

CHAPTER 1.0 FINDINGS AND RECOMMENDATIONS

On September 8, 1994, USAir (now US Airways) Flight 427, a Boeing Model 737-300 airplane, crashed while maneuvering to land at Pittsburgh International Airport, Pittsburgh, Pennsylvania. The National Transportation Safety Board (NTSB) released its determination of probable cause and safety recommendations on March 24, 1999.

The NTSB issued a total of 22 safety recommendations, addressed to the Federal Aviation Administration (FAA). One of these recommendations was that the FAA should form an engineering test and evaluation board to conduct a failure analysis of the rudder actuation and control system of the Boeing Model 737. The FAA responded by forming the **737 Flight Controls Engineering Test and Evaluation Board** ("the ETEB") in May 1999. (See **Chapter 2.0** of this report for more discussion of this team.)

The Boeing Model 737 fleet has flown over 100 million flight hours with an industry dispatch reliability rate of 99.4 percent. The Boeing Model 737 also has .91 hull losses per million departures vs. 1.81 hull losses per million departures for the industry as a whole. For airplanes produced since the mid-1980's, there have been .43 hull losses per million flights for the Model 737, compared to the industry average of 1.34. However, over the life of the Boeing Model 737 fleet, there have been a number of incidents and two accidents attributed to potential malfunctions of the rudder control system.

The ETEB was tasked with conducting an independent failure analysis of the Boeing 737 rudder actuation and control system. This failure analysis was completed without regard either to the minimum certification standards, or to the probability of occurrence of any of the identified failure modes. (See **Chapter 2.0** for more information about the technical approach that was used.)

The resulting findings and recommendations of the ETEB presented in this chapter apply to all models of the Boeing Model 737, except as noted. Additionally, the recommendations that refer to the airplane models are intended to apply to existing, as well as future, derivative Model 737 airplanes. Where applicable, the terms *Initial*, *Classic*, and *Next Generation* are used to specify different series of Model 737 airplanes:

- *Initial* refers to Models 737-100 and 737-200 series airplanes.
- *Classic* refers to Models 737-300, 737-400, and 737-500 series airplanes.
- *Next Generation* refers to Models 737-600, 737-700, 737-800, and 737-900 series airplanes.

The ETEB's findings and recommendations related to the Boeing 737 rudder control system are grouped into four major sections:

- 1.1 Summary of Key Findings and Recommendations**
- 1.2 Rudder Control System Failure Modes and Effects**
- 1.3 Failure Recovery Procedures and Training**
- 1.4 Incident Investigations, and In-Service Problem Reporting**

Section 1.1 contains a synopsis of all key findings and recommendations related to the rudder control system. **Sections 1.2, 1.3, and 1.4** contain additional findings and recommendations and more detail on all individual findings and the associated recommendations. Each finding references the supporting data contained in **Chapters 3.0, 4.0, 5.0, 6.0, and 7.0** of this report. Each recommendation references the associated findings.

Hazard Classifications: The following table defines the four classes of hazards (failure effects) referred to throughout this report.

Class	Description	Definition
I	CATASTROPHIC	Failure conditions that would prevent continued safe flight and landing.
II	HAZARDOUS	Failure conditions that reduce the capability of the airplane or the ability of the crew to cope with adverse operating conditions to the extent that there would be, for example: - a large reduction in safety margins or functional capabilities, - higher workload or physical distress such that the crew could not be relied upon to perform its tasks accurately or completely, or - adverse effects on occupants.
III	MAJOR	Failure conditions that reduce the capability of the airplane or the ability of the crew to cope with adverse operating conditions to the extent that there would be, for example: - a significant reduction in safety margins or functional capabilities, - a significant increase in crew workload or in conditions impairing crew efficiency, or - some discomfort to occupants.
IV	MINOR	Failure conditions that would not significantly reduce airplane safety, and that involve crew actions that are well within the crew's capabilities. "Minor failure conditions" may include, for example: - slight reduction in safety margins or functional capabilities, - a slight increase in crew workload, such as routine changes to the flight plan, or - some inconvenience to occupants.

1.1 SUMMARY OF KEY FINDINGS AND RECOMMENDATIONS

The following is a synopsis of the more detailed findings and recommendations presented in this report.

Key Findings

KEY FINDING 1:

The Model 737 rudder control system is susceptible to a number of:

- failures and jams that can cause uncommanded rudder motion;
- failures and jams that affect the operation of both the rudder main and standby power control units (PCU), thereby defeating the independence of the two systems; and
- latent failures.

These failure modes are single failures, single jams, or latent failures in combination with a detectable failure or jam.

KEY FINDING 2:

The rudder control systems of the Initial and Classic Model 737's without the modifications required by the applicable FAA airworthiness directives (AD) (referred to in this report as the "pre-AD" configurations) have:

- 15 single failures and jams, and 12 latent failure combinations, that have Class I (catastrophic) failure effects in the takeoff and landing regimes, and Class II (hazardous) failure effects in the rest of the flight envelope.
- 8 single failures and jams, and 11 latent failure combinations, that have Class II failure effects.

KEY FINDING 3:

The rudder control system of the Initial and Classic Model 737's with the modifications required by the applicable FAA AD's (referred to in this report as the "post-AD" configurations) have:

- 14 single failures and jams, and 12 latent failure combinations, that have Class I failure effects in the takeoff and landing regimes. These same failure modes have 4 Class II effects and 22 Class III (major) effects in the rest of the flight envelope.
- 8 single failures and jams, and 11 latent failure combinations, that have Class II failure effects.

KEY FINDING 4:

Most of the failure modes identified in **Key Findings 3 and 4**, above, apply to the rudder control system of the Next Generation Model 737's. There are:

- 14 single failures and jams, and 10 latent failure combinations, that have Class I failure effects in the takeoff and landing regimes. These same failure modes have 4 Class II effects and 20 Class III effects in the rest of the flight envelope.
- 8 single failures and jams, and 11 latent failure combinations, that have Class II failure effects.

KEY FINDING 5:

At typical cruise speed and altitude, there are no failure modes that result in Class I failure effects. The reduction in System A hydraulic pressure implemented in accordance with AD 97-14-03, which requires the installation of a pressure reducer, further reduces the effects of rudder hardover failures at altitude from Class II to Class III failure effects.

KEY FINDING 6:

The pressure reducer required by AD 97-14-03 does not eliminate Class I effects of failures and jams during takeoff and landings, but it does reduce the exposure time:

- For the Initial and Classic Model 737's, System A hydraulic pressure is reduced above 1,000 feet above ground level (AGL) on takeoff and above 700 feet AGL on landing. This reduces the upset from a rudder hardover failure above the respective altitudes.
- On the Next Generation Model 737's, the reduction in hydraulic pressure is based on airspeed rather than on height above the ground. This further reduces the exposure time for the Class I rudder hardover failures on takeoff and landing.

KEY FINDING 7:

The ETEB conducted 40 hours of pilot-in-the-loop rudder failure simulations with 10 pilot and co-pilot flight crews from four airlines.

- In general, the flight crews found the existing *Jammed or Restricted Rudder Emergency Procedure* difficult to use.
- The flight crews appeared to have received little training in the use of the *Jammed or Restricted Rudder Emergency Procedure* or the *Uncommanded Yaw or Roll Emergency Procedure*.

- The lack of a clear and unambiguous display of rudder position made it difficult for the crews to diagnose uncommanded rudder deflections and take prompt corrective actions.
- Uncommanded rudder hardover deflections during takeoff and landing resulted in Class I failure effects.

KEY FINDING 8:

There are several latent failures that, when combined with one additional single failure or jam, result in Class I or Class II failure effects. There are insufficient inspections for these latent failures.

KEY FINDING 9:

In-flight temperatures of the rudder main PCU input crank were measured and found to be below freezing with the yaw damper disengaged. When the yaw damper was turned on, the input crank temperature increased, but did not stabilize above freezing before the airplane began a descent into warmer ambient air. During humid conditions or with liquid water present, it is possible that ice could form. If enough ice accumulates, it can interfere with the PCU loop closure function and cause amplified oscillations of the rudder in response to yaw damper commands. This also will result in corresponding movements of the rudder pedals. A yaw damper hardover under such a condition will cause an uncommanded rudder deflection to the blowdown limit.

Key Recommendations

LONG-TERM ACTION:

Modify the Boeing Model 737 rudder control system to ensure that:

- no single failure or single jam of the rudder control system will cause uncommanded motion of the rudder surface that results in a Class I failure effect;
- no combination of failures or jams will result in a Class I failure effect, except for those combinations that are shown to be extremely improbable; and
- no probable single failure or jam will have an effect worse than Class IV.

In addition, The Boeing Company should consider providing a fail-safe rudder control system design that provides protection from latent failures that contribute to a Class I failure effect.

NEAR-TERM ACTIONS:

- **Revise and simplify the current *Jammed or Restricted Rudder Emergency Procedure*.**
- **Provide additional training to flight crews in the use of the *Jammed or Restricted Rudder Emergency Procedure* and the related *Uncommanded Yaw or Roll Emergency Procedure*.**
- **Display rudder position to the flight crew.**
- **Alert flight crews and maintenance personnel to signs of rudder malfunctions, such as uncommanded pedal motion.**

The ETEB considers that the four recommendations listed above are the most important near-term actions that can be taken to protect against the effects of Model 737 rudder malfunctions and should have first priority. The following three items also should be implemented as soon as practical:

- Review the Model 737 rudder system maintenance program and mandate changes, as required, to ensure the prevention or timely detection of latent failures that could lead to Class I or II failure effects. In particular, establish and mandate regular intervals for “on-airplane” testing of the standby rudder control system.
- Provide a means of independent shutoff of the rudder system hydraulic supply pressure without affecting the functionality of other control surfaces.
- Protect the function of the rudder control system from icing.

1.2 RUDDER CONTROL SYSTEM FAILURE MODES AND EFFECTS

The findings and recommendations contained in this section are based on the data presented in **Chapter 3.0 [System Failure Modes and Effects Analysis (FMEA)]** and supported by data in **Chapter 6.0 (Simulation)** and **Chapter 7.0 (Tests)**.

Findings Summary

FINDING	FINDING NUMBER
There are a number of failures and jams of the Model 737 rudder control system that have Class I or Class II failure effects.	F1.2-1
There are insufficient inspections for latent failures that contribute to Class I and Class II failure effects.	F1.2-2
Piloted simulation testing showed that hardover rudder failures are likely to be Class I at low altitude.	F1.2-3
The rudder pressure reducer that was required by AD 97-14-03 greatly mitigated the severity of upsets due to a hardover rudder failure. However, at low altitude, the airplane is still exposed to potential Class I failure effects from hardover rudder failures.	F1.2-4
Piloted simulation testing showed that pilots could control the airplane with a jammed standby power control unit input crank. However, high pedal forces were required to maintain control.	F1.2-5
Significant reduction in the rudder feel spring forces results in an amplification of the effects of other failures. Current maintenance procedures do not include a check for minimum allowable force in the rudder feel spring unit.	F1.2-6
Piloted simulation testing showed that certain failures in the rudder control system might not be recognized by the flight crew until rudder control is required, such as during a crosswind landing.	F1.2-7
Piloted simulation testing showed that complete loss of feel-and-centering was a Class II failure effect and not Class I failure effect, as indicated in earlier failure modes and effects analyses.	F1.2-8
During the piloted simulation testing, several flight crews were reluctant to land with manual reversion control of the ailerons and elevators -- even though this was the appropriate configuration following certain simulated rudder hardover failures.	F1.2-9
No anomalies of the rudder control system were observed during ground tests and flight tests with the Model 737-200 flight-test airplane.	F1.2-10
There are no required checks for inspecting and clearing maintenance areas of foreign objects.	F1.2-11

Ice accumulation on the main PCU input crank can interfere with the PCU loop closure function and cause abnormal rudder response to yaw damper commands. Any such rudder response will also result in a corresponding uncommanded movement of the rudder pedal. A yaw damper hardover under this condition will cause an uncommanded rudder movement to the blowdown limit.	F1.2-12
For the Boeing Model 737, uncommanded pedal movement or "kicks" are an indication of a serious rudder system malfunction. It can be caused by ice build up on the main PCU input crank, a foreign object lodged in the crank gap, a jam in the standby PCU, or any other jam in the feed back loop of the control system.	F1.2-13
The standby rudder PCU on the Initial and Classic Model 737's could not be jammed by ice accumulation.	F1.2-14
The current rudder troubleshooting procedures are not comprehensive in identifying all possible sources of rudder pedal kicks. The current troubleshooting procedures only point to the standby PCU as a source of rudder pedal kicks. Other jams or binding may also cause rudder pedal kicks.	F1.2-15
If the secondary slide in a pre-AD servo valve is jammed, a hardover reversal can be induced by either pedal release or opposing pedal application.	F1.2-16
With a pre-AD dual concentric servo valve, increasing the centering fork and walking beam spring stroke by approximately 0.09 inch or more prevents rudder reversals due to a secondary slide jam and primary slide overstroke.	F1.2-17
Key parameters affecting the effect of a jam in the standby PCU input link are main-to-standby PCU loop gain and stiffness, and feel-and-centering spring stiffness. Increasing the loop gain slightly above unity can lead to instabilities and rudder hardover. The loop gain decreases with increased air load, which provides a stabilizing effect.	F1.2-18
Boeing structural analysis and service history indicate that Boeing Model 737 airplanes may lose flight and engine controls as a result of the collapse or deformation of the floor in the flight deck (Section 41) or main cabin (Section 43 and 46), e.g., a sudden pressure loss in the compartments under the floor.	F1.2-19
The rudder control systems of Initial and Classic Model 737 airplanes are vulnerable to a bird strike that penetrates the forward pressure bulkhead or, to a lesser extent, the vertical fin.	F1.2-20
The effect of a dynamic pressurization of the empennage as a result of a sudden rapid depressurization of the airplane through an opening in the aft pressure bulkhead is unknown and an analysis of this effect has not been conducted for Boeing Model 737 airplanes.	F1.2-21
The rudder is required to counteract the asymmetrical thrust associated with an engine failure at low speed and high power settings. In all Model 737 airplanes, an uncontained engine failure during takeoff has the potential of causing a Class I failure effect, since there is only a single cable system for control of the rudder and the rudder cables pass through the engine rotor burst zone. The Initial Model 737 airplanes are also susceptible to reduced rudder effectiveness due to the possible loss of hydraulic system fluid caused by an uncontained engine failure which also severs a hydraulic line and reduces the available rudder hinge moment.	F1.2-22

Recommendations Summary

RECOMMENDATION	REC. NUMBER
Modify the Boeing 737 rudder control system to ensure that: - no single failure or single jam of the rudder control system will cause uncommanded motion of the rudder surface that results in a Class I failure effect, - no combination of failures or jams will result in a Class I failure effect, except for those combinations that are shown to be extremely improbable, and - no probable single failure or jam will have an effect worse than Class IV.	R1.2-1
Ensure that latent failures are detected in a timely manner through required maintenance and inspections.	R1.2-2
Add periodic checks of rudder pedal feel force to the maintenance requirements for the Boeing Model 737.	R1.2-3
Provide a means of independent shutoff of the rudder system hydraulic supply pressure without affecting the functionality of other control surfaces.	R1.2-4
Establish a requirement to ensure that maintenance area checks are performed to ensure that foreign object debris is cleared before the area is closed.	R1.2-5
Conduct a fleet survey to determine the extent of the ice accumulation problem on the Boeing Model 737 rudder main PCU and possibly other systems with a similar susceptibility to ice.	R1.2-6
Investigate further the susceptibility of the 737 NG Standby PCU to ice formation and its effect on the rudder system functionality.	R1.2-7
Modify the main PCU crank/crank stop design so that ice formation will not affect the function of the rudder system.	R1.2-8
Amend the Maintenance Manual 27-21-0 troubleshooting procedures to direct mechanics to all possible causes of rudder pedal kicks.	R1.2-9
Review the service history of the Boeing Model 737 airplanes with respect to possible loss of flight and engine controls due to deformation of the floor caused by sudden rapid decompression. Depending on the results of the review, the Boeing Model 737 airplanes should be modified as necessary to meet the requirements of § 25.365(e)(2) of the Federal Aviation Regulations (at amendment 25-54, effective October 14, 1980).	R1.2-10
Review the service history of the Boeing Model 737 airplanes with respect to bird strike damage. Depending on the results of the review, the forward pressure bulkhead and the vertical fin of the Initial and Classic Model 737 airplanes should be strengthened to resist penetration by a 4-pound bird, in a manner similar to the Next Generation Model 737 airplanes.	R1.2-11
Conduct a dynamic analysis of the effects of sudden rapid depressurization of the fuselage through the aft pressure bulkhead that pressurizes the empennage.	R1.2-12

The FAA should accurately determine the uncontained failure rate of the JT8D-XX engine series installed on the Initial Model 737 airplanes. The FAA should determine if the probability of an uncontained failure of the JT8D-XX is an unsafe condition and, if so, take appropriate action.	R1.2-13
The FAA and Boeing should determine the effects of a reduced rudder hinge moment capability on the controllability of the Initial Model 737 airplanes during takeoff with an engine failure. If this failure combination is found to result in an unsafe condition, the FAA should take appropriate action.	R1.2-14
Boeing and the FAA to actively pursue identifying foreign operators that have not complied with FAA Airworthiness Directive 97-14-04, which requires replacement of the rudder main PCU dual concentric servo valve and emphasize the importance of the modification.	R1.2-15