continued until the end of the recording.

"At 1903:08.3, an aural tone similar to an altitude alert sounded, and, one second later, the traffic-alert and collision avoidance system [TCAS] sounded 'traffic [traffic],'" the report said. The reason for the TCAS traffic alert was not known, but the report said that the airplane was within approximately three miles of Atlantic Coast Flight 6425 (the Jetstream) at the time.

1900:08	**APR**	Delta ten eighty three, turn left heading one three zero. reduce speed to one niner zero.
1900:12	**HOT-1**	[intermittent static sound (heard on captain's channel only) for seventeen seconds]
1900:12	**HOT-1**	I hate it when you don't hear the other transmissions.
1900:13	**DL1083**	one thirty one ninety speed, Delta ten eighty three.
1900:14	**HOT-2**	[chuckle] yeah.
1900:15	**APR**	USAir four twenty seven turn left heading one four zero, reduce speed to one niner zero.
1900:20	**RDO-1**	OK, one four zero heading and one ninety on the speed, USAir four twenty seven.
1900:24	**CAM**	[sound of three clicks similar to flap handle being moved]
1900:26	**CAM**	[sound of single chime similar to seat belt chime]
1900:26	**HOT-2**	oops, I didn't kiss 'em 'bye.
1900:28	**CAM**	[clicking sound similar to trim wheel turning at auto-pilot trim speed]
1900:31	**HOT-2**	what was the temperature, 'member?
1900:33	**APR**	five Lima Mike contact Pittsburgh departure one two four point seven five.
1900:34	**HOT-1**	seventy five.
1900:35	**HOT-2**	seventy five?
1900:37	**CAM**	[clicking sound similar to trim wheel turning at auto-pilot trim speed]
1900:40	**285LM**	twenty four seventy five, Lima Mike.
1900:43	**PA-4**	… seatbelts and remain seated for the duration of the flight.
1900:44	**PA-2**	folks, from the flight deck we should be on the ground in 'bout ten more minutes. uh, sunny skies, little hazy. temperature, temperature's ah, seventy five degrees. wind's out of the west around ten miles per hour. certainly 'preciate you choosing USAir for your travel needs this evening, hope you've enjoyed the flight. hope you come back and travel with us again. this time we'd like to ask our flight attendants please prepare the cabin for arrival. ask you to check the security of your seatbelts. thank you.
1900:46	**APR**	Delta ten eighty three, turn left heading one zero zero.
1900:48	**DL1083**	one zero zero, ten eighty three.

1901:04	**RDO-1**	did you say two eight left for USAir four twenty seven?
1901:06	**CAM**	[chime similar to seatbelt chime]
1901:06	**APR**	uh, USAir four twenty seven, it'll be two eight right.
1901:08	**RDO-1**	two eight right, thank you.
1901:10	**HOT-1**	two eight right.
1901:11	**HOT-2**	right, two eight right. that's what we planned on. autobrakes on one for it.
1901:18	**APR**	Delta ten eighty three contact approach one two four point one five.
1901:22	**DL1083**	twenty four fifteen, good day.
1901:26	**APR**	USAir fourteen sixty two at six thousand, reduce speed to one niner zero.
1901:35	**HOT-1**	I can't * * *.
1901:36	**APR**	USAir three zero niner, descend and maintain six thousand then reduce speed to one niner zero.
1901:42	**HOT-2**	Bravo thirty nine … that's not too bad that's …
1901:47	**APR**	USAir eighteen seventy four turn right heading one zero zero. contact approach one two three point niner five.
1901:48	**HOT-2**	… 'bout half way.
1901:50	**CAM**	[aural tone similar to altitude alert]
1901:51	**HOT-2**	(then) … (works)
1901:56	**HOT-1**	seven for six.
1901:57	**APR**	USAir fourteen sixty two turn right heading zero eight zero.
1901:58	**HOT-2**	seven for six.
1902:06	**HOT-1**	boy, they always slow you up so bad here.
1902:08	**HOT-2**	that sun is gonna be just like it was takin' off in Cleveland yesterday too. I'm just gonna close my eyes. [sound of laughter] you holler when it looks like we're close. [sound of laughter]
1902:24	**HOT-1**	[sound of chuckle] OK.
1902:24	**APR**	USAir four twenty seven, turn left heading one zero zero. traffic will be one to two o'clock, six miles, northbound Jetstream, climbing out of thirty three for five thousand.
1902:32.0	**RDO-1**	we're looking for the traffic, turning to one zero zero, USAir four twenty seven.
1902:32.9	**CAM**	[sound similar to aircraft engines increasing in RPM to a steady value]

A recording of air traffic control (ATC) communications showed that, at 1903:10, one of the flight crewmembers said, "Oh (unintelligible). Oh (expletive)." The approach controller saw that Flight 427's altitude readout was 5,300 feet, and he said, "USAir four twenty-seven, maintain 6,000 [feet], over." The CVR transcript does not include these transmissions.

"From about 1903:09 to about 1903:22, the first officer's radio microphone was activated and deactivated repeatedly, so the ATC tapes recorded exclamations and other sounds from the accident airplane," the report said.

At 1903:15, the captain told Pittsburgh Approach, "Four twenty-seven, emergency." He then told the first officer two times or three times to "pull."

"During postaccident interviews, air traffic controllers who were in the tower cab when the accident occurred reported that they observed dense smoke rising to the northwest of the airport shortly after USAir Flight 427's final transmission," the report said. "The CVR stopped recording at 1903:22.8."

The airplane struck a densely wooded hill approximately six nautical miles (11 kilometers) northwest of PIT. The report said that the accident occurred in daylight, at 1903:23. The airplane was destroyed by the impact and a postaccident fire. The two pilots, three flight attendants and 127 passengers were killed as a result of "blunt force impact trauma." The report said the accident was not survivable, because no occupiable space remained intact.

"The airplane wreckage was severely fragmented, crushed and burned," the report said. "Some pieces of wreckage were excavated from the hillside at depths of up to eight feet [2.5 meters]. Most of the airplane wreckage … was located within a 350-foot [107-meter] radius of the main impact crater."

The U.K. Air Accidents Investigation Branch (AAIB), which assisted NTSB in reconstructing the airplane, found no evidence of a preimpact explosion. (NTSB asked AAIB to assist in the reconstruction of the B-737 because of the AAIB's experience in reconstructing the Boeing 747 [Pan American Airlines Flight 103] that experienced an in-flight explosion and struck terrain near Lockerbie, Scotland, on Dec. 21, 1988. All 259 airplane occupants were killed, and 11 people on the ground were killed.)

"The wreckage was further examined by explosion experts from the [U.S. Federal Aviation Administration (FAA)] and the [U.S. Federal Bureau of Investigation], and they also found no evidence of any preimpact explosion," said the report.

Because large flocks of migratory birds were seen by people on the ground in the Pittsburgh area throughout the afternoon and evening of the accident, the wreckage was examined for indications of a bird strike. No such indications were found.

Investigators examined whether wake turbulence from the Atlantic Coast Jetstream 31 or from the Delta B-727 was involved in the upset.

The Jetstream was 1,500 feet (458 meters) lower and 3.5 nautical miles (6.5 kilometers) from Flight 427 when the upset occurred. Thus, wake turbulence from the Jetstream did not affect Flight 427, said the report.

The Delta B-727 was descending through 6,300 feet in the approximate location where, 69 seconds later, the initial upset of Flight 427 occurred at 6,000 feet. The report said that a study performed jointly by NTSB and the U.S. National Aeronautics and Space Administration (NASA) determined that Flight 427 likely encountered wake turbulence from the B-727.

The report said that the characteristics of the wake turbulence could not be identified because of FDR data limitations. The FDR recorded 13 parameters, including altitude, indicated airspeed, heading, roll attitude, pitch attitude, control-column position and vertical acceleration. The FDR did not record flight-control-surface positions or movements of the rudder controls and aileron controls.

The report said, however, that further studies, including flight tests, indicated that the wake turbulence from the Delta airplane should not have caused significant control problems for the USAir crew.

"According to the flight-test-pilot statements, although the wake encounters had varying effects on the [B-]737 flight-handling characteristics, the effects usually lasted only a few seconds and did not result in a loss of control or require extreme or aggressive flight control inputs to counteract," the report said. "The flight-test pilots with experience flying in air carrier operations stated that the wake encounters experienced during the flight tests were similar to those that they had experienced during normal flight-line operations. The pilots described the wake encounters as 'routine' and not startling."

Sounds recorded by the CVR in the airplane used for the wake-turbulence flight tests were similar to the thumps recorded by the accident airplane's CVR. The clickety-click sounds recorded by the accident airplane's CVR were identified as possibly resulting from wake turbulence striking the windshield wipers and causing them to chatter or slap against the windshield.

The report said that air traffic controllers had maintained the required wake-turbulence separation between the airplanes.

"The accident airplane and the [B-727] that preceded it inbound to PIT (Delta Flight 1083) were separated by at least 4.1 [nautical] miles [7.6 kilometers] when they were at the same altitude," said the report.

Investigators examined the possibility that the upset was caused by several other factors, including: asymmetric

1902:34.8	**CAM**	[clicking sound similar to trim wheel turning at auto-pilot trim speed]
1902:54.3	**HOT-2**	oh ya, I see zuh Jetstream.
1902:57.0	**HOT-1**	[sound similar to three thumps]
1902:57.3	**HOT-1**	sheeez.
1902:57.5	**HOT-2**	zuh.
1902:58.0	**CAM**	[sound of thump]
1902:58.5	**HOT-1**	[sound similar to person inhaling/ exhaling quickly one time]
1902:58.6	**CAM**	[sound of "clickety click"]
1902:59.1	**CAM**	[sound of thump of less magnitude than the first thump]
1902:59.3	**HOT-1**	whoa.
1902:59.5	**CAM**	[sound of "clickety click"]
1903:00.3	**HOT-2**	[sound similar to pilot soft grunting]
1903:00.7	**CAM**	[sound of unknown click]
1903:01.1	**HOT-1**	hang on.
1903:01.1	**CAM**	[sound similar to aircraft engines increasing in RPM]
1903:01.5	**HOT-2**	[sound similar to pilot loud grunting]
1903:01.9	**HOT-1**	hang on.
1903:02.1	**CAM**	[sound of click and wailing horn similar to auto-pilot disconnect]
1903:03.6	**HOT-1**	hang on.
1903:04.4	**HOT-2**	oh #.
1903:05.2	**HOT-1**	hang on.
1903:07.5	**CAM**	[sound of increasing amplitude similar to onset of stall buffet]
1903:07.9	**CAM**	[vibrating sound similar to aircraft stick shaker starts and continues to end of recording]
1903:08.0	**HOT-1**	what the hell is this?
1903:08.3	**CAM**	[sound of aural tone similar to altitude alert]
1903:09.4	**JSAP**	traffic traffic
1903:09.4	**CAM**	traffic traffic
1903:09.6	**HOT-1**	what the …
1903:09.9	**HOT-2**	oh …
1903:10.6	**HOT-1**	oh God … oh God.
1903:13.3	**APR**	USAir …
1903:15.0	**RDO-1**	four twenty seven emergency.
1903:17.4	**HOT-2**	#.
1903:18.1	**HOT-1**	pull
1903:18.5	**HOT-2**	oh #.

1903:19.1	**HOT-1**	pull
1903:19.7	**HOT-1**	(pull)
1903:20.8	**HOT-2**	God.
1903:21.1	**HOT-1**	[sound of screaming]
1903:22.5	**HOT-2**	no.
1903:22.8		**End of Recording**

RDO	=	Radio transmission from accident aircraft
CAM	=	Voice or sound source recorded through cockpit area microphone
HOT	=	Voice or sound source recorded through cockpit hot microphone
PA	=	Voice or sound source recorded through public address system
JSAP	=	Voice or sound source recorded through jump seat audio panel
-1	=	Voice identified as captain
-2	=	Voice identified as first officer
-4	=	Voice identified as male flight attendant
APR	=	Radio transmission from Pittsburgh approach controller
DL1083	=	Radio transmission from Delta flight 1083
285LM	=	Radio transmission from aircraft 285LM
*	=	Unintelligible word
#	=	Expletive
( )	=	Questionable insertion
[ ]	=	Editorial insertion
…	=	Pause

Source: U.S. National Transportation Safety Board

deployment of thrust reversers; asymmetric activation of the ailerons and spoilers; uncommanded flight control movements resulting from transient electronic signals; yaw damper malfunctions; and a rudder cable break or pull. The investigation eliminated each of these factors as a possible cause of the upset.

The report said that another factor that might have caused the upset — an uncommanded movement of the rudder — was identified very early in the investigation. Rudder-control anomalies were suspected of having been involved in the following accident and incident:

- On March 3, 1991, United Airlines Flight 585, a Boeing 737-291, was on a visual approach to Colorado Springs (Colorado, U.S.) Municipal Airport in moderate-to-severe turbulence and gusty-wind conditions when it yawed right, rolled right, pitched nose down and struck terrain. The 25 occupants were killed.

  The probable cause of the accident was not determined, but NTSB said that the two most likely events that could have resulted in the upset were a malfunction of the airplane's lateral control system or directional control system, or a severe atmospheric disturbance, such as a rotor.[3, 4]

- On June 9, 1996, Eastwind Airlines Flight 517, a Boeing 737-200, abruptly yawed right and then rolled right while descending through 4,000 feet on approach to Richmond, Virginia, U.S. The captain, who was hand-flying the airplane, said that he "stood pretty hard on the [left] rudder pedal," applied left aileron and advanced the right power lever. The airplane rolled back to a wings-level attitude, momentarily banked left, but then abruptly banked right again. The crew conducted the emergency checklist, which included disengaging the yaw damper. The upset event stopped, and the airplane flew normally throughout the remainder of the approach and landing. None of the 53 occupants was hurt, and the airplane was not damaged.

  The investigation revealed that about one month before the incident, the captain flew the same airplane back to the departure airport after feeling a series of "taps" on the rudder pedals just after takeoff. The main rudder PCU was replaced, and the airplane was returned to service. On June 1, 1996, and June 8, 1996, other pilots reported yaw/roll events in the airplane.

  "As a result of these reports, the yaw damper transfer valve and the yaw damper linear variable displacement transducer were removed and replaced on June 8," the report said. A postmaintenance test flight was satisfactory, and the airplane was returned to service. The incident occurred the next day, June 9.

  After the incident, the main rudder PCU and yaw-damper coupler were replaced, and new wiring was installed between the PCU and the yaw-damper coupler. The report said that no further rudder anomalies were reported.

The B-737-300 has a single rudder panel that normally is actuated by a single PCU; a standby actuator is available if either, or both, of the airplane's primary hydraulic systems fails. The report said that the B-737 is the only large transport category airplane with two wing-mounted engines that was designed with a single rudder panel and a single rudder actuator.

"All other large transport category airplanes with twin wing-mounted engines were designed with a split rudder panel, multiple hydraulic actuators or a mechanical/manual/trim tab rudder-actuation system," said the report.

The B-737 main rudder PCU is powered by the two primary hydraulic systems, each of which provides approximately 3,000 pounds (1,361 kilograms) of pressure to move the rudder. The PCU is mounted on the vertical-fin structure and has an actuator rod attached to the rudder.

"The [PCU] operates by converting either a mechanical input from the rudder pedals or an electrical signal from the yaw-damper system into motion of the rudder by means of mechanical linkages (summing levers, input cranks and shafts) and a servo valve that directs hydraulic fluid either to extend or retract the PCU actuator rod that moves the hinged rudder surface," said the report.

The servo valve comprises a primary slide that moves within a secondary slide that, in turn, moves within the servo-valve housing (see Figure 2). The slides are moved by summing levers activated by the rudder pedals or by the yaw-damper system. Each slide can move a total distance of about 0.09 inch (2.3 millimeters).

"The primary slide is normally displaced first, and the secondary slide is displaced only when the primary slide does not provide enough hydraulic flow to keep up with the input commanded by the pilots or the yaw damper (that is, when the movement of only the primary slide is not sufficient to move the rudder at the commanded rate)," said the report.

The slides are designed to provide an equal flow of hydraulic fluid. With no aerodynamic load on the rudder, the primary slide can provide a rudder-travel rate of approximately 33 degrees per second; the primary slide and secondary slide together can provide a rudder-travel rate of approximately 66 degrees per second.

The report said that flight tests and computer simulations showed that the heading-change rates recorded by the FDR during the upset of Flight 427 were consistent with the rudder being deflected at 1903 to its left aerodynamic blowdown limit.

"This movement of the airplane's rudder could only have been caused by a flight-crew action or a mechanical rudder-system anomaly," said the report. "The potential for such a mechanical rudder anomaly was demonstrated during postaccident tests in which the [PCU] secondary slide was intentionally jammed (pinned) to the servo valve housing and a rapid input was applied in a direction that would oppose the jam.

"These tests showed that the primary slide could overtravel, resulting in hydraulic fluid porting in such a way that the rudder moves to its aerodynamic blowdown position in the direction opposite to the rudder input (rudder reversal)."

When the accident airplane's PCU was tested with hydraulic fluid heated to a temperature 180 degrees F (82 degrees C) higher than the temperature of the servo valve housing, the secondary slide jammed against the servo valve housing, and a momentary rudder reversal occurred. Following the tests, there was no physical evidence that a jam had occurred, and the slides moved freely.

"The temperature differential to which the accident PCU servo valve was exposed [in these tests] was greater than that expected in normal operation," the report said. "Nonetheless, these thermal tests demonstrate that it is possible for the secondary slide … to jam to the valve housing and leave no evidence of physical marks.

"These tests also demonstrate that, with the secondary slide thus jammed, it is possible for the primary slide to overtravel and cause a rudder hardover in the direction opposite to that commanded without leaving any physical evidence."

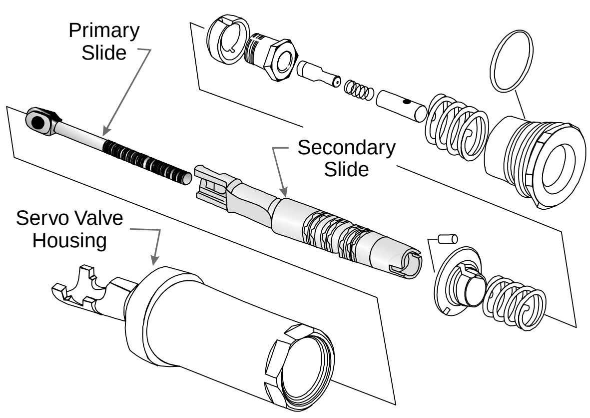
The report said that the USAir Flight 427 upset — and the upsets of United Flight 585 and Eastwind Flight 517 — were most likely caused by movement of the rudder surfaces to their blowndown limits in directions opposite to that commanded by the pilots.

"The rudder surfaces most likely moved as a result of jams of the secondary slides to the servo valve housings offset from their neutral position and overtravel of the primary slides," said the report.

The report said that evidence showed that the following scenario likely occurred during the final moments of Flight 427:

> The captain's "sheeez" and the first officer's "zuh" at 1902:57 were exclamations of surprise regarding the wake-turbulence encounter. The first officer then applied significant right control wheel input to correct the left roll caused by the turbulence. The airplane began rolling back toward level flight, and the first officer relaxed the right control wheel input.
>
> Between 1902:58 and 1903, a significant yawing motion caused the airplane's heading to move rapidly past the assigned 100 degrees to 94 degrees. The captain's "whoa" at 1902:59.3 likely was in response to the yawing motion. (The captain did not make any control inputs

Boeing 737-300 Main Rudder Power Control Unit Servo Valve



Source: U.S. National Transportation Safety Board

Figure 2

when the upset began; however, the captain might have made control inputs later.)

"It would have been reasonable for the first officer to respond to this yawing motion (and, possibly, to the captain's statement) by applying right rudder pedal pressure about 1903," the report said. "This right rudder input, intended to relieve the sideforce and return the airplane to its assigned heading, was instead followed by a rapid rudder deflection to the left (rudder reversal) that increased the left-yawing motion and accelerated the airplane's heading change to the left."

As the rudder moved left to its blowdown position, the right rudder pedal rose against the first officer's right foot and opposed his effort to depress the pedal. The first officer grunted loudly as a result of expending significant physical effort against the right rudder pedal. He also applied full right control wheel in response to the airplane's left rolling and yawing motion.

The first officer's loud grunting stopped at 1903:02.1, the same time the CVR recorded the sound of the autopilot disengaging. The control wheel briefly was returned to near neutral, and no more grunting or straining sounds were recorded until a few seconds before ground impact.

"This evidence is consistent with the first officer slightly relaxing his control wheel [inputs] and rudder pedal inputs — perhaps because he thought that he was contending with a malfunctioning autopilot, in which case autopilot disengagement would restore normal control," said the report.

The left bank continued to increase, however. The first officer — and, possibly, the captain — applied aft control column input to prevent the airplane from pitching nose-down. Airspeed began to decrease. The airplane pitched nose-down and began to descend. When the stick shaker activated at 1903:07.9, the airplane was descending through 5,700 feet in a 70-degree left bank and a 20-degree nose-down pitch attitude.

"[About 1903:11], the control column reached its full-aft position; the airplane's bank angle had gone beyond vertical (90 degrees), and its pitch attitude had exceeded 50 degrees below the horizon," said the report. The airplane struck terrain about 11 seconds later.

Flight tests and computer simulations showed that the crew might have regained control of the airplane during the early stages of the upset if they had *maintained* full right control wheel input and applied sufficient forward pressure on the control column to maintain airspeed above 187 knots — the *crossover airspeed*.[5]

"The flight tests revealed that … at airspeeds above 187 KCAS [knots calibrated airspeed], the roll induced by a full rudder deflection could be corrected by control wheel input; however, in the same configuration at airspeeds of 187 KCAS and below, the roll induced by a full rudder deflection could not be completely eliminated by full control wheel input in the opposite direction, and the airplane continued to roll into the direction of the rudder deflection."

The report said, "Flight simulations indicated that, with a rudder deflected to its aerodynamic blowdown limit and in the configuration and conditions of the USAir Flight 427 accident airplane, the roll could not be completely eliminated (and control of the airplane could not be regained) by using full control wheel inputs if the airspeed remained below 187 KCAS.

"The pilots who were involved in the flight [tests] and simulator tests indicated that successful recovery required immediate flight-crew recognition of the upset event and subsequent prompt control wheel inputs to the full authority of the airplane's roll control limits and pitch flight control inputs to maintain a speed above the crossover airspeed.

"To return the airplane to a wings-level attitude, the pilots had to avoid excessive maneuvering that would increase the vertical load factor, or angle-of-attack, and, thus, increase the crossover airspeed."

The report said that the crew of Flight 427 could not be expected to have assessed the flight-control problem and to have conducted the appropriate rudder-reversal recovery procedure.

"The pilots did not have foreknowledge of the problem, immediate awareness of its onset and prior training and experience with the crossover airspeed phenomenon," said the report.

At the time of the accident, the pilot-training programs used by USAir and four other major airlines surveyed by investigators did not include training in recovery from unusual attitudes or upsets. Another airline surveyed by investigators, United Airlines, recently had implemented flight-simulator training of B-757 pilots and B-767 pilots in unusual-attitude-recovery procedures.

According to FAA, as of January 1999, at least 13 U.S. air carriers, including US Airways, had implemented "special-events training." FAA, however, does not require such training and does not address flight-control malfunctions in guidance materials for unusual-attitudes-training programs.

The report said that training of many B-737 pilots in recovering from a jammed or restricted rudder condition is inadequate because flight simulators are not being used and the crossover-airspeed phenomenon is not being demonstrated.

Also, the report said that many B-737s are operated at *block maneuvering speeds*[6] that do not provide an adequate margin above the crossover speed.

"The Boeing-recommended block-maneuvering-speed schedule specifies 190 knots, which only slightly exceeds the 1 G crossover airspeed, as the minimum speed for a [B-]737 operating at a gross weight of 110,000 pounds [49,896 kilograms] in the flaps 1 configuration," the report said. "Only one-third of the 12 U.S. [B-]737 air carrier operators contacted … in July 1998 … actively promoted the practice of adding 10 knots to the [B-]737 block maneuvering speeds (for which Boeing has expressed neither support nor disapproval)."

FAA in 1996 issued an airworthiness directive (AD) requiring revision of the B-737 airplane flight manual (AFM) to include procedures for maintaining airplane control during an uncommanded yaw or roll, or with a jammed or restricted rudder. Another AD, issued in 1997, required installation within three years of a device to limit rudder authority in flight conditions that do not require full rudder authority.

"The hydraulic-pressure reducer that is being retrofitted on earlier series [B-]737 models and the hydraulic-pressure limiter being installed in the [new] models should provide flight crews with a greater margin of controllability and additional response time for executing the required [AFM] procedures," said the report.

Nevertheless, the report said that the AFM procedures establish the pilot's ability to center the rudder pedals as an indication of successful resolution of the rudder malfunction. This is not a valid indication that a rudder reversal has been resolved.

"Compliance [elastic deformation] in the rudder system could allow the rudder pedals to reach the neutral position while the rudder surface remains deflected to the blowdown limit," said the report.

From April 1980 through January 1998, FAA issued 10 ADs regarding the B-737 rudder system. (Two ADs were issued before the accident; eight were issued after the accident.) A 1997 AD required installation of a redesigned PCU servo valve.

"The redesigned main rudder PCU servo valve should eliminate the possibility of a rudder reversal from the specific circumstances of a secondary slide jam to the servo valve housing combined with overtravel of the primary slide," the report said. "When completed, the rudder design changes to the [B-]737 should preclude the rudder reversal failure mode that most likely occurred in the USAir Flight 427 and United Flight 585 accidents, and the Eastwind Flight 517 incident.

"However, even with these changes, the [B-]737 series airplanes … remain susceptible to rudder-system malfunctions that could be catastrophic."

On Feb. 23, 1999, a US Airways Metrojet 737 experienced a rudder hardover in flight. (Preliminary investigation indicated that the rudder, which incorporated the redesigned main rudder PCU servo valve, had traveled slowly to its blowdown limit.) The flight crew regained rudder control after activating the standby-rudder-actuating system, as prescribed by the airline's "jammed-or-restricted-rudder" checklist.

"This event could have resulted in an unrecoverable loss of control if it had occurred at a lower altitude or airspeed," said the report.

The original type certificate for the B-737 was issued in 1967. The B-737-300 was added to that type certificate in 1984. Thus, the airplane was not required to comply with a 1970 amendment of U.S. Federal Aviation Regulations (FARs) Part 25, the certification standards for transport category airplanes, that requires that an airplane be capable of continued safe flight after flight-control malfunctions, including "a runaway of a flight control to an adverse position and jam … if such runaway and subsequent jamming is not extremely improbable."[7]

The report said, "The [B-]737 has a history of rudder system-related anomalies, including numerous instances of jamming."

When the main rudder PCU jams, the crew must manually activate the standby PCU. Thus, the rudder-actuation system is redundant, but it is not reliably redundant, because the standby system does not activate automatically.

"If a jam were to occur close to the ground or result in an unusual attitude, the pilots could lose control of the airplane before they were able to diagnose the problem and engage the standby rudder," the report said.

The report said that the B-737 needs a reliably redundant rudder-actuation system, one in which the standby PCU activates automatically and immediately if the main PCU jams or moves the rudder without a pilot command or yaw damper command.

As a result of the investigation, NTSB made the following recommendations to FAA:

- "Require that all existing [B-737s] and future [B-737s] have a reliably redundant rudder-actuation system. (A-99-20);
- "Convene an engineering-test-and-evaluation board to conduct a failure analysis to identify potential failure modes, a component and subsystem test to isolate particular failure modes found during the failure analysis, and a full-scale integrated systems test of the [B-737] rudder-actuation-and-control system to identify potential latent failures and validate operation of the system without regard to minimum certification standards and requirements in [FARs] Part 25. Participants in the engineering-test-and-evaluation board should include [FAA], [NTSB] technical advisers, The Boeing Company, other appropriate manufacturers and experts from other government agencies, the aviation industry and academia. A test plan should be prepared that includes installation

of original [B-737 main rudder PCUs], redesigned [B-]737 main rudder [PCUs] and related equipment, and exercises all potential factors that could initiate anomalous behavior (such as thermal effects, fluid contamination, maintenance errors, mechanical failure, system compliance and structural flexure). The engineering board's work should be completed by March 31, 2000, and published by the FAA. (A-99-21);

- "Ensure that future transport category airplanes certificated by [FAA] provide a reliably redundant rudder-actuation system. (A-99-22);

- "Amend [FARs Part] 25.671(c)(3) to require that transport category airplanes be shown to be capable of continued safe flight and landing after jamming of a flight control at any deflection possible, up to and including its full deflection, unless such a jam is shown to be extremely improbable. (A-99-23);

- "Revise [AD] 96-26-07 so that procedures for addressing a jammed or restricted rudder do not rely on the pilots' ability to center the rudder pedals as an indication that the rudder malfunction has been successfully resolved, and require Boeing and U.S. operators of [B-]737s to amend their [AFMs] and operations manuals accordingly. (A-99-24);

- "Require all [FARs] Part 121 air carrier operators of the [B-]737 to provide their flight crews with initial and recurrent flight simulator training in the 'uncommanded yaw or roll' [procedures] and 'jammed or restricted rudder' procedures in Boeing's 737 Operations Manual. The training should demonstrate the inability to control the airplane at some speeds and configurations by using the roll controls (the crossover airspeed phenomenon), and include performance of both procedures in their entirety. (A-99-25);

- "Require Boeing to update its [B-]737 simulator package to reflect flight-test data on crossover airspeed and then require all operators of the [B-]737 to incorporate these changes in their simulators used for [B-]737 pilot training. (A-99-26);

- "Evaluate the [B-]737's block-maneuvering-speed schedule to ensure the adequacy of airspeed margins above crossover airspeed for each flap configuration, provide the results of the evaluation to air carrier operators of the [B-]737 and [to NTSB], and require Boeing to revise the block maneuvering speeds to ensure a safe airspeed margin above crossover airspeed. (A-99-27);

- "Require that all [B-]737 airplanes operated under [FARs] Parts 121 or 125 that currently have a flight-data acquisition unit be equipped, by July 31, 2000, with [an FDR] system that records, at a minimum, the parameters required by [Parts] 121.344 and 125.226, dated July 17, 1997, applicable to that airplane plus the following parameters: pitch trim; trailing-edge [flaps] and leading-edge flaps; thrust-reverser position (each engine); yaw damper command; yaw damper on/off discrete; standby rudder on/off discrete; and control wheel [forces], control column [forces] and rudder pedal forces (with yaw damper command; yaw damper on/off discrete; and control wheel [forces], control column [forces] and rudder pedal forces sampled at a minimum rate of twice per second). (A-99-28); [and,]

- "Require that all [B-]737 airplanes operating under [FARs] Parts 121 or 125 that are not equipped with a flight-data acquisition unit be equipped, at the earliest time practicable but no later than Aug. 1, 2001, with [an FDR] system that records, at a minimum, the parameters required by [Parts] 121.344 and 125.226, dated July 17, 1997, applicable to that airplane plus the following parameters: pitch trim; trailing-edge [flaps] and leading-edge flaps; thrust-reverser position (each engine); yaw damper command; yaw damper on/off discrete; standby rudder on/off discrete; and control wheel [forces], control column [forces] and rudder pedal forces (with yaw damper command; yaw damper on/off discrete; and control wheel [forces], control column [forces] and rudder pedal forces sampled at a minimum rate of twice per second). (A-99-29)."

On June 25, 1999, (three months after NTSB adopted the final accident report), FAA issued the following responses to the NTSB recommendations:

- "[Regarding A-99-20], [FAA] has established an engineering-test-and-evaluation board to conduct an in-depth fault analysis of the rudder system. This group will provide the FAA with valuable insights, information and data to determine an appropriate course of action. In the meantime, the FAA is working closely with The Boeing Company to explore various design options for existing and future [B-]737 airplanes;

- "[Regarding A-99-21], the FAA agrees with the intent of this safety recommendation and has convened an engineering-test-and-evaluation board to conduct a failure analysis of the rudder system. The engineering board consists of representatives from the FAA (including two national resource specialists), The Boeing Company, [NTSB, NASA], the [U.S.] Department of Defense, the Air Line Pilots Association [International] and the Air Transport Association of America. The engineering board will also include an engineer from the Ford Motor Co. and an engineer from Ilyushin Aviation Complex (a Russian aircraft-manufacturing company). The engineer from Ford is included on the engineering board to obtain an industry perspective that is different from the aviation industry's perspective.

"The group will identify potential failure modes, component and subsystem tests to isolate particular failure modes found during the failure analysis and a full-scale integrated system test of the [B-]737 rudder-actuation-and-control systems to identify potential latent failures and to validate operation of the system without regard to minimum certification standards and requirements in [FARs] Part 25. The engineering board will also focus on any malfunction that could affect lateral/directional control of the [B-]737 airplane.

"The engineering board will prepare a test plan to include installation of original and redesigned [B-]737 main rudder [PCUs] and related equipment, and exercise all potential factors that could initiate anomalous behavior (like thermal effects, fluid contamination, maintenance errors, mechanical failure, system compliance and structural flexure). The engineering board is tasked to complete its action and publish a report by March 31, 2000;

- "[Regarding A-99-22], the FAA has convened an engineering-test-and-evaluation board to conduct a failure analysis of the [B-]737 rudder system. It is expected that this group will provide the FAA with valuable insights, information and data for the [B-]737 [rudder] and other rudders of similar design to determine an appropriate course of action;

- "[Regarding A-99-23], currently, [Part] 25.671(c)(3) has two separate requirements concerning jams. The first is related to normally encountered positions for six specified phases of flight, and the second is related to runaways followed by jams. [Safety Recommendation A-99-23] asks that the FAA replace those two separate requirements with a single, all-encompassing requirement. The FAA does not agree with this approach.

"From a practical standpoint, continued safe flight and landing with full deflection of certain control surfaces is not possible in all regimes of flight. For example, it is possible (though unlikely) that a pilot could command full elevator deflection during high-speed flight. On many conventional aircraft, this would likely be a catastrophic event, as the airplane would exceed its structural limits. Such an event could not be shown to be extremely improbable. On the other hand, full deflection of certain surfaces might not prevent continued safe flight and landing (for example, a spoiler panel hardover). Adopting this safety recommendation would not allow differentiation between these two kinds of events as currently allowed in [Part] 25.671(c)(3).

"The Flight Controls Harmonization Working Group has been tasked with revising [Part] 25.671 … to take into account any safety recommendations, but specifically Safety Recommendation A-96-108 [in which NTSB said that Part 25.671 should be revised to account for the failure or jamming of any flight-control surface at its design-limited deflection, and that all transport category aircraft should be required to comply with the revised criteria]. The subject of normally encountered flight-control positions is currently being discussed. One of the early proposals would have permitted a time-based averaging approach to determine the normally encountered flight-control positions. That would have led to a small range of deflections since most of the flight is spent in cruise. That approach was rejected. The eventual product of the working group's discussion will be an advisory circular, which would define one means of establishing normally encountered flight-control positions for the various phases of flight. However, in general, the proposals of the working group do not include full-surface deflections in the range of normally encountered flight-control positions. In addition, the working group is also tasked with revising [Parts] 25.671(c)(1) and 25.671(c)(2) to address control-surface runaway, regardless of whether or not the runaway leads to a jam.

"Through the working group, the FAA has addressed this safety recommendation completely;

- "[Regarding A-99-24], the FAA started an initiative, with participation from The Boeing Company and [NTSB] staff, to determine the scope and appropriate revision to the procedures for addressing a jammed or restricted rudder. It is anticipated that this project will result in a formal evaluation of the current procedures using the [B-]737 engineering simulator. Based on the results of the evaluation, an appropriate revision to existing procedures and [AD] 96-26-07 will be made;

- "[Regarding A-99-25], the FAA is working with Boeing and [NTSB] staff to determine the scope and appropriate revision to the procedures for addressing a jammed or restricted rudder. It is anticipated that this project will result in a formal evaluation of the current procedures using the [B-]737 engineering simulator. The FAA will take action to address the issues of this safety recommendation upon completion of the evaluation in response to Safety Recommendation A-99-24;

- "[Regarding A-99-26], on April 30, 1999, The Boeing Company, based upon new flight-test results, updated the [B-]737-300 aerodynamic model, which more accurately represents roll [characteristics] and yaw characteristics of the [B-]737-300 aircraft. In addition, similar handling characteristics exhibited by other [B-]737 models will result in the development of revisions to other [B-]737 simulator models.

"As a result of new Boeing flight-test data, the FAA sent a letter to all U.S. operators of [B-]737-300 simulators on May 28, 1999, requiring that the [B-]737-300 aerodynamic revisions be incorporated in the [B-]737-300

Other Parties' Submissions to the Official Accident Investigation Report

Representatives of the U.S. Federal Aviation Administration (FAA), The Boeing Co., Parker Hannifin, USAir and the Air Line Pilots Association, International (ALPA) were parties to the investigation of the accident involving USAir Flight 427, a Boeing 737-300, near Aliquippa, Pennsylvania, U.S., on Sept. 8, 1994. The following information is from party submissions that were made in September 1997 and August 1998 to the U.S. National Transportation Safety Board (NTSB) and included in NTSB's final report on the accident.

U.S. Federal Aviation Administration

FAA said, "While the investigation has produced evidence [that supports] the scenarios where the rudder moved to a full-left position after an encounter with wake turbulence, the cause of the movement is still at issue. The FAA, upon review of the evidence, cannot conclude that a failure mode which resulted in an uncommanded rudder movement on Flight 427 has been identified.

"Any causal findings, to be legitimate, must have conclusive evidence to support findings of a [rudder] hard-over or [rudder] reversal. Such evidence has yet to be found. Consequently, a specific causal finding of this nature may not be appropriate."

FAA said that the B-737 rudder-system abnormalities discovered during the investigation were not shown to have occurred on USAir Flight 427.

"While the FAA acknowledges the fact that some failure modes of the main rudder power-control unit [PCU] servo valve have been discovered during this accident investigation, it has not been substantiated that any of these failures occurred on the accident aircraft," the FAA said. "The FAA also acknowledges that a secondary slide jam to the housing of the servo valve or interference with the rudder input link could provide both full rudder rate and full hinge movement. However, once again, there is no direct evidence that this occurred."

FAA said, "[Boeing] and the FAA have reacted to the discovered failure modes with modifications of the [B-737] rudder system, including some [modifications] recommended by [NTSB] that are designed to prevent future events of this type.

"However, the FAA does not believe sufficient evidence exists to establish a rudder-system failure as the cause of the accident."

The Boeing Co.

Boeing said that the flight crew was startled by the severity of the unexpected wake encounter, a full rudder deflection occurred, the pilots applied aft pressure on the control column, and the airplane entered a stall and remained stalled for approximately 14 seconds as it descended to the ground. Boeing said that the cause of the rudder deflection was "not clear" and that there is no proof that the rudder deflection was caused by a system malfunction.

"There is no evidence to support a conclusion that an uncommanded full rudder deflection occurred," Boeing said. "While there is [no] conclusive evidence of a crew-commanded, sustained left-rudder input, such a possibility is plausible and must be seriously considered, especially given the lack of evidence of an airplane-induced rudder deflection."

Boeing said that the following were the most significant findings of the accident investigation:

- "Commercial transport flight crews need to be specifically trained to handle large upsets. Transport-pilot training widely used in the 1994 time frame did not prepare flight crews for recovery from the highly unusual roll rates and roll-and-pitch attitudes encountered by the crew of Flight 427;
- "[B-]737 yaw damper reliability enhancements are needed to reduce potential airplane contribution to upsets;
- "[The following] highly unlikely potential failure modes can be eliminated:
  - "Potential [B-]737 rudder PCU failure modes; [and,]
  - "Potential [B-]737 rudder PCU input rod fastener failure mode;
- "We can reduce the impact of either airplane-related or crew-input-related rudder upsets by limiting [B-]737 rudder control authority;
- "Research is needed on better ways to detect and avoid wake vortices;
- "Existing [B-]737 flight-control anomaly procedures could be improved; [and,]
- "The flight data recorder information from this accident was inadequate to prove definitive events."

Boeing also recommended that "the appropriate organizations within the industry take steps to improve industry understanding of possible flight crew responses to wake vortex encounters and other upset events."

Parker Hannifin

Parker Hannifin, manufacturer of the Boeing-designed main PCU servo valve, said that examination of the accident airplane's PCU revealed no physical evidence of a jam or other anomaly.

"The conclusion reached by Boeing was that the accident PCU would not seize if subject to thermal shocks or temperature differential consistent with those which could be encountered in realistic flight conditions," said Parker Hannifin.

The company said that a significant indication of the PCU's reliability is a comparison of the unit's performance during acceptance tests when it was manufactured in 1987, maintenance tests in September 1992 and postaccident tests in September 1994 and August 1997.

"In each of these instances, the PCU consistently operated normally and within specifications," Parker Hannifin said. "In sum, after years of one of the most critical examinations in aviation history, there is no evidence that the main rudder PCU from Flight 427 malfunctioned or was other than fully operational."

USAir

USAir said, "Data demonstrate, and all parties seem to agree, that USAir Flight 427's rudder moved to a full-left position shortly after the aircraft encountered wake vortices generated by a preceding aircraft. It is also clear that the wake vortex encounter did not directly cause the accident."

The airline said, "[The pilots] did not apply full-left rudder during the wake vortex encounter, oppose it with opposite aileron and spoiler, and hold these cross-controlled positions while the aircraft spiraled to the ground."

USAir said that the probable cause of the accident was "an uncommanded, full rudder deflection or rudder reversal that placed the aircraft in a flight regime from which recovery was not possible using known recovery procedures."

The airline said that the rudder deflection or rudder reversal resulted from a mechanical malfunction of the rudder PCU.

The airline said that a contributing cause of the accident was "the manufacturer's failure to advise operators that there was a speed below which the aircraft's lateral control authority was insufficient to counteract a full rudder deflection."

Air Line Pilots Association, International

ALPA said, "Aircraft performance analysis revealed that the maneuver of USAir 427 is consistent with full nose-left rudder travel. … There is no evidence to support the hypothesis that the flight crew mishandled the flight control[s] following the upset event, or that this control mishandling led to the accident."

ALPA said, "The airplane experienced an uncommanded full rudder deflection. This deflection was a result of a main rudder [PCU] secondary valve jam which resulted in a primary valve overstroke. This … caused USAir Flight 427 to roll uncontrollably and dive into the ground.

"Once the full rudder hard-over occurred, the fight crew was unable to counter the resulting roll with aileron because the B-737 does not have sufficient lateral control authority to balance a full rudder input in certain areas of the flight envelope."

The pilots' union made the following recommendations:

- "Boeing and Parker [Hannifin] should work diligently to replace existing B-737 rudder PCUs with improved units as quick[ly] as possible without sacrificing quality;
- "The FAA should eliminate the current practice of derivative certification. Newly developed aircraft should be carefully evaluated against [U.S. Federal Aviation Regulations (FARs)] criteria in place at the time of aircraft development;
- "For aircraft which were certificated as 'derivative' models, the FAA should evaluate those aircraft against existing [FARs], and those aircraft, to the extent feasible, should be modified in order to be in compliance with the current [FARs];
- "The FAA should require all FAA-certified repair stations to meet all standards of the original equipment manufacturer;
- "In order to increase B-737 lateral control margin to an acceptable level, the FAA should mandate the development of additional operational techniques, such as increasing B-737 minimum maneuvering speed to Boeing-recommended 'block' speed plus 10 knots; [and,]
- "The industry should continue with the development and implementation of 'advanced-maneuver' [training] or 'selected-event' training, and the FAA should require the inclusion of this training in every airline's training program."♦

flight simulators by Oct. 1, 1999. … The FAA will also issue similar letters to applicable operators when Boeing completes the revisions to other [B-]737 models;

- "[Regarding A-99-27], on March 24, 1999, the FAA issued Flight Standards Information Bulletin for Air Transportation 99-02, *Maneuvering Speeds and Recovery Procedures for Boeing 737 Airplanes*. The bulletin recommended an across-the-board increase of 10 knots to the published [B-]737 maneuvering-speed schedule for flap settings of 'flaps up,' '[flaps] 1,' '[flaps] 5' and '[flaps] 10.' Subsequently, on April 5, 1999, The Boeing Company issued Flight Operations Flight Crew Information Bulletin 99-1, *Maneuvering Speeds for Boeing 737-100/200/300/400/500*. The bulletin revised all maneuvering speeds for 'flaps up,' '[flaps] 1,' '[flaps] 5' and '[flaps] 10' by at least 10 knots (and as much as 20 knots for certain conditions with flap settings of 'flaps 5') and added new information for airplanes operating at weights lower than 103,000 pounds [46,721 kilograms]. The FAA will revise the [B-]737 [AFM] to reflect the new maneuvering speeds by July 1999; [and,]

- "[Regarding A-99-28 and A-99-29], the FAA agrees with the intent of these recommendations and will develop a notice of proposed rule making (NPRM) proposing to address these safety recommendations. It is anticipated that the NPRM will be published by Sept. 30, 1999."♦

[Editorial note: This article, except where specifically noted, is based entirely on U.S. National Transportation Safety Board *Aircraft Accident Report: Uncontrolled Descent and Collision with Terrain, USAir Flight 427, Boeing 737-300, N513AU, Near Aliquippa, Pennsylvania, September 8, 1994*. NTSB/AAR-99/01, March 24, 1999. The 348-page report contains diagrams, illustrations and appendixes.]

Notes

1. The U.S. National Transportation Safety Board (NTSB) accident report defined blowdown limit as "the maximum amount of rudder travel available for an airplane at a given flight condition/configuration." The report said, "Rudder blowdown occurs when the aerodynamic forces acting on the rudder become equal to the hydraulic force available to move the rudder."

2. The B-737-300 autoflight system includes the autopilot, flight director and autothrottles. The autoflight system does not provide control commands to the airplane's rudder system.

3. For more information, see NTSB *Aircraft Accident Report: United Airlines Flight 585, Boeing 737-291, N999UA, Uncontrolled Collision with Terrain for Undetermined Reasons 4 Miles South of Colorado Springs Municipal Airport, Colorado Springs, Colorado, March 3, 1991*, NTSB/AAR-92/06, 1992. See also "U.S. Report: No Conclusive Evidence Found to Explain Boeing 737 Crash." *Accident Prevention* Volume 50 (May 1993): 1–6.

4. The NTSB accident report defined rotor as "(when referring to weather), an atmospheric disturbance produced by high winds, often in combination with mountainous terrain … . Rotation can occur around a horizontal or vertical axis."

5. The NTSB accident report defined crossover airspeed as "the speed below which the maximum roll control (full roll authority provided by control wheel input) can no longer counter the yaw/roll effects of a rudder deflected to its blowdown limit."

6. The NTSB accident report defined block maneuvering speeds as "the recommended maneuvering speeds for each flap configuration that provide, for all airplane weights, adequate airspeeds for maneuvering in at least a 40-degree bank without activation of the stick shaker."

7. The NTSB accident report said that the FAA defines an extremely improbable failure condition as "a condition that is so unlikely that it is not anticipated to occur during the entire operational life of all airplanes of one type and that has a probability on the order of 1 x 10^{-9} or less each flight hour based on a flight of mean duration for the airplane type."

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