AIR LINE PILOTS ASSOCIATION, INTERNATIONAL

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August 7, 1998

The Honorable James Hall
Chairman
National Transportation Safety Board
490 L'Enfant Plaza East, S. W.
Washington, D.C. 20594

Dear Chairman Hall:

In September 1997 ALPA forwarded to the NTSB its submission regarding the accident involving USAir Flight 427. Today ALPA feels even more strongly that the points raised in that submission are valid and correct. However, during this past year there has been additional investigative work, resulting in additional evidence on which ALPA would like to offer comment. This addendum focuses on this new evidence and **is not intended to replace the findings from our 1997 submission, but rather to further explain and refine our positions through use of this new evidence.**

Thank you for the opportunity to comment.

Sincerely,

Captain Herb LeGrow
ALPA Coordinator

Cc: Robert Francis, Vice Chairman
John Hammerschmidt, Member
John Goglia, Member
George Black, Member
Bernard Loeb, Director-Aviation Safety
Thomas Haueter, Chief-Major Investigations Division

Aircraft Performance

In ALPA's September 30, 1997 submission we detailed our thoughts regarding the limitations in any results obtained from the kinematic study conducted during this investigation. We wanted to take this opportunity to reiterate or re-enforce those thoughts. The results of any kinematic study are a function of:

- Flight Data Recorder data accuracy and sampling rate,
- Simulator model equations of motion and the accuracy in modeling the effects of wind or other atmospheric disturbances such as wake vortices,
- Aerodynamic and fight control system data used in the simulator model, and
- Assumptions regarding aircraft weight, center of gravity, effect of wind or atmospheric disturbances on the aircraft.

Changing any of the above can alter the results of the kinematic study. Overall ALPA believes that the kinematic model was a useful tool to use during the course of this investigation. However, the results of this model can change depending on the variables listed above. With the known limitations of the kinematic study, the Board must consider the results of the kinematic study in context with the results obtained from the other investigative groups. The other, key, groups during the course of this investigation include Aircraft Systems and Human Performance.

Recently the NTSB has developed their own B737 simulation enabling them to also conduct a kinematic analysis. By using this simulation NTSB staff experts were able to match the flight recorder information from the Eastwinds B737 upset incident by simulating a secondary valve jam of the main rudder PCU. Boeing, using their simulation model, was also able to match the Eastwinds DFDR but assumed a pilot rudder input in conjunction with a yaw damper malfunction. Both scenarios match the same recorded DFDR data, demonstrating that it is possible to match the maneuver with different scenarios by varying the assumptions and interpretations of the source data. However ALPA believes that the Board is more accurate in their scenario since the rate of the rudder input required to match the maneuver is the same rate which would result from a PCU secondary valve jam.

NTSB staff, using their simulation, has also been able to match both the USAir 427 and UAL 585 accident upsets by assuming a PCU secondary valve jam. In all three cases the rudder input rate needed to match flight recorder data is consistent with the rudder rate which would result from a secondary valve jam. It is extremely unlikely that three different pilots in three different B737s, on three different days would use the same rudder rate. Yet, if the secondary valve were jammed in each case, it would result in the same rudder input rate.

As mentioned, the kinematic study is just one investigative tool. The results of the kinematic study must be reviewed in context with the results of the other investigative groups. A secondary valve jam of the PCU matches the DFDR data for each of the events and is consistent with possible failure modes identified by the Aircraft Systems Group.

Human Performance

ALPA recognizes that an analysis of the crew's speech and breathing patterns is only circumstantial evidence, however, we feel that it is some of the most direct evidence of the crew's actions. In our previous submission, we examined and offered explanations for the crew's breathing patterns and speech utterances such as rapid inhalations and grunting. In that submission we concluded, based on the work of experts who were consulted by the Safety Board, that the first officer was attempting to operate the flight controls throughout the upset period, and that the captain did not attempt to take over controls until the aircraft was clearly unrecoverable. We likewise noted that analysis performed by expert consultants to the NTSB suggested that neither crewmember panicked or "froze- up" during the initial stages of the upset. That submission also referred to "grunting sounds" and "rapid inhalations" that were indicative of physical straining, as referenced in NTSB's "Speech Examination Factual Report," dated May 5, 1997.

On June 16, 1998, the NTSB issued "Speech Examination Factual Report Addendum." That addendum stated, "These observations of pilot straining are of critical interest to the human performance investigation, since they occurred during a brief time period during which the airplane went from controlled flight into a loss of control situation. Therefore Safety Board staff attempted to measure all sounds by the first officer related to physical straining on the possibility that this information would be meaningful to understanding the actions of the first officer during this period." The Safety Board identified and documented six distinct human sounds between times 1902:57.6 and 1902:57.8 (134.6 - 142.1).[1] These sounds, as documented by the NTSB Speech Examination Group, were as follows:

- the statement "zuh" from 1902:57.6 to 1902:57.8 [134.6-134.8]
- a sound like a rapid inhale from 1902:59.7-1902:59.9 [136.7-136.9]
- a sound like soft grunting from 1903:00.3-1903:00.5 [137.3-137.5]
- a sound like loud grunting from 1903:01.5-1903:01:6 [138.5-138.6]
- a sound like a loud exhale from 1903:01.8-1903:02:1 [138.8-139. 1]
- the statement "oh #" from 1903:04.6 to 1903:05:1 [141.6-142.1]

To better understand the significance of these speech sounds, ALPA referred to the "NTSB Speech Examination Factual Report," dated May 5, 1997. In this report the NTSB cites the work of two experts that the NTSB consulted for this accident, Dr. Alfred Belan and Dr. Scott Meyer. Below are direct quote excerpts from the reports of these experts:

Dr. Meyer stated:

> "The two grunting sounds of the F/O heard after the onset of the emergency are indicative of muscular exertion or physical straining." [underline added for emphasis]

[1] When times are expressed in this report, the first numbers are eastern daylight time, while the second number which are listed in either brackets or in parenthesis, are the equivalent values expresses as elapsed FDR time.

"Generally, during increased muscular exertion, it is common for the individual performing the movement to apply a considerable exhalatory force against a closed or partially closed glottis in the throat. When the breath is finally exhaled, it is forceful and quick and usually accompanied by a grunting sound. The forceful movements of weight lifting and other short duration, high intensity physical activities are routinely accompanied by grunting." [underline added for emphasis]

"The grunts suggest that the F/O was straining possibly in an attempt to manipulate the controls of the aircraft to override the autopilot." [underline added for emphasis]

According to Dr. Belan:

"A person making a great physical effort develops a musculoskeletal "fixation" (of the chest), which leads to deterioration of the normal expansion and ventilation of the lungs (inhaling and exhaling). These changes are manifested during speech. Sounds such as grunting and strain appear in speech as the person tries to minimize the outflow of air. Inhaling and exhaling become forced and rapid." [underline added for emphasis]

"The first officer, from the moment 1902:59.5 most likely was actively involved in the control of the airplane. Beginning at this time, and continuing for several seconds, speech disruptions could be observed that included grunting and forced exhalations (1902:59.5, 1903:01.1, and 1903:02.0)... These are signs of high physical loads. Normal use of the cockpit controls should not produce the types of sounds shown in this period. These sounds indicate that the first officer was struggling unusually hard, for example if he was pushing a control against its stops or if he was experiencing an unusual resistance in the use of a control." [underline added for emphasis]

The words that ALPA underlined above for emphasis are: muscular exertion, physical straining, increased muscular exertion, high intensity physical activities, straining, great physical effort, strain, high physical loads, and struggling unusually hard. By these descriptive adjectives, it is clear that each of these experts believed that the first officer was straining and under high physical loads during this time period.

ALPA evaluated a comprehensive list of events that could have caused the first officer to strain and exert high physical loads on the aircraft. We narrowed the list to four hypotheses.

The evaluated hypotheses were that the first officer was:

1) struggling with the flight controls because each pilot was "on the controls" in an attempt to regain aircraft control;
2) struggling to push or pull the control column forward or aft;
3) struggling to turn the aircraft with roll control (aileron) by turning the control wheel left or right;
4) struggling to depress a rudder pedal.

Hypothesis 1

With respect to Hypothesis 1, we note the work of Drs. Belan and Meyer. Dr. Belan stated that, "... Sounds such as grunting and strain appear in speech as the person tries to minimize the outflow of air. Inhaling and exhaling become forced and rapid. None of these effects appear in the captain's speech during this period. Based on all the above evidence, it could be concluded that the captain did not apply high physical loads to the controls. His actions were limited to the commands and attempt to evaluate the situation." Dr. Belan concluded from his analysis, "From the beginning of the accident sequence until the time 1903:17.4 the captain did not apply high physical loads to the controls and, most likely did not participate in the control. The first officer applied physical loads and controlled the airplane."

Dr. Meyer stated, "It is difficult to determine with certainly from the tape whether the PIC used increased muscular force on the controls during the emergency period. There was no audible grunting or straining indicative of muscular exertion heard. There was no indication of muscular strain during any of the verbal communications from the PIC heard on the tape. His initial comments were calm and controlled. His nonverbal breathing was unobstructed. That is not to say that the PIC was not on the controls, but only that he did not appear to be exerting increased muscular force during that time."

Although they both weighed 210 pounds, the first officer was taller and younger that the captain. The captain had undergone back surgery approximately six months prior to the accident. It is highly unlikely that the captain could have been "on the controls" without straining, when the FO would have been straining to overpower him. If both pilots were on the controls, one would expect to have found that both pilots were straining, and not just the first officer.

Based on all of this information, ALPA rejected the hypothesis that the first officer was straining because he was struggling with the flight controls because each pilot was "on the controls" in an attempt to regain aircraft control. (Hypothesis 1)

Hypothesis 2

We evaluated Hypothesis 2, which stated that the first officer was straining due to his struggling to push or pull the control column forward or aft. This hypothesis was rejected because control column was recorded on the FDR and was shown to be in approximately the "neutral" position during this portion of the upset.

Hypothesis 3

This hypothesis considered that the first officer was straining as he struggled to turn the aircraft with roll control (aileron) by turning the control wheel left or right. To evaluate this, it is important to look at the sequential order of events.

At 1902:57.6 (134.6), the first officer uttered "zuh." As explained by Dr. Meyer's report, "The emergency period starts with the F/O having just remarked that he had located the aircraft traffic. Immediately following his statement and coincidental with the initial, unusual movement of the aircraft was the remark "zuh." This appeared to be an attempt to continue speaking that was abruptly halted with the abnormal departure (pitch, roll, or yaw) of the aircraft. He may have been responding to the situation by seizing the controls to correct the movement and reflexively stopped speaking to concentrate on his duties."

ALPA also believes that at this time the first officer immediately grabbed the control wheel and reflexively began turning it rapidly to the right. The NTSB's independent kinematic analysis and the one largely constructed by Boeing both indicate that a full control wheel input was introduced at this time. In addition to Dr. Meyer's above comments, there are two additional facts that lead ALPA to conclude that the first officer made these inputs:

- the FDR shows small, but rapid, forward and aft movements on the control column, which is characteristic of human input rather than autopilot input.
- the rate of input on the control wheel was aggressive and exceeded the autopilot parameters; to exceed the autopilot parameters would have required approximately 50 pounds of force.

It is very important to note that despite his rapid control wheel movements, which required force to override the autopilot rate, there is no evidence that the first officer grunted or strained at this point. This demonstrates that the first officer could (and did) manipulate the control wheel without any outward signs of straining.

When the straining did occur, it was some 2.5 seconds later. Because the first officer had already demonstrated that he could manipulate the control wheel without straining, ALPA concluded that the CVR sounds that were indicative of straining beginning at 1903:00.3-1903:00.5 (137.3-137.5) were most likely <u>not</u> due to his additional attempts to turn the aircraft with roll control (aileron).

There was another factor that played into ALPA's conclusion that the first officer's grunting was not in response to the fighting against the autopilot. According to Dr. Meyer's analysis, "After the onset of the emergency, two rapid grunting exhalations were heard. The first grunting sound was soft and indicated some submaximal muscular exertion. The second grunting sound was louder and more forceful representative of the use of increased, but probably submaximal, muscular force. The grunts suggest that the F/O was straining possibly in an attempt to manipulate the controls of the aircraft to override the autopilot."

Although Dr. Meyer suggests that grunting may be in response to attempting to override the autopilot, ALPA does not believe that a constant input to override the autopilot would result in a "louder and more forceful ... muscular force." In fact, when overriding an autopilot one would expect a steady or even a declining force instead of an increasing force.

Additionally, the kinematic analysis shows that during the time of the first officer's grunting sounds ("soft grunting" 1903:00.3-1903:00.5 [137.3-137.5] and "loud grunting" 1903:01.5-1903:01:6 [138.5-138.6]), the wheel position was not a continuous "ramping-up" of movements. Quite simply, when overlaying these grunting sounds with the derived control positions from the kinematic analysis, there is no reason why the first officer would have been straining due to manipulating the control wheel. There is nothing in the kinematic analysis to support why the first officer would have straining with the control wheel at this point.

For these reasons, ALPA rejected the hypothesis that the straining observed on the CVR was the result of his attempts to fight against the autopilot by attempting to turn the control wheel left or right.

Hypothesis 4

ALPA looked at the possibility that struggling documented on the CVR could have been in response to the first officer depressing a rudder pedal. This straining occurred within a few milliseconds of the kinematic analysis indicating initial left rudder input. The question raised by ALPA is why would a pilot who is in excellent health strain to depress the pedal of a normally functioning rudder? If the pilot were depressing on the left ruder pedal, then why would this require such a physical load such that it caused him to strain? There are a few situations that require pilots to input large rudder inputs, yet pilots routinely do them without straining. Crosswind takeoffs and landings are two such examples. Another is that during training (every 6 months in the simulator at USAir) pilots are required to perform at least one engine failure at takeoff. Although this maneuver requires a heavy rudder input, the required rudder pedal forces are never high enough to cause pilots to experience muscular exertion, physical straining, increased muscular exertion, high intensity physical activities, straining, great physical effort, strain, high physical loads, and struggling, which were the exact words that the experts used to describe the first officer's utterances on the CVR

In these examples, there is no need for straining because the rudder is powered by hydraulics, i.e., the pilot makes a rudder pedal input and the rudder is then moved by a rudder power control unit actuator. Dr. Meyer stated that, "[T]he physical act of manipulating the control surfaces of modern aircraft under normal conditions does not usually require excessive muscular force... Nevertheless, during emergency situations, increased muscular force may be needed to manipulate the controls of an aircraft. Generally, during increased muscular exertion, it is common for the individual performing the movement to apply a considerable exhalatory force against a closed or partially closed glottis in the throat, when the breath is finally exhaled, it is forceful and quick and usually accompanied by a grunting sound."

To summarize this point, when a rudder is properly working the pilots will not have reason to struggle with the rudder. However, as documented, pilots attempting to interact with jammed or blocked rudder can require extreme forces. For example, on June 9, 1996, Eastwind Airlines flight 517, a Boeing 737-200, N221US, experienced a roll/yaw upset while on approach to land at Richmond, VA. The crew was able to counteract the failure and safely land the aircraft. While the NTSB's investigation of this event is ongoing (DCA-96-IA-061), it is believed that the event was precipitated by a yaw damper hardover. Following the event the Safety Board interviewed the crew. According to the "Human Performance Group Chairman's Factual Report," dated July 29, 1996, the captain stated that he "pushed quite hard" on the rudder pedal in an attempt to regain control of the aircraft. The first officer stated that he observed the captain "fighting to regain control" by "standing on the left rudder" pedal.

In June 1997, Boeing Commercial Airplane Group conducted a ground demonstration to evaluate rudder pedal movement during simulated rudder Power Control Unit (PCU) secondary servo valve slide jams at different positions. Malcolm Brenner, NTSB Human Performance Group Chairman for this accident, participated in the Boeing-conducted tests. According to his June 12, 1997 memo, Dr. Brenner stated that he occupied the right cockpit seat during these tests while wearing his seat belt.

Dr. Brenner found that when the slide jams were introduced, pressing on the opposite rudder pedal did not resolve the jam. He stated that the movement against his foot pressure was "unrelenting," meaning that no matter how hard he pushed on the pedal, the harder it seemed that the pedal was being forced against his foot. In one case (the 25% off neutral simulated jam), the only way to neutralize the rudder and return it to its normal state of usage was to release all rudder pedal pressure. In another simulated jam (the 50% off neutral jam), Dr. Brenner found that releasing rudder pedal pressure had no effect on stopping the uncommanded rudder movement.

As stated in ALPA's 1997 submission to the Safety Board, ALPA believes that a secondary slide jam occurred during the wake encounter, resulting in an uncommanded rudder movement to the left. As the roll rate began to intensify to the left, the first officer correctly applied right rudder to counter the roll. However, using Dr. Brenner's remarks from above, ALPA concludes that the more pressure that the first officer applied to the right rudder pedal, the more likely it became that the rudder reversal would not clear. The more the aircraft turned to the left, the stronger the first officer's tendency would have been to apply increased right rudder pedal pressure; the harder he pushed on the right rudder pedal, the more certain it became that the jam would not clear. Under these circumstances the strength that the first officer likely used while attempting to press on the right rudder pedal would have required muscular exertion, physical straining, increased muscular exertion, high intensity physical activities, straining, great physical effort, strain, high physical loads, and struggling. These, of course, are the exact words that the experts used to describe the first officer's speech utterances.

After reviewing the above evidence, ALPA accepts the hypothesis that straining heard on the CVR was the result of the first officer attempting to depress a rudder pedal. As supported in the above discussion, we further conclude that the rudder pedal that he attempted to operate was the right rudder pedal, which could not move due to an internal malfunction of the aircraft's rudder system.

Conclusion

Based on the above analysis, ALPA believes more strongly that ever that the cause of the accident was a rudder anomaly.

U·S AIRWAYS

SUPPLEMENTAL PARTY SUBMISSION OF

US AIRWAYS, INC.

TO THE

NATIONAL TRANSPORTATION SAFETY BOARD

USAIR FLIGHT 427

SEPTEMBER 8, 1994

ALIQUIPPA, PENNSYLVANIA

DCA-94-MA-076

SUBMITTED AUGUST 12, 1998

2345 Crystal Drive Arlington, VA 22227

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EXECUTIVE SUMMARY

The Speech Examination Factual Report Addendum, dated June 16, 1998, is composed entirely of speculation, without any factual basis whatsoever. Moreover, USAir believes the Rudder Jam Simulation Study, dated January 27, 1998, authorized by Dennis Crider of the Board, indicates that a mechanical malfunction caused a rudder reversal or uncommanded deflection onboard USAir Flight 427 on September 8, 1994.

The Boeing Submission to the Board seeks to establish that the cause of this accident is attributable to the crew. It is, however, inaccurate and misleading in several respects.

- the anecdotal reports of flight crews being "startled" or "surprised" by a wake turbulence encounter, somehow suggesting that the Flight 427 crew forgot the basics of flying, is without any logic or support.
- the suggestion that the crew of Flight 427 "overestimated" the angle of roll caused by the wake turbulence encounter and reacted improperly has no basis in fact or logic.
- the incidents cited by Boeing dealing with misapplication of rudder are either taken out of context or bear no relationship to the facts.
- the suggestion that both pilots were on the controls and trying to simultaneously manipulate the controls is without any basis in fact.

The probable cause of the crash of USAir Flight 427 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 techniques. A contributing cause 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.

I. INTRODUCTION

Party submissions related to this accident investigation were provided to the NTSB on September 30, 1997. Ten months having passed since those submissions, the NTSB has afforded the parties the opportunity to supplement their submissions.

Since US Airways' initial submission to the Board, there have been several significant developments in the investigation. The Systems Group completed and published the results of its Factual Report Addendum (Rudder PCU Testing), which tested the USAir Flight 427 rudder PCU ram output force, position, and velocity under various secondary slide jam scenarios. The Performance Group, using the Systems Group's data, found consistency between USAir Flight 427's FDR data and the flight path that would have resulted from a rudder PCU servo valve secondary slide jam at the 71% or 50% position. These results were published in the Group's Rudder Jam Simulation Study.

The Human Performance Group, which analyzed the voices of the pilots during the accident, published a Speech Examination Factual Report Addendum on June 16, 1998.

Finally, US Airways has had the opportunity to read and evaluate the other parties' submissions to the NTSB.

In this Supplemental Submission, US Airways will comment on the Systems Group's and the Aircraft Performance Group's efforts, the Human Performance Group's continuing examination of speech patterns, and Boeing's Submission to the Board.

II. POST-SUBMISSION INVESTIGATION ACTIVITIES

A. Rudder Jam Simulation Study

The Rudder Jam Simulation Study, authored by Dennis Crider and dated January 27, 1998, is a significant step forward in the search for the cause of the crash of USAir Flight 427.

Mr. Crider's study relied on the Systems Group Chairman's Factual Report Addendum, Rudder PCU Testing, dated October 10, 1997 ("Systems Group Report"). The Systems Group Report presented the results of testing designed to determine the USAir Flight 427 Rudder Power Control Unit ("PCU") ram output force, position, and velocity with the PCU servo valve secondary slide jammed at neutral and various other positions between neutral and full effective secondary stroke.

Mr. Crider's study used rudder rates and available hinge moments from the Systems Group Report in simulations designed to determine whether a secondary slide jam was consistent with Flight Data Recorder (FDR) data from USAir Flight 427. Rudder time histories developed for the 71% and 50% secondary slide displacement jams were found to be consistent with Flight 427 FDR data. It is our understanding that the simulations may be refined by using more finely-tuned data on rudder rates with a partially-displaced and jammed secondary slide. Nevertheless, we believe the results obtained so far by Mr. Crider's study are important and indicate a mechanical malfunction of the USAir Flight 427 rudder PCU resulted in a rudder reversal or uncommanded deflection that caused USAir Flight 427 to depart controlled flight and crash.

B. Speech Examination Factual Report Addendum

The Speech Examination Factual Report Addendum, dated June 16, 1998, contains brief summaries of some of the conclusions of speech consultants Dr. Alfred Belan and Dr. Scott

Meyer. The portion of Dr. Meyer's report that is quoted in the draft Addendum speculates that the grunts recorded on the USAir Flight 427 First Officer's channel of the Cockpit Voice Recorder ". . . suggest that the first officer was straining possibly in an attempt to manipulate the controls of the aircraft to override the autopilot."

The very tone of Dr. Meyer's "opinion" indicates it is nothing but speculation. A true "opinion" is based on knowledge and experience, and an opinion that a pilot's grunts were the result of straining to override the autopilot would require intimate knowledge of the characteristics of the flight controls of the aircraft at issue, including the force required to override the autopilot during various modes of its operation. Nowhere in the record have we been able to establish that Dr. Meyer possesses such extensive experience in and knowledge of the Boeing 737-300 autopilot system.[1] Dr. Meyer's speculation that noises made by the First Officer of USAir Flight 427 indicate the First Officer was making certain flight control motions is not based on fact and should be disregarded.

III. COMMENTS ON BOEING SUBMISSION

A. "Flight Crew Scenarios, Operational Experience"

Section V of Boeing's Submission to the Board contains an explanation of possible crew-caused scenarios for the USAir Flight 427 accident. Although US Airways disagrees with the conclusions of this section of Boeing's Submission, US Airways will not respond to those conclusions here. However, US Airways believes it is necessary to respond to the inaccurate and

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[1]In fact, in Dr. Meyer's March 7, 1996 report to Dr. Brenner, Dr. Meyer apparently misinterprets the First Officer's "Jetstream" comment as being a comment on contrails.

misleading use of anecdotal reports of inflight incidents that are presented as support for Boeing's conclusion that pilot error may have initiated the accident sequence.

1. Wake Vortex Encounters and "Startle"

Boeing's Submission offers six anecdotal reports in which airline flight crews reported being "surprised" or "startled" upon suddenly encountering uncommanded aircraft rolling or wake turbulence.[2] No pilot would disagree that wake turbulence encounters can come without warning. In that sense, pilots might be "surprised" by a wake vortex encounter. However, that does not conclude the inquiry, for the important question is how do pilots react to wake vortex encounters.

To infer that pilots can be so "startled" by a wake vortex encounter that they, in effect, forget how to fly is a leap in logic wholly unsupported by the facts. Indeed, in the five wake vortex incidents offered to support this section of Boeing's Submission, each crew immediately recognized they had encountered wake turbulence, and each applied correct controls to recover the aircraft, some under low altitude, low speed, high bank angle conditions where instant recognition and recovery were necessary to save the aircraft.[3] In the sixth incident, an uncommanded roll caused by an autopilot malfunction, the crew recognized the uncommanded roll and applied aileron and rudder opposite the roll to effect recovery.[4] The inference invited by Boeing's presentation of these reports, that crews are typically so "startled" by wake vortex

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[2]Boeing Submission at 41-42; Boeing Human Factors Supplement, Tabs 60; 5, 55, 56, 57 (all relating to one event); 9; 10; 91; 15.

[3]Boeing Human Factors Supplement, Tabs 60, 9, 10, 91, 15.

[4]Id.,Tabs 5, 55, 56, 57 (reporting one incident).

encounters that they forget the basics of their flying training, simply is not supportable, even by the very reports offered in support.

2. Pilot Overestimates of Bank Angle

Boeing's Submission states, "Crews typically over-perceive the magnitude of unexpected rolls by a factor or two or three, and may react accordingly."[5] This statement is simply not supportable by the evidence offered in Boeing's Submission.

In one British study of pilot errors in reporting bank angle experienced during wake vortex encounters, four of the 19 reports involved crews who underestimated their actual bank angle -- by factors of two or more in three of the four cases.[6] Boeing's Submission fails to inform us of the significance of this data. In eight of the remaining 15 examples -- 53% -- pilots overestimated their bank angle by six degrees or less. In fact, in one example offered, the pilot's error was one degree. The examples of "factors of two or three" include an incident where the aircraft rolled five degrees and the pilot later reported the roll as 10 degrees. In another example, the aircraft rolled 5 degrees, and the pilot estimated the roll to have been 15 degrees. Simply stated, the majority of these reports just do not represent significant errors.

In any event, the issue isn't whether pilots, suddenly faced with an aircraft experiencing uncommanded yaw or roll or the effects of wake turbulence, take the time to accurately record the exact bank angle the aircraft reached. In a typical example, the crew reported they disconnected the autopilot "at 20-30 degrees of bank."[7] The same crew stated the aircraft

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[5]Boeing Submission at 42.

[6]Boeing Human Factors Supplement, Tabs 32, 86.

[7]Boeing Human Factors Supplement, Tab 91.

reached "approximately" 30 degrees of bank. The actual bank angle recorded on the FDR was 20 degrees. In the charts provided with Boeing's submission,[8] crew estimates of bank angle are presented in increments of five degrees, indicating that pilots tend to estimate bank angle in five degree increments.

These inaccuracies in reporting are understandable because flight crews who experience uncommanded rolls in flight properly place their priorities on taking action to maintain control of the aircraft, not on precisely recording the bank angle experienced during the emergency. Wake vortex encounters and uncommanded inflight aircraft movements due to flight control malfunctions are not engineering test flight exercises, and the pilots' inability later to recall the precise bank angles experienced does not provide a basis on which to speculate that they or other pilots might overreact to similar uncommanded rolls.

The most egregious aspect of this argument is the statement that the tendency of pilots to overestimate bank angle may lead them to "react accordingly." Boeing's Submission never defines "react accordingly," instead leaving the nature of this undefined reaction to the reader's imagination. However, the facts are again contrary to the inference invited by Boeing's Submission. In every one of the anecdotes offered in Boeing's Submission, the pilots reacted by applying appropriate aileron and/or rudder controls opposite the roll to maintain aircraft control. Perhaps this is what is meant by "react accordingly." If so, the entire discussion of pilot overestimation of bank angle is completely irrelevant and bolsters the obvious conclusion as it relates to this accident, namely that an unexpected roll of less than 20 degrees bank angle, similar to that experienced by the Flight 427 flight crew, in clear air with a distinct horizon is not going to

[8] Id., Tabs 32, 86.

cause highly experienced airline pilots to forget the basics of how to use the flight controls to stop an uncommanded roll.

3. Flight Crews React to Unexpected Rolls by "Immediately Manipulating the Flight Controls"

Boeing's Submission never explains the possible significance of this restatement of the obvious. Five examples are offered.[9] In each, the flight crews reacted immediately to unexpected rolls by applying the proper opposing flight controls to stop the roll and maintain control of the aircraft.[10] These anecdotes do nothing except to provide yet more evidence that when faced with an unexpected roll, experienced airline crews know what to do and how to do it.

4. Training Using Rudder and Aileron

Boeing's Submission states that airlines are now teaching pilots to use rudder and aileron to recover from roll upsets, implying airline pilots have not been taught to do so before. Pilots, including airline pilots, have always been taught, beginning with their very first flight as a student, to use coordinated aileron and rudder in a turn. Airline training has always taught the same. To imply otherwise is simply misleading and untrue.

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[9]Boeing Human Factors Supplement, Tabs 44, 42, 65, 90, 6.

[10]Boeing's Submission contains a theory that higher-than-normal control forces, caused by maneuvering the aircraft with the autopilot in the Control Wheel Steering mode, contributed to the USAir Flight 427 First Officer's "confusion" during the response to the wake vortex encounter. Boeing Submission at 47. To the contrary, one of Boeing's cited incidents reports that the incident crew maintained control of the aircraft after a wake vortex encounter while leaving the autopilot engaged in the Control Wheel Steering mode. Boeing Human Factors Supplement, Tab 90. Flying the aircraft during a wake vortex encounter in CWS mode apparently presented no difficulties to the incident crew during their successful recovery. Boeing's speculation that the same circumstances caused an experienced First Officer on USAir Flight 427 to become so confused that he held full left rudder for 23 seconds as the aircraft spiraled to the ground is belied even by its own supporting data.

5. Misapplication of Rudder

To support a theory that pilots sometimes misapply rudder, Boeing's Submission again relies on anecdotal reports, with data often taken out of context and presented in a misleading fashion. Each will be dealt with in turn.

The Sahara India accident involved a student on his first B-737 flight, an instructor on his first B-737 instructional flight, and an improperly-given, unbriefed, unplanned engine out exercise on takeoff.[11] The reports indicate the student mishandled the simulated emergency, the instructor allowed the student's mistakes to go uncorrected too long, and the instructor took control too late to save the aircraft. In addition, the possibility of a rudder control system malfunction has not been totally eliminated as a possible cause for the sudden full rudder deflection in the wrong direction for the flight conditions. Yet, even if the accident was strictly the result of pilot error, the error was made by a low time pilot with no large jet aircraft experience. This is not an incident from which a valid inference can be drawn about the possible actions of pilots with thousands of hours of airline experience.

Inappropriate inferences are also invited by reference to accidents involving engine failures just after takeoff.[12] Recently, airlines have increased training emphasis on post-takeoff engine failures, partly because of the flight regime entered when complying with certain noise abatement procedures.[13] During these nose-high, low altitude, low airspeed, engine out scenarios, training

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[11]Boeing Human Factors Supplement, Tab 29 and Appendix C.

[12]Boeing Submission at 44; Boeing Human Factors Supplement, Tabs 37, 92.

[13]Boeing Human Factors Supplement, Tab 34.

must emphasize correct analysis prior to application of the correct rudder because the nose-high attitude provides few visual references for pilots to determine the direction of yaw.[14]

There was no lack of visual cues for the crew of Flight 427. In addition, the reaction of the aircraft to the wake vortex encounter was not a yawing motion, but instead was a roll to the left which the crew apparently countered with right aileron and rudder. Further, there is no credible evidence in the investigation that the crew of USAir Flight 427 applied left rudder when right rudder was the proper input. Therefore, any attempt to draw an analogy between the events that occurred during the USAir Flight 427 accident and the misapplication of rudder during nose-high, low altitude, low airspeed, engine out conditions is entirely inappropriate.

Two events cited in Boeing's Submission involved the apparent continued application of rudder after the FDR data indicated rudder was no longer needed to maintain control of the aircraft.[15] Setting aside the questionable validity of a criticism of successful emergency pilot actions based on a review of engineering data in the safety and comfort of an office, the full context of the data shows these incidents to be an inappropriate basis for drawing inferences about the possible actions of the crew of USAir Flight 427. In the July 1995 incident cited in Boeing's Submission,[16] the crew reported later that they were fully aware of their continued application of rudder after the aircraft regained wings level flight.[17] The crew stated they

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[14]Id.

[15]Boeing Human Performance Supplement, Tabs 6, 59.

[16]Id., Tab 6.

[17]Human Performance Group Chairman's Factual Report of Investigation, Second Addendum, October 5, 1995, docket No. SA-510, Exhibit 14X-A, at 24-27.

continued to apply rudder because the combination of rudder and aileron input they were applying was successfully maintaining directional control of the aircraft and they did not want to risk loss of control. The also reported they were fully conscious of the recent USAir Flight 427 accident and subsequent uncommanded roll incidents, and that this knowledge affected their decision-making.

A review of the data associated with the second cited incident, June 1997,[18] indicates the pilot applied full rudder over a four-second period and removed the rudder gradually over a 12-second period, suggesting the pilot knowingly put the rudder in, was aware of the rudder application throughout the incident, and gradually took it out when he or she perceived it was no longer needed.

None of these incidents supports Boeing's conclusion that USAir Flight 427's First Officer applied left rudder to counter a right roll, but then somehow forgot about his legs and continued to apply full left rudder for 23 seconds as the aircraft spiraled left, out of control, toward the ground.

6. Both Pilots on Controls

This section of Boeing's Submission cites anecdotal reports to support a conclusion that both pilots of transport aircraft sometimes manipulate the controls simultaneously, sometimes without the knowledge of the other pilot.

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[18]Boeing Human Performance Supplement, Tab 59.

Six examples are cited.[19] In two, the reports indicate the pilots were on the controls in a conscious, coordinated attempt by both pilots to maintain control of the aircraft.[20] In one case, the best information is that the First Officer later "thought" he might have applied rudder.[21] One example simply does not say what Boeing's Submission says it does.[22] The report does not indicate both pilots were on the controls. Instead, the report contains two reports of the same incident, with different accession numbers, apparently reported by two different people. One describes the events in first person, and the other describes the actions in the third person, attributing the actions to the First Officer. Neither report indicates that both pilots were simultaneously on the aircraft's controls.

In one case, a captain recovered the aircraft from a sudden yaw after the first officer, who was also the captain's personal friend, became incapacitated.[23] In fact, the captain thought the first officer was dead or dying. Under the stress of a perceived dead or dying first officer and an aircraft that was not properly responding to flight control inputs at low altitude and low airspeed in a wind shear environment, the captain failed to notice the incapacitated first officer's left leg was locked at the knee, applying full left rudder. However, as soon as another person, a flight attendant who was also a pilot, entered the cockpit, the problem was identified and solved. This appears to be the only reported incident in airline aviation history in which one pilot was

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[19]Boeing Human Factors Supplement, Tabs 97, 12, 81, 33, 5, 80.

[20]Id., Tabs 5, 12.

[21]Id., Tab 33.

[22]Id., Tab 81.

[23]Boeing Human Factors Supplement, Tab 97.

inappropriately applying full rudder, causing control difficulties, while the other pilot failed to notice and correct the situation.[24]

Further, the Captain in this incident was essentially "solo" after the onset of the event, and over tasked with multiple, simultaneous, life threatening emergencies, and he failed to note the rudder input. However, as soon as another pilot, even a relatively inexperienced one, entered the cockpit, the problem was identified and solved. These facts support the conclusion that it is extremely unlikely that two conscious, experienced pilots in the same cockpit, having experienced a relatively routine wake vortex encounter at 6,000 feet, would both fail to notice and correct a continued, inappropriate full rudder input by one of the pilots.

In a final example, a first officer reached for the left rudder pedal with his foot as the captain lost control of the aircraft on landing roll.[25] He found the captain had already applied full rudder in the appropriate direction. There being no apparent relationship between this incident and the crash of USAir Flight 427, no valid inference about the actions of the crew of USAir Flight 427 can be drawn.

IV. CONCLUSION

Test data obtained since the parties' September 1997 submissions indicates a rudder PCU secondary slide jam with primary slide overtravel is consistent with USAir Flight 427's flight path. The possibility of rudder reversal caused by such a malfunction in the PCU has been demonstrated

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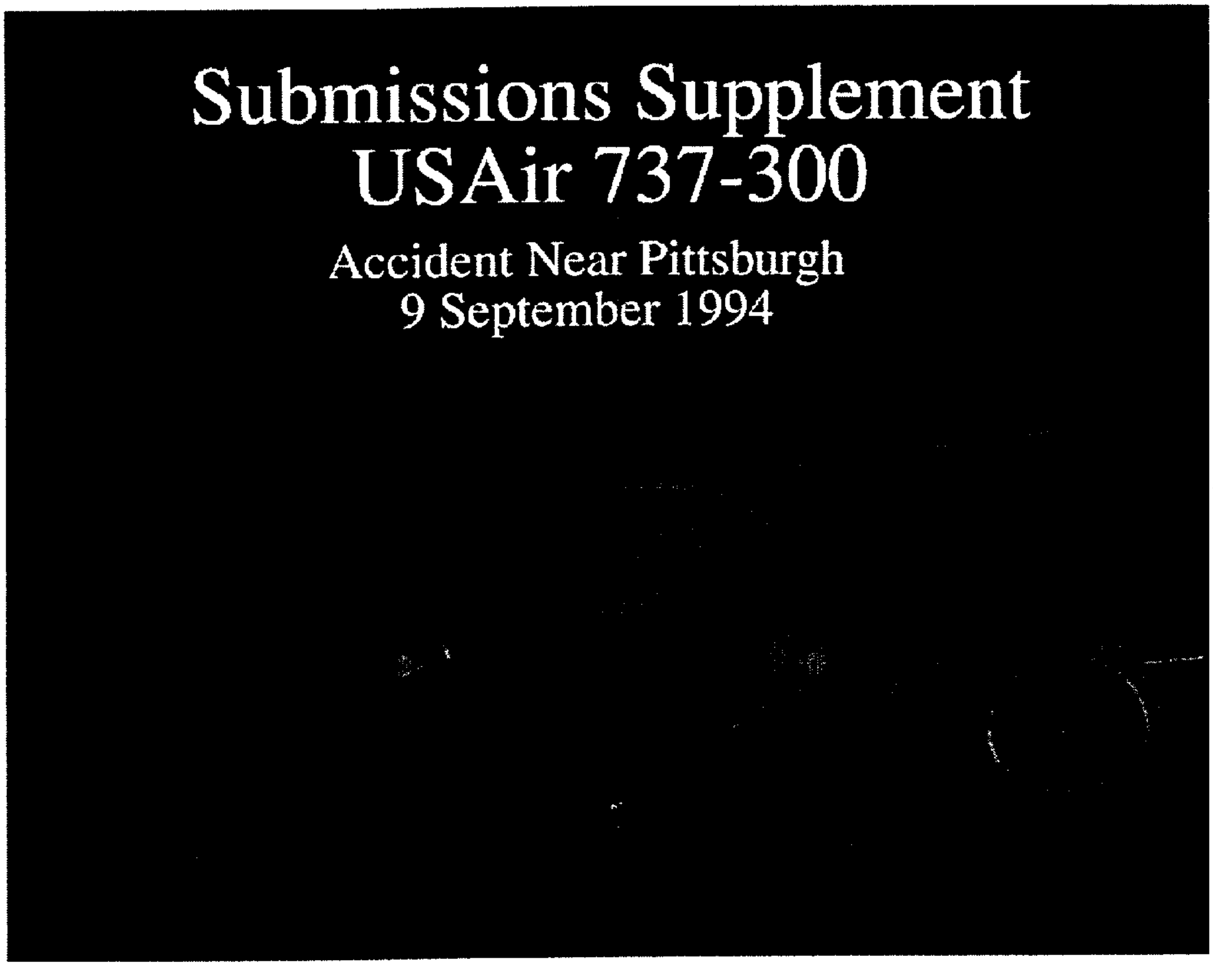
[24]One cannot avoid wondering what the outcome would have been in this incident had the aircraft been at or below the "crossover speed."

[25]Boeing Human Factors Supplement, Tab 80.

repeatedly. Conversely, a finding that the persistent full left rudder input was made by USAir Flight 427's flight crew must necessarily rest solely on rank speculation which is itself based on anecdotal reports inaccurately and misleadingly interpreted and in many cases taken out of context.

For these reasons, US Airways reaffirms the suggested probable cause findings submitted with its September 30, 1997 Submission to the Board:

> The probable cause of this 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.
>
> A contributing cause of this 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.


Submissions Supplement
USAir 737-300
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Contents

1.0 Executive Summary

Purpose of Submissions Supplement

The National Transportation Safety Board (NTSB) has invited all parties to the USAir Flight 427 investigation to provide supplemental information concerning investigative activities that have taken place since September 30, 1997.

In this submissions supplement, Boeing documents the latest data and analyses produced on the following subjects:

- Eastwind Airlines Flight 517 event on June 9, 1996.
- Recent inspection of the UAL Flight 585 accident aircraft rudder power control unit (PCU).

In addition, an update is provided on the status of the 737 rudder system improvement program and the industrywide upset recovery training program.

Eastwind Flight 517 Event on June 9, 1996

Event Description

On June 9, 1996, a Boeing 737-200, N221US, operating as Eastwind Airlines Flight 517, experienced a yaw/roll upset on approach. The airplane had just completed a heading change to the right and was rolling back to wings level when the crew reported feeling a slight bump on the right rudder pedal without any actual pedal movement. The event began with a heading change to the right of approximately 6 degrees, followed by a roll to the right of less than 12 degrees. The flight crew reported responding to the upset by making a hard-left rudder input, rotating the wheel to the left, and bringing the right throttle forward. During recovery, 13 degrees of left roll was experienced. The event concludes after approximately 13 seconds, the heading moving sharply back to the left. The airplane completed its flight without further difficulty, and there was no airplane damage or serious personal injury.

Boeing Conclusions

1. Multiple scenarios have been identified that match at least some of the data and crew reports from the Eastwind 517 event. None of the scenarios fully match all the data, kinematic analysis, and crew reports.
2. Boeing believes that, under the NTSB standard for identifying "probable cause," there is insufficient data to find a "probable cause" for this event. The following factors are significant to reaching this conclusion.
   - No data indicates that a rudder power control unit failure occurred during the event sequence. To the contrary, the event and flight test data indicate that the yaw damper *was functioning* as the event progressed. A rudder jam/reversal could not have occurred because the yaw damper system cannot affect rudder position during a rudder reversal. (See Section 2.2.7)

- The extremely cold environmental conditions and hydraulic system failure necessary for a thermally produced secondary slide jam were not present on Eastwind Flight 517. (See Section 2.4)
- Inspection results of the power control unit servo valve showed no physical indications of jams to the primary or secondary slide. No known or reasonably hypothesized mechanism can result in a rudder power control unit servo-valve jam for approximately 12 seconds and subsequently clear without leaving physical traces of the jam mechanism. (See Sections 2.2.2, 2.2.4, and 2.4)
- The pilot reports of pedal travel and pedal forces are not consistent with a rudder reversal scenario. (See Section 2.4)
- There is no recorded data that indicates the flight crew was responsible for the right rudder deflection sustained for 12 seconds. However, a scenario that includes a pilot input of right rudder matches the data from both the flight data recorder and the kinematic analysis more closely than any other scenario identified. (See Sections 2.2.1, 2.2.8, 2.3, and 2.4)
- The application of kinematic analysis, as employed in the four scenarios discussed in this submission, is not exact. All four evaluated scenarios produce results reasonably close to the event's recorded data. However, without additional parameter recordings or higher data sampling rates, it is not appropriate to draw definite conclusions about the event from kinematic analysis alone. (See Sections 2.2.5, 2.2.6, and 2.3)

3. All parties generally agree that the initiation of the Eastwind event involved some form of activity from the yaw damper system. This resulted in an airplane upset and flight crew inputs to the flight control system to regain control. Thereafter, either a rudder system fault, additional crew inputs to the rudder, or unknown factors generated a final rudder deflection of approximately 6 degrees to the right, which is required for the magnitude of heading change recorded. (See Sections 2.2.2, 2.2.4, and 2.3)

4. The most likely explanation for the Eastwind event involves a preexisting yaw damper fault that subsequently cleared itself. This scenario is most consistent with the physical evidence, pilot reports, and kinematic analysis. The yaw damper system includes a yaw damper coupler (electronic box) with a mechanical rate gyro, which senses yaw motion. The coupler sends a variable electrical current to the electro-hydraulic servo valve on the rudder PCU which commands movement of the rudder PCU up to the yaw damper authority. In-service experience has shown that intermittent yaw damper system faults can occur and subsequently clear and not be duplicated during shop testing. (See Sections 2.2.7 and 2.4)

5. There is no data to indicate that the Eastwind Flight 517 event, the United Flight 585 accident, and USAir Flight 427 accident were caused by a common airplane malfunction.

Inspection of the Rudder PCU From the UAL Flight 585 Accident Aircraft

The dual concentric servo-valve slides from the UAL Flight 585 accident aircraft rudder PCU have marks created by the post-crash fire that indicate that the PCU servo valve secondary slide was at the neutral position during the entire fire. The rudder PCU cannot reverse when the secondary slide is at neutral. (See Section 3.0)

737 Rudder System Improvement/Training Program Update

Based on knowledge gained during the course of the USAir Flight 427 investigation, Boeing, the aviation industry, and the U.S. government have already implemented a number of improvements to:

- Remove highly unlikely potential for rudder PCU jam/reversal (modified rudder PCUs make rudder reversal physically impossible).
- Incorporate 737 yaw damper system reliability improvements to significantly reduce the number of yaw-damper-caused upsets (this includes the fault believed to have initiated the Eastwind 517 event).
- Incorporate a hydraulic pressure reducer to improve the match between rudder deflection capability and airplane control requirements (this reduces airplane reactions to rudder deflections no matter what the cause).
- Improve pilot responses to upset circumstances by training on upset recovery techniques.

Approximately one-third of the rudder PCU upgrades have been accomplished to date; changes were incorporated into all production aircraft and made available for retrofit beginning in July 1997. The yaw damper system and airplane controllability improvements will be incorporated into all production airplanes and available for retrofit beginning in October 1998. The FAA has mandated that the PCU change and the yaw damper/airplane controllability changes be incorporated by August 4, 1999, and August 1, 2000, respectively. Additionally, Boeing, our suppliers, and the airlines have established a retrofit plan to allow all airplanes in the worldwide fleet to be modified by these dates. (See Section 4.0)

The industry team completed work on the upset recovery training package in July 1998. Shipments of the training package are now under way.

Recommendations

No additional recommendations for airplane design, procedure, or training changes are needed as a result of the Eastwind Flight 517 investigation or the additional work on the UAL Flight 585 rudder PCU.

2.0 Eastwind Investigation

The NTSB has invited all parties to the USAir Flight 427 investigation to provide supplemental information concerning activities arising out of this investigation that have taken place since September 30, 1997. As in the previous submittal, this document will offer proposed findings that are drawn from the analyses and data produced during the course of this investigation.

In this supplemental submission, Boeing documents the extensive work accomplished by all parties in reference to the June 9, 1996, Eastwind Flight 517 (N221US) upset event (Ref. Appendix C, page 66, of the original Boeing submittal), and presents the Boeing conclusions reached and resultant recommendations. How and why the postulated event scenarios were selected is explained. Analyses and data that support or refute each of these scenarios is presented and evaluated as a probable cause for this event. An assessment of how this event may or may not be relevant to the USAir Flight 427 investigation is also included.

In this supplemental submission, Boeing will also address the findings from the recent inspection of the UAL Flight 585 main rudder power control unit (PCU) servo valve. Given the findings of the Eastwind Flight 517 investigation and other recent in-service events, Boeing will also assess the appropriateness of the 737 rudder improvement program that is currently under way.

2.1 Event Overview

On June 9, 1996, Boeing 737-200, N221US—operating as Eastwind Airlines Flight 517—experienced a yaw/roll upset on approach to Richmond Airport, Richmond, Virginia. The airplane was not damaged, and no one was seriously injured.

The event occurred during descent through 4,000 feet at 250 knots with the flaps and gear retracted. The airplane had just completed a small heading change to the right and had just returned to wings level when the captain (flying pilot) reported feeling a slight kick, or "bump," on the right rudder pedal without any actual pedal movement. This happened just prior to the onset of the event.

The event started with a rapid heading change to the right of approximately 6 degrees followed by a roll to the right of just less than 12 degrees. The flight crew reported reacting to the upset by making a hard left rudder input ("standing on the left pedal"), rotating the wheel to the left and pushing the right throttle forward. After approximately 13 seconds the heading moved sharply back to the left and began a damped oscillation, consistent with the airplane Dutch-roll mode. The right throttle was retarded back to idle. During the recovery the bank angle reached about 13 degrees past wings level to the left (opposite the direction of the upset) due to the combination of left wheel and increased thrust on the right engine. The flight crew declared an emergency, completed the descent, and accomplished an uneventful landing.

2.2 Investigation History

The event airplane had been the subject of flight squawks for both rudder trim and rudder upset problems during the previous month of service. During this time, maintenance actions included rudder system hardware changes, flight control system operational checks, airplane wiring checks, and check flights, with no significant faults found. Pertinent information from the airplane logbook for these maintenance actions was documented in the *Systems Group Chairman's Factual Report of Investigation,* dated June 11, 1997 (see Ref. 1). Flight data recorder data from two of these previously squawked flights were provided to Boeing for analysis. The analysis could not find any airplane flight path upsets or rudder system anomalies within the recorded data from these flights.

2.2.1 Flight Data Recorder Information

The flight data recorder on N221US recorded only the parameters listed below at the sampling rates noted. Rudder, pedal, wheel and lateral surface deflections were not recorded. It was determined after conducting an instrumented flight test aboard N221US that the pitch, roll, and heading information recorded on the flight data recorder were subject to unusual errors, as described in Section 2.2.3, in the subsection headed *Issue 3: Flight Data Recorder Information*. Efforts were made to account for these errors using flight test data, as discussed in Section 2.2.5, *Results of Kinematic Analysis of Event.*

Parameter	Pitch	Roll	Heading	Column	Eng press ratios (L and R)		Normal load factor	Long. accel.	Airspeed	Altitude	Mic keying
Sample rate, samples/ second	4	2	1	2	1	1	8	4	1	1	1

Time histories of pertinent parameters for the event, corrected for measurement errors, are shown in Figure 1 (page 18), along with the wheel and rudder positions estimated by kinematic analysis. Several observations are of interest:

- The data show that the bank angle during the initial upset did not exceed 12 degrees to the right and that during the recovery it peaked at about 13 degrees to the left.
- Roll attitude shows a shallow turn to the right and return to wings level just prior to the event.
- The heading trace shows a distinct airplane Dutch-roll oscillation after the event was over indicating that the yaw damper was no longer functioning (crew reported turning off the yaw damper).

2.2.2 Initial Airplane Systems and Hardware Inspections and Tests

On June 10, 1996, the airplane's rudder system, including the power control unit and yaw damper system, was subjected to a series of nonintrusive tests to determine if the upset could have been a result of a mechanical or electrical malfunction within these systems. The tests included:

- Visual examination.
- Rudder trim operation.
- Rudder oscillation.
- Rudder authority.
- Standby power control unit input force.
- Yaw damper hardover tests.
- Continuity checks.
- Rudder centering.
- Rudder pedal forces.
- Yaw damper authority.
- Rudder friction.
- Nose wheel steering.

The above testing was accomplished with various combinations of A, B, and Standby hydraulic systems pressurized as well as yaw damper engaged and disengaged. No significant faults were found.

It was determined that the yaw damper linear variable differential transformer was not properly rigged. The misrigged linear variable differential transformer caused the yaw damper to have an authority of 1.5 degrees left and 4.5 degrees right. The mechanical limits of the yaw damper actuator limit the total authority of the yaw damper to 6 degrees. With a properly rigged linear variable differential transformer, the authority will be a symmetrical ±3 degrees. The misrigged linear variable differential transformer was caused by previous maintenance activity that removed and replaced the linear variable differential transformer probe and transformer.

The visual inspection included examination of the rudder cable runs throughout the entire airplane. No anomalies were noted with the rudder cables other than a plastic sheet that was found partially wrapped around the rudder "A" cable at the aft pressure bulkhead. It was determined by observing operation of the cables that the plastic sheet did not cause any dragging or binding.

The main rudder power control unit, standby rudder power control unit, feel-and-centering, and the aft cable quadrant/torque tube installation were examined. There were no significant anomalies noted with any of the installations. However, there were several minor discrepancies that cannot be directly linked to the Eastwind yaw event of June 9, 1996. These discrepancies are described below.

The rudder system, rudder power control unit, and yaw damper system inspections found that the yaw damper's linear variable differential transformer was misrigged, the standby power control unit was slightly out of rig, and the rudder backlash was slightly out of limit. The yaw damper's linear variable differential transformer was misrigged 1.5 degrees to the left as a result of previous maintenance activity. The standby power control unit was out of rig by approximately 0.55 inches (0.75 inches total) at the trailing edge of the rudder surface. The rudder backlash was estimated to be approximately 0.04 inches. The limit is 0.02 inches while applying ±12 pounds to the surface. An additional complication to this test was the wind on the rudder surface experienced during the testing.

A visual and continuity check was accomplished on the yaw damper system electrical wiring. Some of the electrical continuity checks were accomplished while "freezing" various connectors with Freon. No anomalies were noted as a result of this testing.

2.2.3 Flight Test Results

Reasons for Flight Testing

Several issues surfaced early during the investigation that prompted further investigation. These issues were:

- The pilot's comment regarding stiffness in the rudder control system.
- The aft cabin attendant's comment regarding hearing a "thud" coincident with the onset of the upset.
- The need for additional flight data to better understand the rudder deflection time history during the event.

It was agreed by all parties to the investigation that the best way to acquire the needed additional data would be to conduct an instrumented flight test on the event airplane. The flight test plans (Refs. 2, 3, 4, and 5) were developed jointly by the Performance and Systems Groups, and implemented by a Boeing Flight Test Team. The plan called for specific instrumentation to obtain the necessary data for resolution of the rudder deflection and noise issues. To better understand the issue regarding the feel of the rudder system during the event, the Eastwind captain who was at the controls during event flight participated in the test flying and was subjected to multiple rudder upsets.

Airplane and Test Condition

All of the rudder system equipment, except for the yaw damper coupler, that was installed on N221US during the event was left undisturbed on the airplane for flight testing. This included a linear variable differential transformer in the yaw damper system which was known to be misrigged. This linear variable differential transformer misrig allowed a 4.5 degree yaw damper authority to the right (the direction of the upset) while limiting yaw damper authority to the left to 1.5 degrees. Changes to the event airplane for flight testing consisted of the addition of instrumentation to measure and record the parameters required to fully analyze the test data, and the replacement of the yaw damper coupler box in the airplane's avionics bay with a similar unit that allowed external insertion of faults.

The conditions flown during the flight test included yaw damper hardovers and rudder steps. The yaw damper hardovers were flown to determine if a yaw damper fault could have caused an upset equivalent to that experienced by N221US on June 9, 1996. Rudder steps larger than the yaw damper authority were flown to further define the upset magnitude. Rudder steps were flown both with the yaw damper turned on, and yaw damper turned off.

Findings

This testing resulted in a number of significant findings in the areas of system feel, noise, and flight data recorder information. These issues are discussed below.

Issue 1: System Feel

The Eastwind event pilot was asked to qualify his statement concerning rudder system "stiffness" through recoveries from rapid rudder deflections while flying at approximately the event flight conditions. This was considered necessary because of the flying pilot's limited experience in the 737-200 airplane, and the normally infrequent need for rudder inputs at the event flight condition. Also, no rudder system force information was recorded on the flight data recorder. The NTSB conducted pre- and post-flight interviews of the Eastwind pilot and documented this information in Ref. 6. Additional information regarding the crew/airplane interaction is presented in Section 2.2.8, *Human Factors Assessment*.

Issue 2: Noise

A significant noise impulse was recorded on a series of acoustical instruments located in the aft cabin during two of the many yaw event (rudder deflection) test conditions. The first impulse was recorded during a flight test condition in which the test pilot manually introduced a rudder kick of approximately 6 degrees through a combination of rudder trim and rudder pedal inputs. The second recorded impulse occurred during the first flight test condition flown by the Eastwind captain, who commanded almost 11 degrees of rudder in opposition to an induced yaw damper hardover. Neither of these two noise impulses was recorded by the cockpit voice recorder (see Ref. 7 for additional information).

A noise sensor analysis program was utilized to determine the dimensional location for the origin of these noise impulses. Analyses of data from the test conditions placed the origin of the impulses in roughly the same location—approximately 4 feet aft of the aft pressure bulkhead, centered approximately 5.5 feet above the main cabin floor. Within this general area is the rudder hinge mounting point. Validation of the analytical tool was accomplished through the accurate prediction of multiple noise impulse origins recorded by the instrumentation microphone array when the aft airstair assembly was manually extended and released, producing an impact and subsequent metal rattling noise that matched the rattling noise described above.

From these tests, it was concluded that:

- Part of the recorded noise came from the inertial forces acting laterally on the unrestrained airstairs.
- Part of the recorded noise was due to an unknown source, the origin of which is likely to be at the locations described above.

- The two noise events described immediately above were separate in time, with the unknown impact preceding the airstair event by about 0.84 seconds.

Issue 3: Flight data recorder information

- The rudder deflection required to produce the recorded upset *could not have been generated by yaw damper activity alone*. This is apparent in Figure 2 (page 19), which shows the event data compared to several yaw damper hardover test conditions and a 6-degree rudder step. The event heading change is greater than the change recorded during the yaw damper hardovers. Note that the event bank angle is not consistent with the flight test data because of recovery wheel commands during the event. Correcting for the difference in bank angle between the event and flight test conditions would increase the heading change during the event.
- A comparison of the Dutch-roll characteristics shown in Figures 3 and 4 (pages 20 and 21) demonstrates that the event sideslip amplitude (peak to peak) is about half that of the yaw-damper-OFF flight test data, and about the same as the yaw-damper-ON flight test data.
- The heading, pitch, and roll information recorded on the flight data recorder disagree with the data from the onboard flight test instrumentation by as much as several degrees. because of errors in the airplane's gyros. However, these errors are of a slow, cyclic nature and do not have a significant effect on the analysis of a short-term yaw upset. Additionally, gimbal error in the heading data from the directional gyro is small, because of the limited roll angle experienced during the event, and is correctable as discussed in Section 2.2.6, *Kinematic Analysis Validation and Error Assessment*.

2.2.4 Post-Flight Airplane Systems and Hardware Inspections and Tests

Equipment Removed From Airplane

Upon completion of flight testing, all rudder and yaw damper systems hardware was removed from the airplane for laboratory testing and examination. No anomalies were uncovered during the flight test program or during the systems hardware examinations that provided an explanation for the upset. Refs. 8 and 9 document the results of these test and inspection activities.

Functional tests of the gyros from the event airplane, conducted by the NTSB, confirmed that the hardware did not meet Quality Control Functional Test requirements. Inspection of the flight data recorder led to a concern on the accuracy of data recorded by the heading, pitch, and roll gyros. Tests were conducted on the #1 and #2 directional gyros; #1, #2, and auxiliary vertical gyros; and the -901 and -902 yaw damper coupler rate gyros. These tests checked the calibration and drift of these components over long periods of time. Results indicated that both directional gyros, all three vertical gyros, and the event yaw damper coupler failed portions of their respective Quality Control Functional Tests. Additionally, both the directional gyros and all three vertical gyros showed excessive and erratic drift. The event yaw damper failed Honeywell's signal damping test. However, the manufacturer pointed out that failure of this test would not indicate that the yaw damper would go hardover. Rather, the manufacturer indicated that failure would result in rapid rudder movement.

Rudder Power Control Unit Examination and Test

The main rudder power control unit was examined at the Parker Hannifin facilities in Irvine, California, on June 28, 1996. The unit underwent visual inspection followed by functional testing. It passed all functional tests with the exception of those tests relating to the yaw damper's linear variable differential transformer. These tests include the Transducer Output, Transducer Null, and Yaw Damper Authority tests.

To verify the misrigging of the linear variable differential transformer as the cause of the above test failures, the linear variable differential transformer was adjusted per overhaul manual procedures and the tests were performed again. After adjustment, the unit performed within all linear variable differential transformer and yaw damper requirements.

Eastwind Servo Valve Inspections (NTSB Testing)

The condition of the Eastwind servo valve secondary slide and housing were compared to other 737 main rudder power control unit dual concentric servo valves, including the USAir Flight 427 servo valve. The inner diameter of the servo valve housing exhibited "polished bands" near the end of each bore. The polished bands could only be seen under very specific lighting conditions (indicating the depth of the polished areas to be very shallow). These bands were approximately 0.010 inches wide by 0.050 to 0.070 inches long. The diagonal marks created during the original manufacture of the servo valve traversed through the polished bands, also indicating the depth of the polished areas to be superficial.

The outer diameter of the secondary slide did not exhibit nearly as many polished bands as the inner diameter of the housing. These bands were only visible under very specific lighting conditions and the original manufacturing marks could be distinguished within the bands.

This type of feature is not uncommon on servo valves that have seen many hours of in-service operation. Several exemplar servo valves have been examined that exhibit this polishing feature. The secondary slide is primarily supported by the housing at the extremities of the bore much like any cylinder within a cylinder. More wear or polishing occurs in these areas.

The primary and secondary slide clearances were measured for comparison with the current drawing specifications. The primary and secondary slide clearances are as follows:

- Primary slide 0.000180–0.000200 inches (180–200 millionths of an inch)
- Secondary slide 0.000170–0.000190 inches (170–190 millionths of an inch)

Both the primary and secondary slide diametrical clearances are within the currently specified requirements of 150 to 200 millionths minimum clearance. Additionally, a most-material-condition (MMC) valve was produced to determine the primary and secondary slide clearances at which the valve could no longer meet the minimum friction requirements. It was determined that if the primary slide clearance is less than 120 millionths or if the secondary slide clearance is less than 70 millionths, the minimum friction requirements cannot be met. The Eastwind servo valve clearance is well above that required to meet the minimum friction requirements.

2.2.5 Results of Kinematic Analysis of Event

The flight data recorder information from the event was subjected to a kinematic analysis to determine the control inputs that were not directly recorded. A kinematic analysis uses the attitude and motion parameters recorded on the flight data recorder to solve for the forces and moments that must be applied to the airplane to cause the recorded motion. A simulation of the airplane can then be used to calculate the control surface deflections that will cause the required forces and moments.

Predicted control surface deflections are generally fairly accurate, given accurate airplane motion data recorded at sufficiently high frequency. Verification of the analysis methods with high-sample-rate flight test data is shown in Section 2.2.6, *Kinematic Analysis Validation and Error Assessment*. For the older flight data recorder installed on the Eastwind airplane, airplane heading was recorded just once per second. At this low sampling rate, information about the measured signal is lost, details disappear, and only the long-term, slowly varying character of the signal is preserved. To partially compensate for this effect and enhance the Eastwind data, special non-linear interpolation techniques were employed. This enhanced data was then used to estimate the rudder deflection. It should be noted, however, that given the limitations of the recorded data, it is not possible to identify a single unique solution with complete certainty.

References throughout this report to "rudder deflection" mean the deflection of the rudder surface with respect to the centerline of the airplane. Right rudder deflection is defined as movement of the trailing edge of the rudder to the right, which is associated with a command from the right rudder pedal and a heading change to the right. The aerodynamic data relating aerodynamic forces to rudder deflection are based on wind tunnel tests calibrated by flight tests.

Two corrections to the recorded flight data recorder information were applied prior to performing the kinematic analysis. The roll attitude data were biased approximately 1.5 degrees right-wing-down (positive) to put the airplane in trim with zero rudder just prior to the upset. In addition, heading was corrected for a phenomenon known as gimbal error. The magnitude of this error depends on the heading orientation of the gyro at the time it is initially powered up, and on the heading, pitch, and roll attitude of the airplane at any given time. The initial heading of the gyro during power-up was determined by examining turns flown subsequent to the event, prior to touchdown. Heading errors during the turns manifest themselves as anomalous rudder movements in the kinematic analysis. When the heading data have been properly corrected, these anomalous rudder movements are minimized. For this particular event, the heading corrections are relatively small because of the limited roll attitude excursions.

The results of the kinematic analysis are shown in Figure 1 (page 18), along with the pertinent flight data recorder information parameters. As noted above, the accuracy of this analysis is constrained by the limited number of parameters and low sampling rates of the event airplane's flight data recorder. Nevertheless, this kinematic analysis confirmed that the rudder deflection required to cause this event was greater than that which would be expected from an operational yaw damper experiencing an electrical fault and going hardover, even if the yaw damper had a misrigged linear variable differential transformer as found on the event airplane.

This initial extraction of required control deflections led to some interesting observations:

- If the event initiates with a rudder deflection to the right, the estimated wheel starts moving to the left coincident with the beginning of the event (no response time lag).
- The rudder deflects about 5 degrees to the right and then increases to 6 to 7 degrees.
- Near the end of the event the rudder deflection is reduced momentarily to about 5 degrees and then increases to approximately 7 degrees.

Detailed kinematic analysis of the flight data recorder showed that the flight control movements were consistent with the reports except for rudder deflection, which went opposite to what was reported by the flying pilot. The analysis also indicated that the rudder deflection required to explain the upset (i.e., match the flight data recorder information) was more than could be explained by yaw damper activity, which is the suspected initiator of the upset.

2.2.6 Kinematic Analysis Validation and Error Assessment

The test flights conducted on the Eastwind airplane were analyzed kinematically using a 737-300 simulator model tuned to match the flight test data. This analysis was conducted to calculate rudder deflection data that could be compared to the rudder position actually measured during the flight test. Showing that the simulation produces results that match the test flight parameters increases confidence that the simulation can be used to determine the control deflections during the Eastwind event. Instrumentation added to the Eastwind airplane measured and recorded rudder deflection during the test flights.

The following comparisons validate that the kinematic extraction method provides a reasonable match to the flight test results. The errors between extracted and measured rudder deflections shown in these figures are generally within ±0.5 degrees.

- Figure 5 (page 22) compares the rudder estimated from Portable Airborne Digital Data System information with the actual measured rudder deflection for a series of flight test yaw damper hardovers and a 5.9-degree step rudder with the yaw damper OFF.

- Flight test rudder deflection for a yaw-damper-ON condition is shown compared to rudder estimated from Portable Airborne Digital Data System and flight data recorder information in Figure 6 (page 23).
- Figure 7 (page 24) shows an example of predicted rudder deflection that results from flight test measured pedal displacement, combined with the response of the yaw damper control law to actual yaw rate for a given test condition. This calculated rudder is compared to the rudder deflection measured during the test condition and to that which was estimated kinematically from the flight data recorder information.

An additional evaluation of the flight test data was conducted using a 737-200 simulation. This evaluation was necessary so that a comparison could be made with a yaw damper hardover scenario analyzed by the NTSB, which used a 737-200 simulation. Because of time constraints no attempt was made to adjust this simulation to improve the match of the available flight test data. Instead, a method was developed to account for errors between measured and simulated heading.

The rudder deflection from a flight test condition was used to drive the 737-200 simulator while the pitch and roll angles were maintained at the measured levels by wheel and column. The resulting error in heading between the simulator and measured heading values is plotted in Figure 8 (page 25) for the six conditions evaluated. Also plotted is the average error of all the flight test conditions evaluated. The errors were determined only for rudder steps and hardovers confirmed to be similar in magnitude and character to the event upset. This average error was then used to adjust the free response heading data for the various proposed scenarios. The results are discussed in Section 2.3.5, *Scenario Discussion Summary*.

The errors determined for the 737-200 simulation are generally larger than those for the modified 737-300 simulation with cyclic heading errors of up to about ±1 degree.

2.2.7 Yaw Damper Analysis

Yaw Damper System Description and Operation

The yaw damper's function is to improve ride quality by suppressing the airplane's natural Dutch-roll tendency. The 737-200 yaw damper system is a single-thread system driving through a hydraulic actuator to move the rudder surface. This yaw damper actuator creates small rudder inputs using a control law based on yaw rate and airspeed signals. Command from the yaw damper coupler is derived from a mechanical yaw rate sensor that is shaped by analog electronics to drive a T-valve in the hydraulic actuator. The yaw damper engage logic and controls laws are contained in the yaw damper coupler.

Electronic rudder position commands generated by the yaw damper coupler are sent to an electro-hydraulic servo valve installed in the "B" hydraulic system side of the main rudder power control unit. The electro-hydraulic servo valve positions the yaw damper mod piston and main rudder power control unit servo valve, which actuates the power control unit and ultimately drives the rudder surface. The yaw damper control loop is closed via a linear variable differential transformer, which measures the mod piston position and is fed back to the yaw damper coupler.

Yaw damping is provided in series with the pilot commands, and does not backdrive the pedals. Yaw damper inputs via the main power control unit will not be possible if the "B" hydraulic system is depressurized.

Control of the yaw damper is accomplished through the yaw damper engage switch, a solenoid-held switch on the overhead panel. When the engage switch is in the disengaged position, (1) the hydraulic control of the electro-hydraulic servo valve is deactivated, and (2) the yaw-damper-disengaged warning light is ON. After the engage switch latches, a 2-second easy-on transition occurs to the engaged mode, during which time, (1) hydraulic control of the transfer valve is activated, (2) the yaw damper switches out of its disengaged mode into its engaged mode, and (3) the yaw-damper-disengaged warning lights turn OFF. The 2-second easy-on ensures a smooth yaw damper engagement.

The rate limit of the yaw damper system is controlled by mechanical means within the main rudder power control unit. Yaw damper inputs are rate limited to about 50 deg/sec of commanded rudder rate. The yaw damper rate limit is controlled by maximum electro-hydraulic servo valve flow (0.3 gpm) and the area of the mod piston (0.307 in^2).

Yaw damper travel limit is provided by mechanical stops in the yaw damper actuator equivalent to ±3 degrees of commanded rudder.

Servo Valve Analysis

Dynamic analysis of the yaw damper system was performed for the Eastwind event to determine whether the airplane's yaw damper actuator could move the secondary slide to at least some 40% or more of the secondary slide stroke, and then jam in that position so as to support the kinematic analysis scenarios involving a rudder reversal.

The conditions used for this analysis were (1) a flight level of 3,900 ft above ground level, (2) an airspeed of 250 knots, and (3) rudder trimmed to zero prior to the step input.

This dynamic analysis revealed that with a step input to the yaw damper of 4.5 degrees, the secondary slide will be moved to 53% of its effective stroke. If the step input is increased to 6 degrees, the secondary slide can be moved to as much as 71% of its effective stroke. As a result, the yaw damper is capable of moving the secondary slide to a position required to provide a kinematic match for a reversal condition. Therefore, this scenario cannot be ruled out on the basis of yaw damper operation on the secondary valve.

Indications of Yaw Damper Activity During the Event

Comparison of the event flight data recorder information with the data obtained in the Eastwind flight testing *showed a marked similarity between the extracted rudder data for the event and for a yaw-damper-ON rudder step as shown in the top graph in Figure 9 (page 26)*. To better illustrate the similarity between the two time histories, the bottom graph in Figure 9 shows a comparison of the flight test rudder biased to overlay the event rudder.

Next, using the previously validated simulation, the yaw damper command was calculated based on the yaw damper control law and the yaw rate from the Eastwind event heading. In Figure 10 (page 27), this yaw damper command was added to a 6.5-degree rudder step, demonstrating a much-improved match with the estimated event rudder through the first Dutch roll cycle. The degree of similarity in this match is a strong indicator of yaw damper activity during the event.

Another strong indicator of yaw damper function is the Dutch roll damping characteristics following a yaw upset. The Dutch roll motion is most easily seen in the derived airplane sideslip angle as shown in Figure 11 (page 28), which compares the Eastwind event with a 5-degree yaw-damper-ON flight test rudder-step condition. These data show:

- A similar but scaled-down sideslip response for the basic 5-degree flight test rudder step.
- An improved similarity in the first Dutch-roll oscillation when the flight test data are scaled to a 6.5-degree rudder step.
- A further improvement in the sideslip time history match when the effect of asymmetric thrust is added to the flight test data.

With the aforementioned adjustments, *the event and flight test data show a very close match in the Dutch-roll damping characteristics providing another strong indication of normal yaw damper activity.*

The ability to differentiate between an operational and failed yaw damper is shown in Figure 12 (page 29). The yaw damper response to the yaw rate experienced in the flight test is plotted as a long dashed line and is quite different for the two cases. The rudder deflection, estimated using kinematic extraction methods, is very close to the rudder deflection measured during the test conditions.

The above analysis will be further validated during the upcoming validation flight testing scheduled for late August 1998.

2.2.8 Human Factors Assessment

Crew Reports of Event

On the evening of June 9, 1996, the Eastwind Airlines 517 flight crew was engaged in casual conversation while descending under calm conditions into RIC. Without warning, the crew experienced a sudden, unusual yaw/roll upset to which the captain quickly responded with almost simultaneous wheel, rudder, and engine control inputs. They successfully controlled the airplane's attitude to within a bank angle of 13 degrees and restored the airplane to a stable flight path 13 seconds later. They then proceeded to land the airplane safely without serious injury to passengers or crew.

Despite the crew's successful resolution of the situation, their perceptions of the event as well as their reactions can offer potential insights into the cause. Consequently, the human factors analysis focused on the initial pilot report and the subsequent NTSB interviews with both flight crew members.

In order to understand the interview data, it is important to appreciate how one's memory of such an event may be affected by the situation, particularly the elements of surprise, fear, and sudden response. The flight crew was very relaxed at the time of the upset and surprised by its occurrence, as confirmed by the captain during the subsequent flight test. The pilot's immediate reaction, and his simultaneous use of every available control, is consistent with an instinctive corrective reaction based on the perception of an extreme, threatening event. The characterization of his response as "instinctive" also fits his citing of extensive turboprop experience to explain his quick but coordinated reaction to the event.

Pilots reacting instinctively and suddenly would not be expected to remember the exact direction, sequence, or extent of inputs they made, especially when asked several days or months after the event. Thus, it is not surprising that there are several inconsistencies in the crew's comments about their memory of the event. For example, the captain's description of the amount of rudder pedal movement is twice as large in the first interview (3 to 4 inches) as it is in the third interview (1 to 2 inches). Also, the captain attributes first noticing the event to an initial left rudder pedal "bump" during the first interview but to a sudden right yaw in the third interview. Then, in response to a question about retrimming the rudder after the event, he says they never touched the trim in the first interview, but in the third interview he says that he does not recall. These differences in recall may also be partially attributable to the fact that the captain participated in the flight test between the first and third interviews and that the interviews took place two years apart.

In addition, the crew's statements on airplane movement during the upset are not consistent with known data obtained from the flight data recorder. For example, the roll angle actually reversed during the event from about 12 degrees to the right to about 13 degrees to the left. Yet both members of the flight crew reported that the airplane remained in a 25 to 30 degree right bank during this period of time. All of these inconsistencies complicate any effort to rely substantially on the interview data to determine the cause of the event.

Flight Test Cockpit Voice Recorder

The flight test revealed several important facts that are relevant to understanding the human factors aspects of the crew's reaction to and reporting of this event. First, the Eastwind pilot remarked that he had relatively little experience on the 737 (about 800 hours). Second, he pointed out that he had complained about the rudder trim on this particular airplane as soon as he started flying it, and that the chief pilot reportedly reacted by expressing his belief that the airplane flew straight. Other evidence reveals that he continued to write-up the trim on this airplane. The pilot's concern about this issue was unique among his colleagues because he was the only one among 29 other crew members who raised this criticism. Finally, the Eastwind pilot emphasized on the cockpit voice recorder how he relied on the flying skills derived from his extensive turboprop experience. Hence, he shoved the right throttle forward immediately. His rapid input of substantial rudder when surprised by the first yaw damper hardover during the flight test is consistent with the turboprop habit patterns he cited during the testing and his relatively low amount of jet airplane flight time.

Historical data

The Human Factors Appendix to Boeing's Submission on the USAir Flight 427 accident documents several events where the flight crew's recollection of in-flight upsets and their responses to such upsets were not substantiated by the flight data recorder. Such crews were typically in a very relaxed state and quite surprised by the upset event. While crew report data must be taken into consideration in investigating such events, caution should be exercised to not place too much reliance on such data due to its subjective nature.

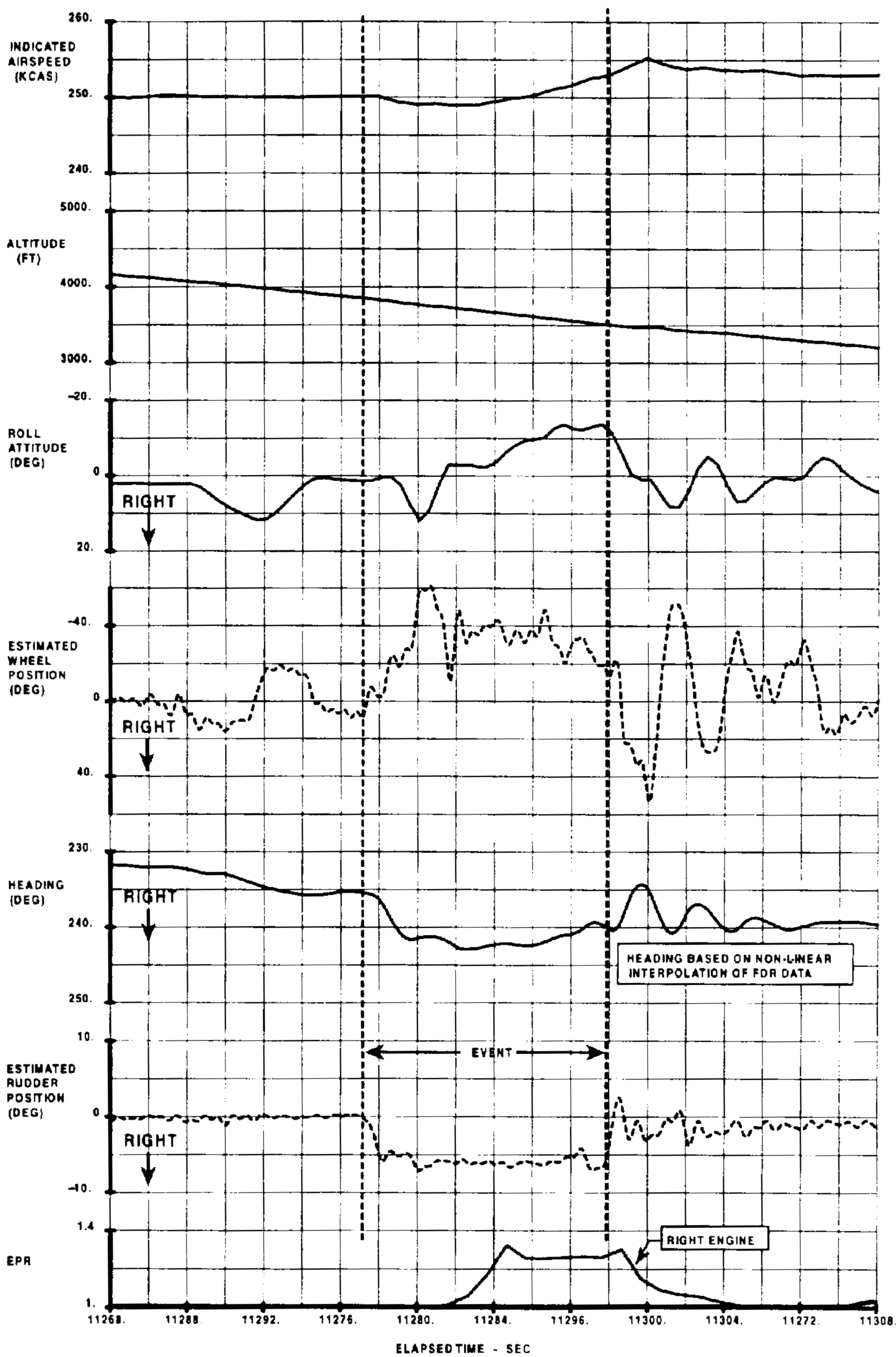


Figure 1

Time Histories of Pertinent Parameters

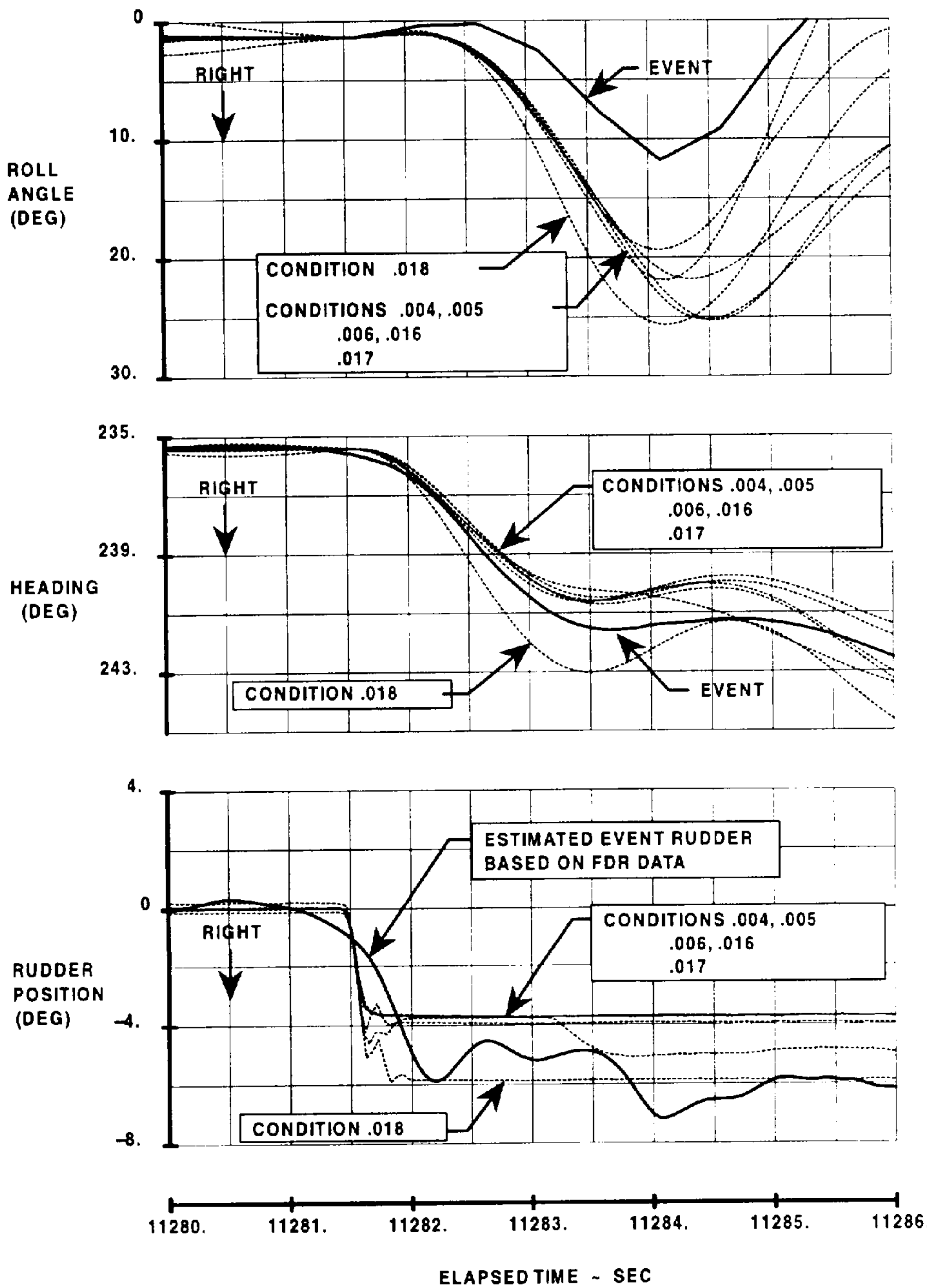


Figure 2

Comparison of Airplane Roll and Yaw Response for Eastwind Event Vs. Various Flight Test Rudder Steps

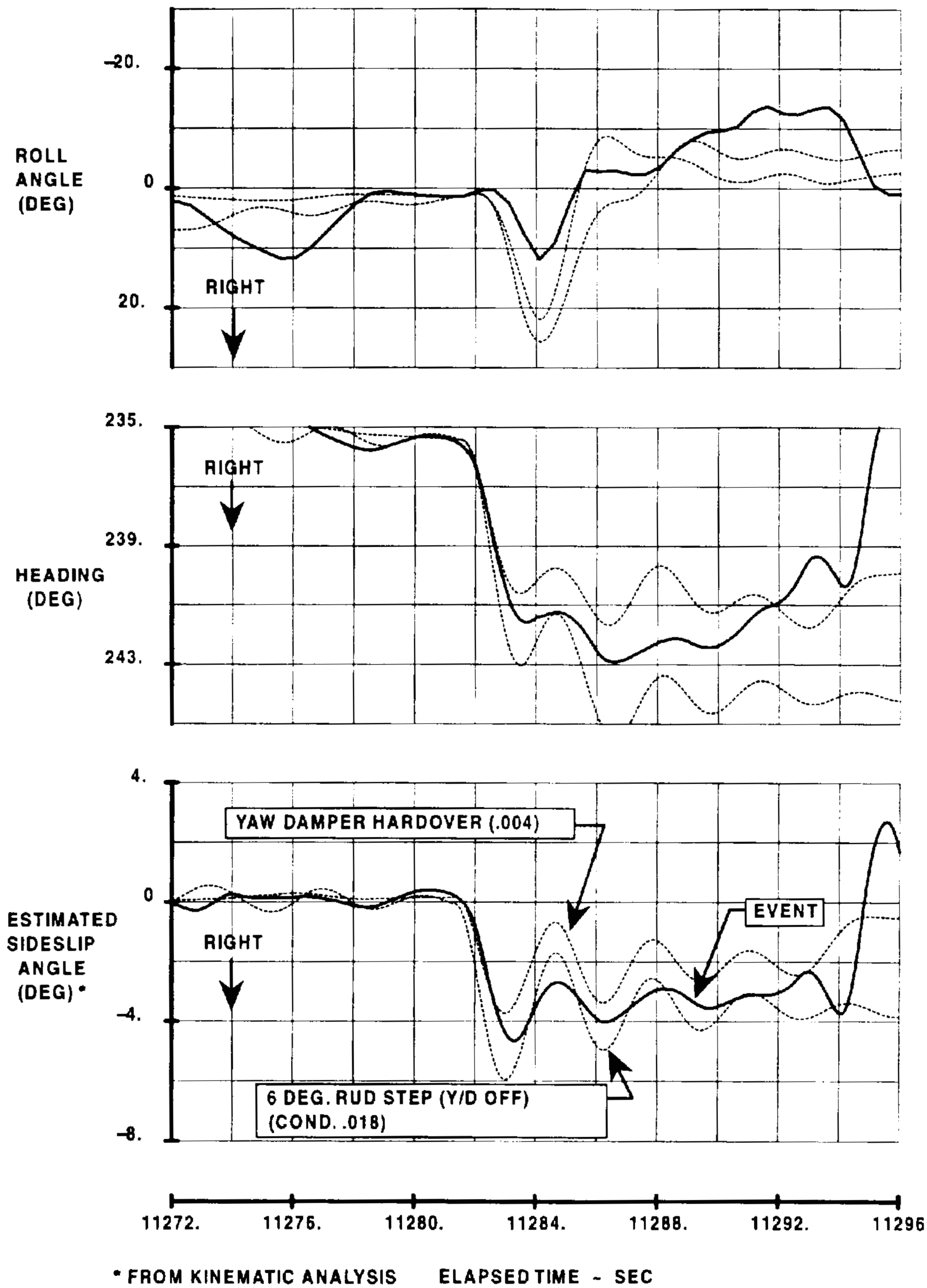


Figure 3

Comparison of Airplane Roll, Yaw and Sideslip Response for Eastwind Event Vs. Yaw-Damper-Off Flight Test Conditions.

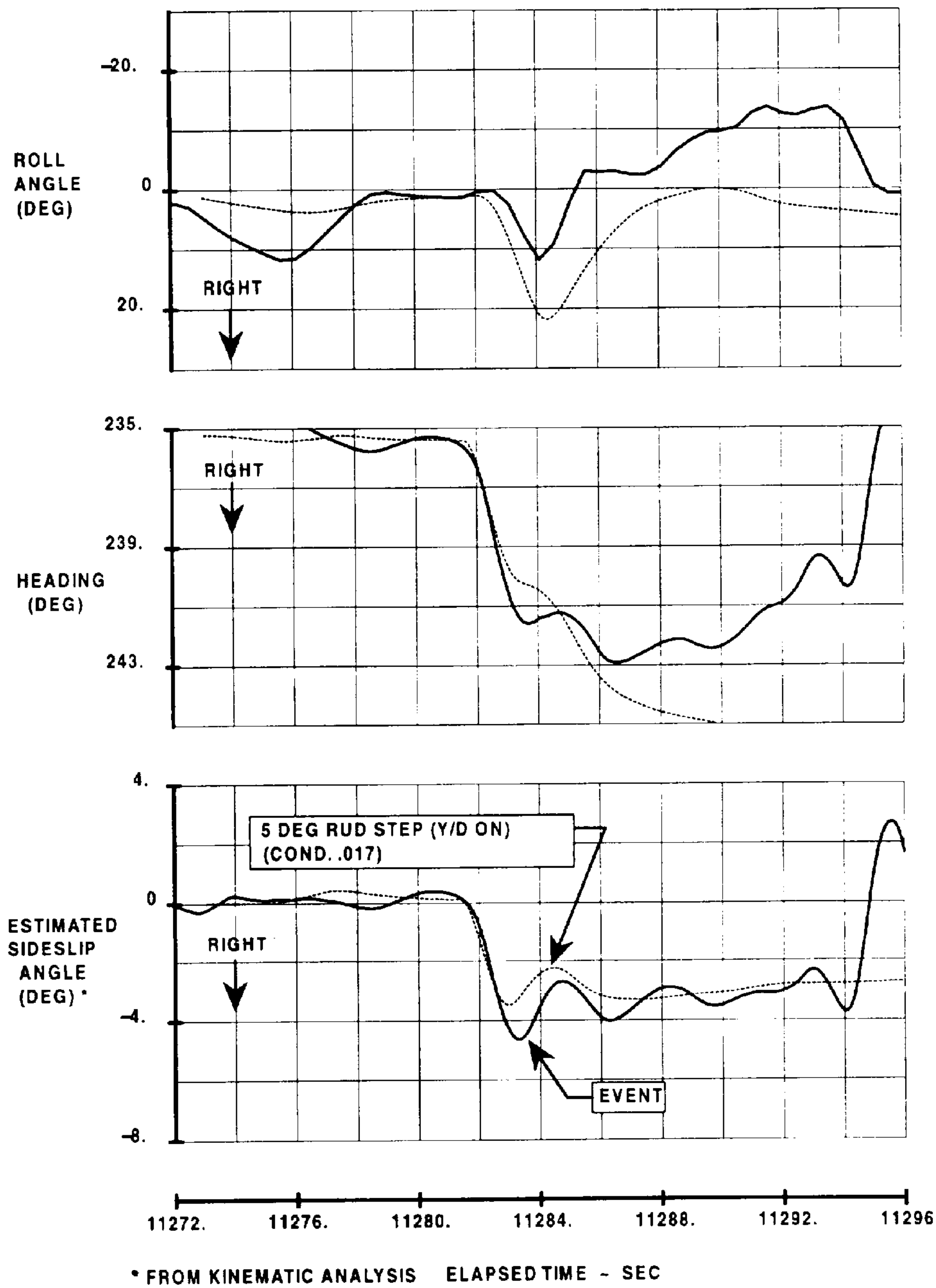


Figure 4

Comparison of Airplane Roll, Yaw and Sideslip Response for Eastwind Event Vs. Yaw-Damper-On Flight Test Condition

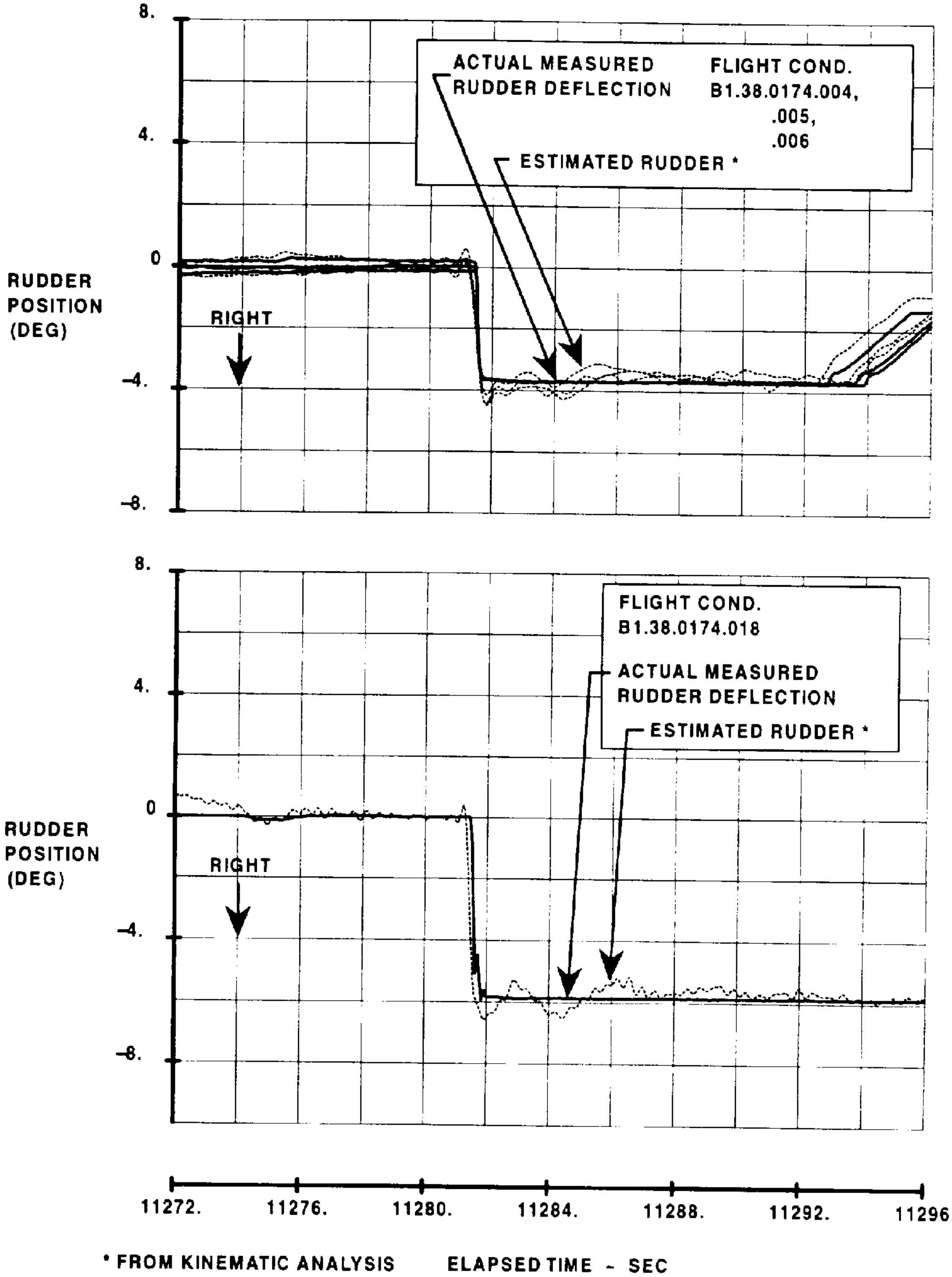


Figure 5

Validation of Estimated Rudder Position for a Series of Induced Y/D Hardovers and a 5.9 Deg Rud Step (Yaw Damper OFF)

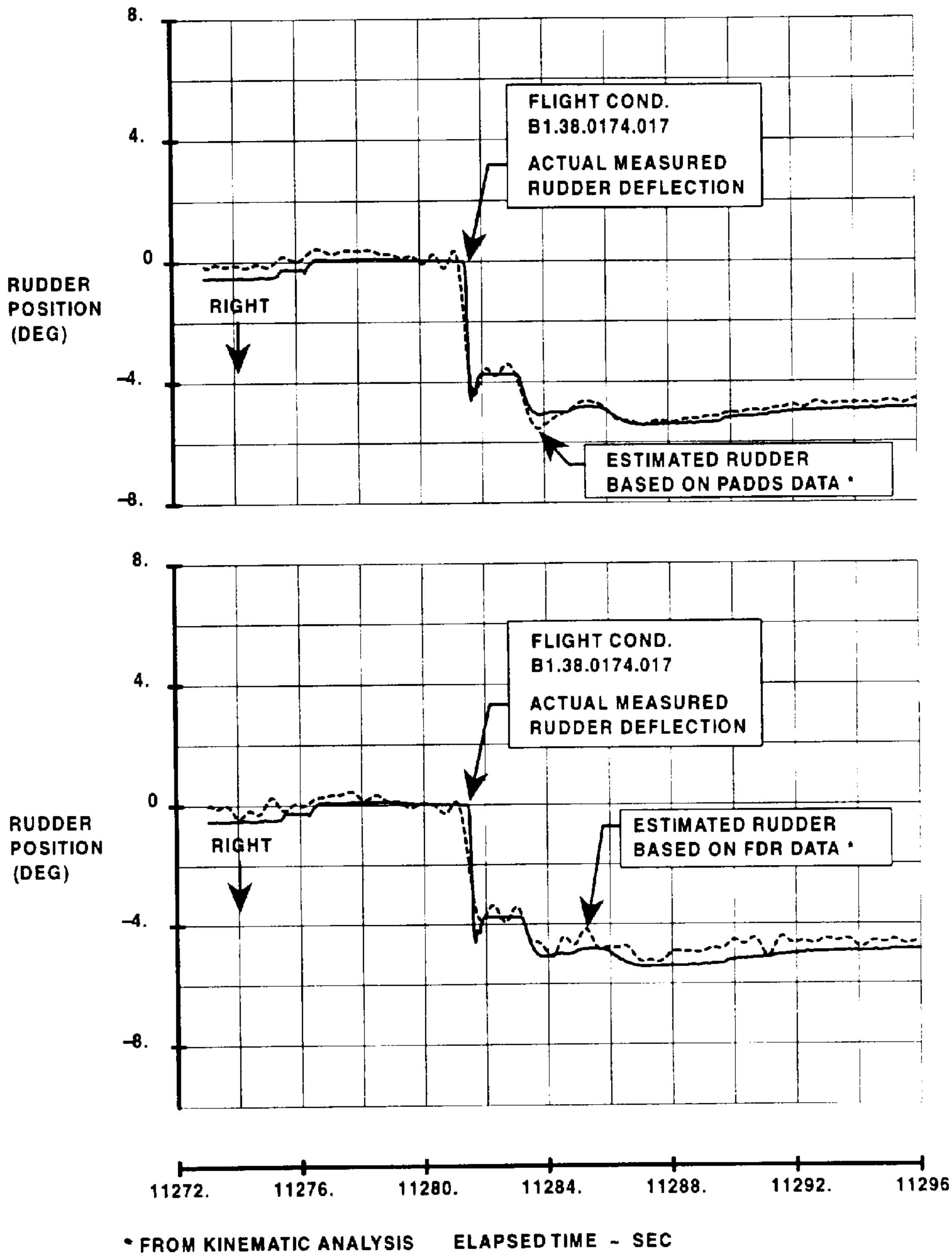


Figure 6

Validation of Estimated Rudder Position
for a 5 Degree Rudder Step (Y/D ON)
(FDR Data)

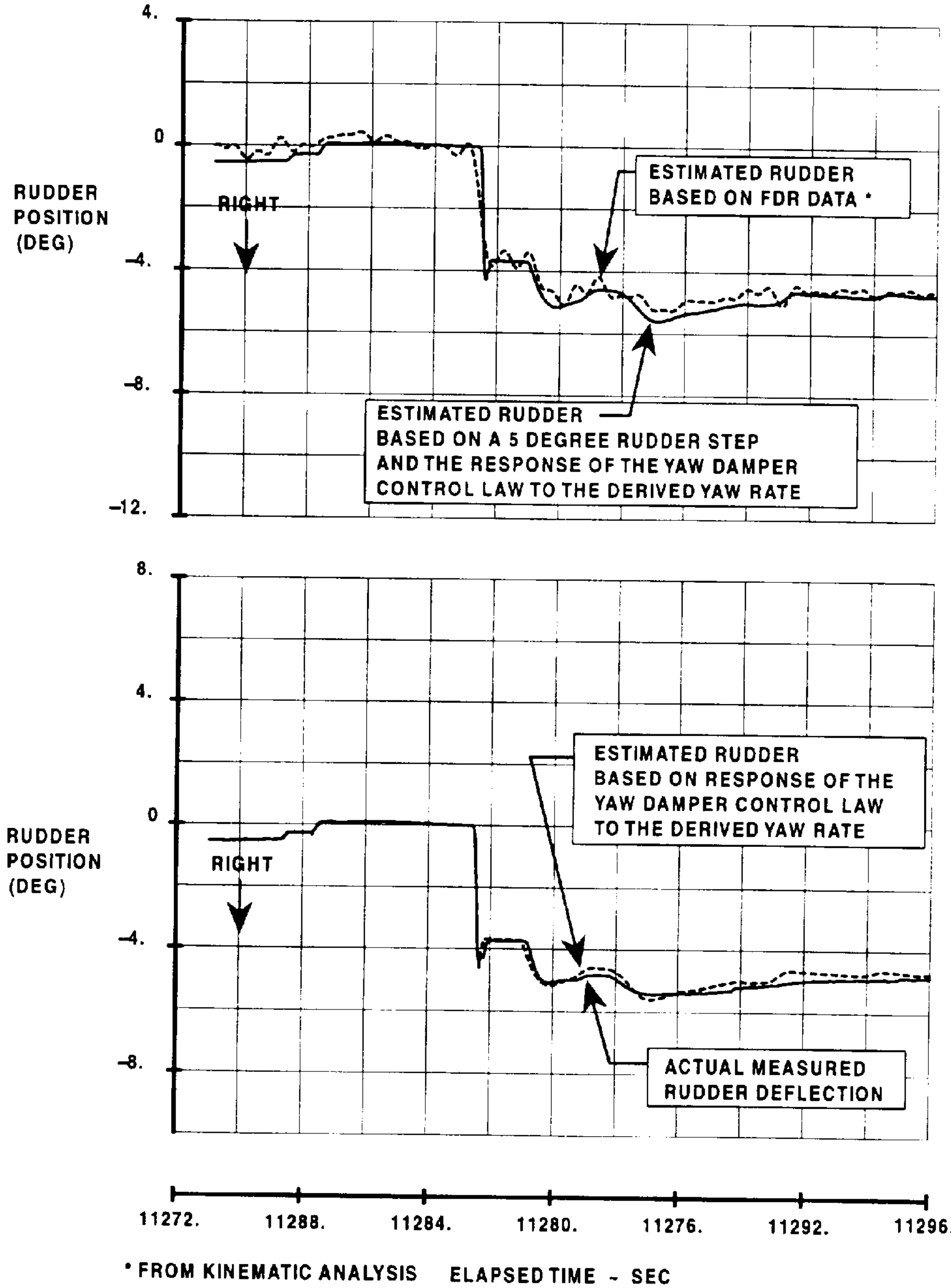


Figure 7

Validation of the Predicted Yaw Damper Response to a 5 Degree Rudder Step Input

S

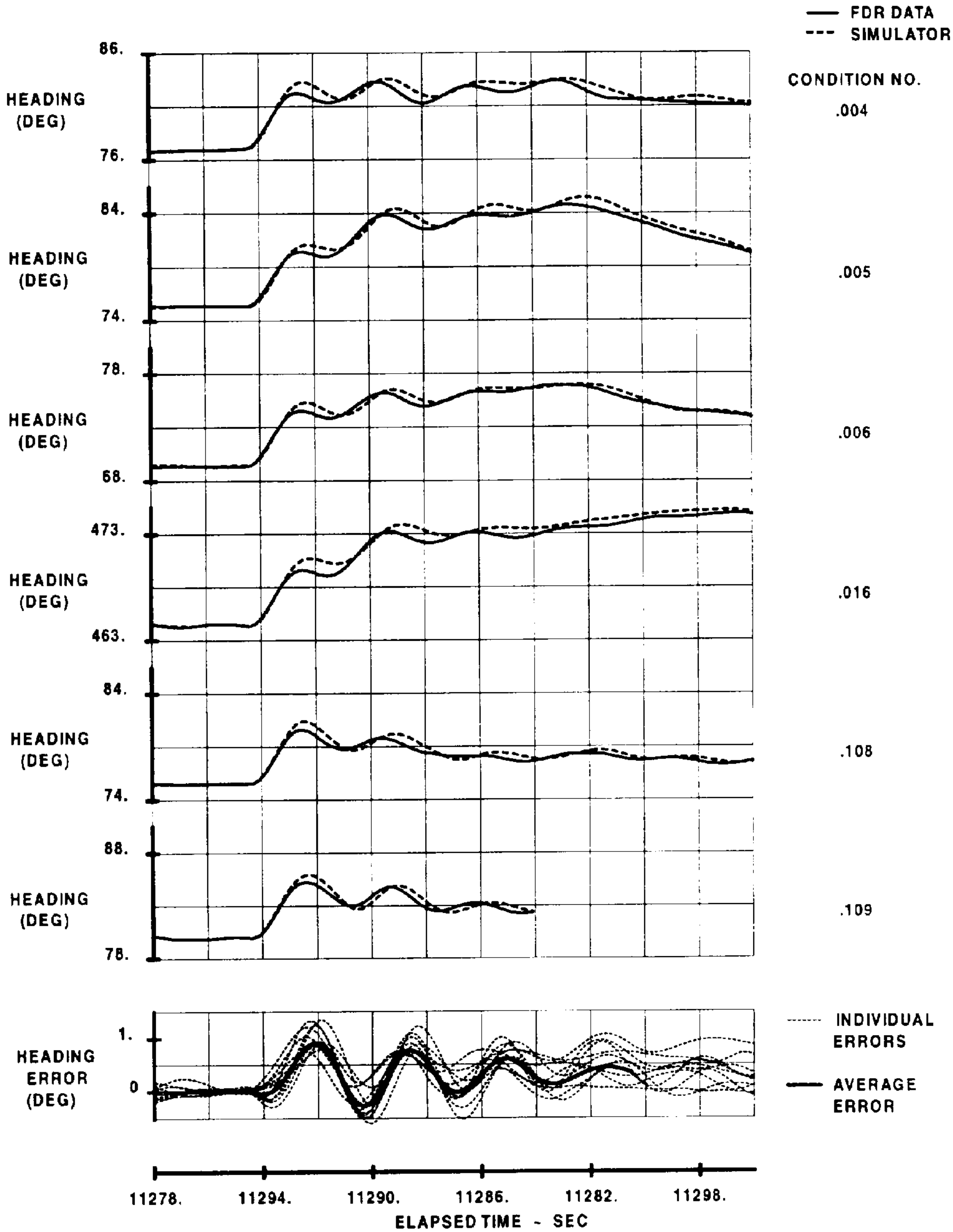
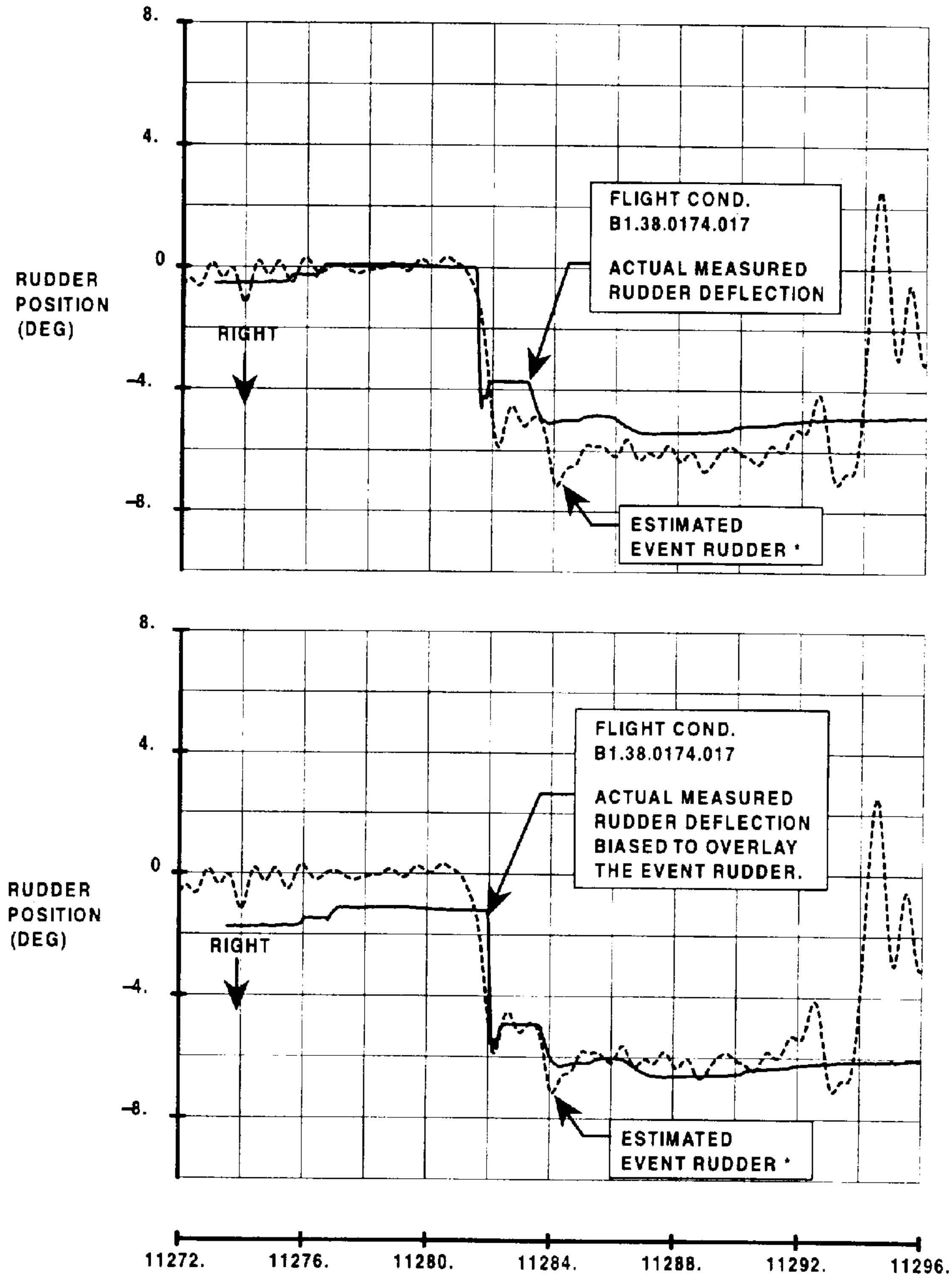


Figure 8

Open Loop Simulator Matches For Eastwind Flight Terst Conditions (Based on 737-200 Simulation)

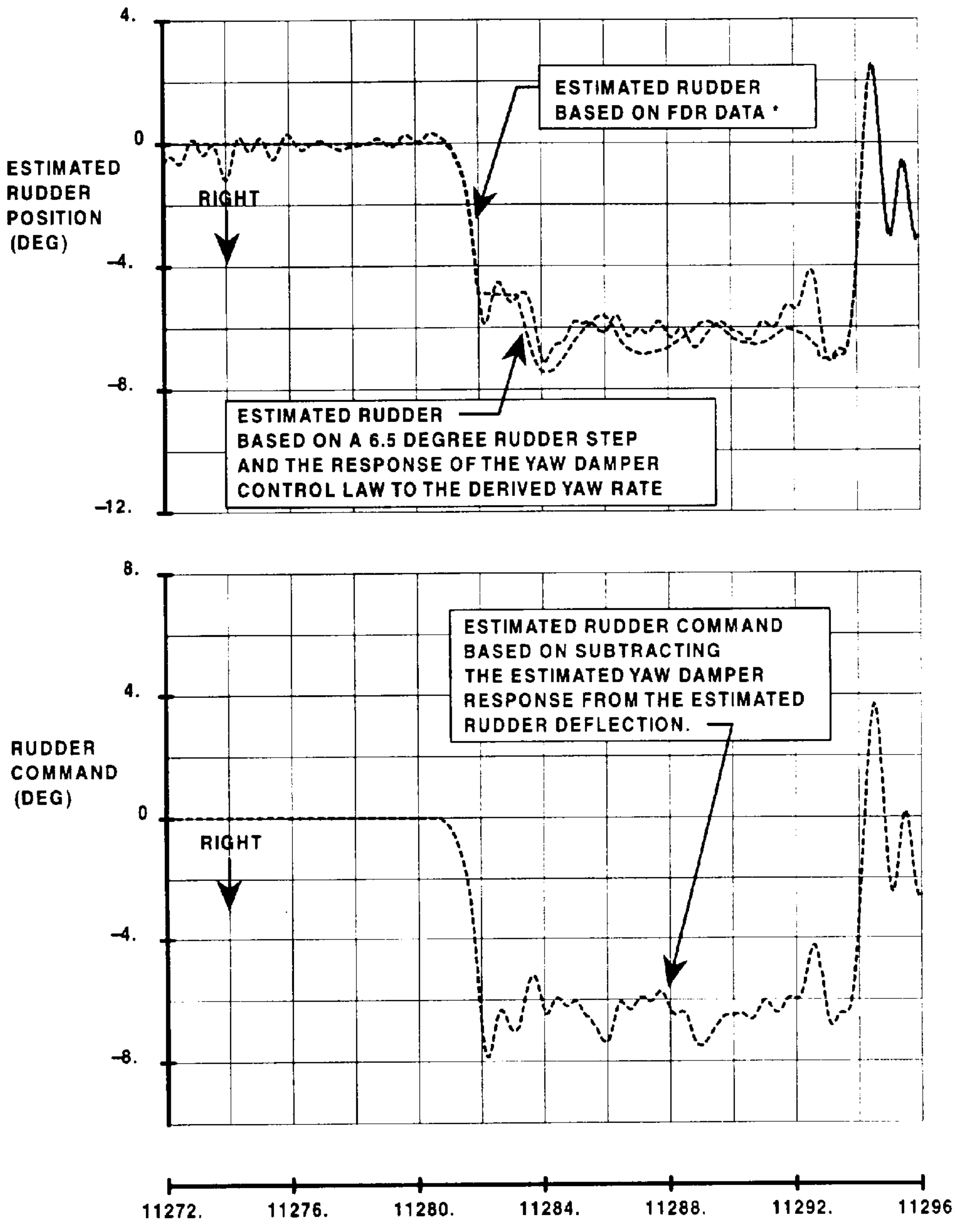


*FROM KINEMATIC ANALYSIS

ELAPSED TIME - SEC

Figure 9

Comparison of Eastwind Event Estimated Rudder and Wheel Vs. Flight Test Data for 5 Degree Rudder Step (Yaw Damper ON)



* FROM KINEMATIC ANALYSIS

Figure 10
Estimated Rudder, Yaw Damper Response and Rudder Command to Match the Eastwind Event

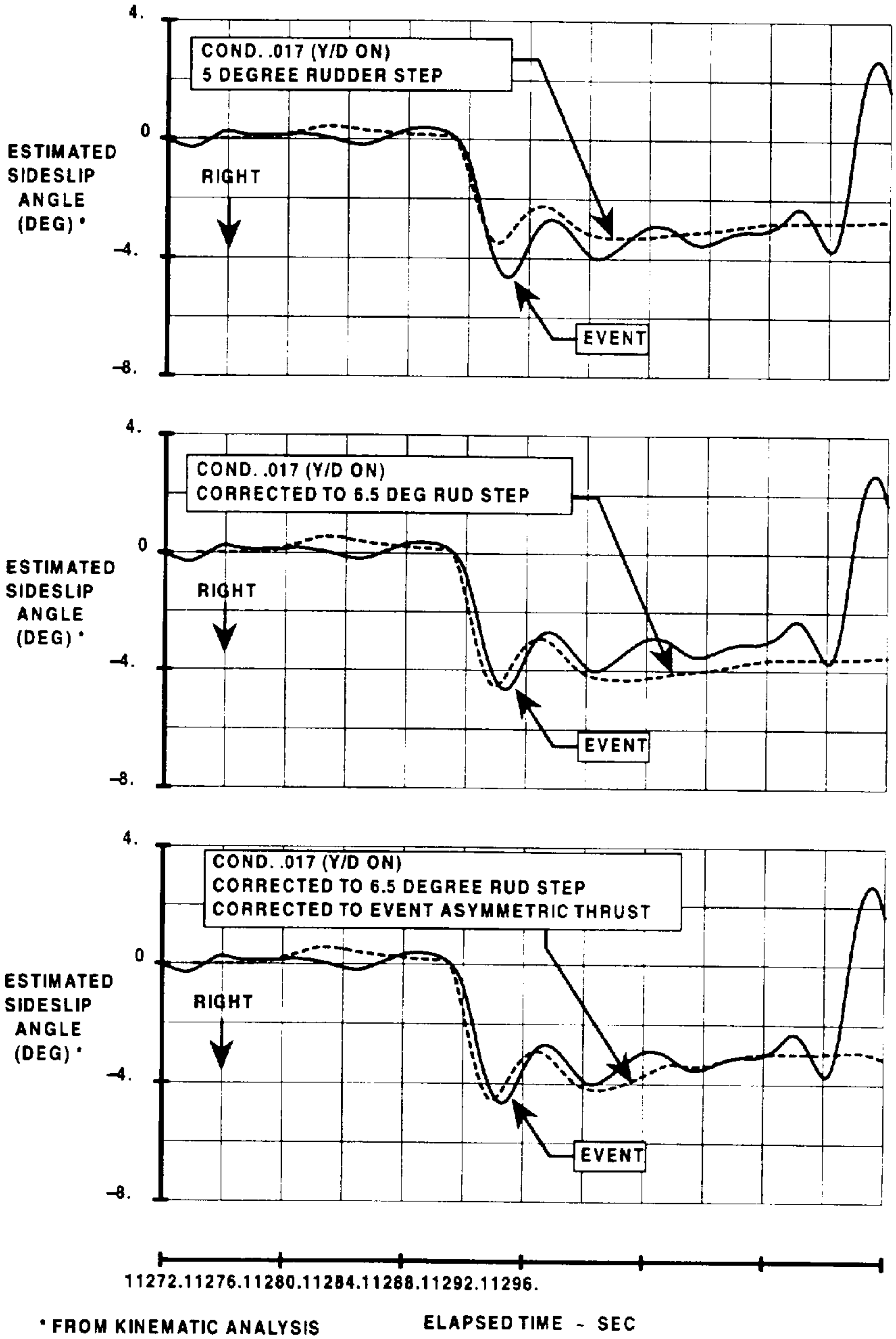


Figure 11

Comparison of Sideslip Response for Eastwind Event Vs. Yaw-Damper-ON Flight Test Condition (.017)

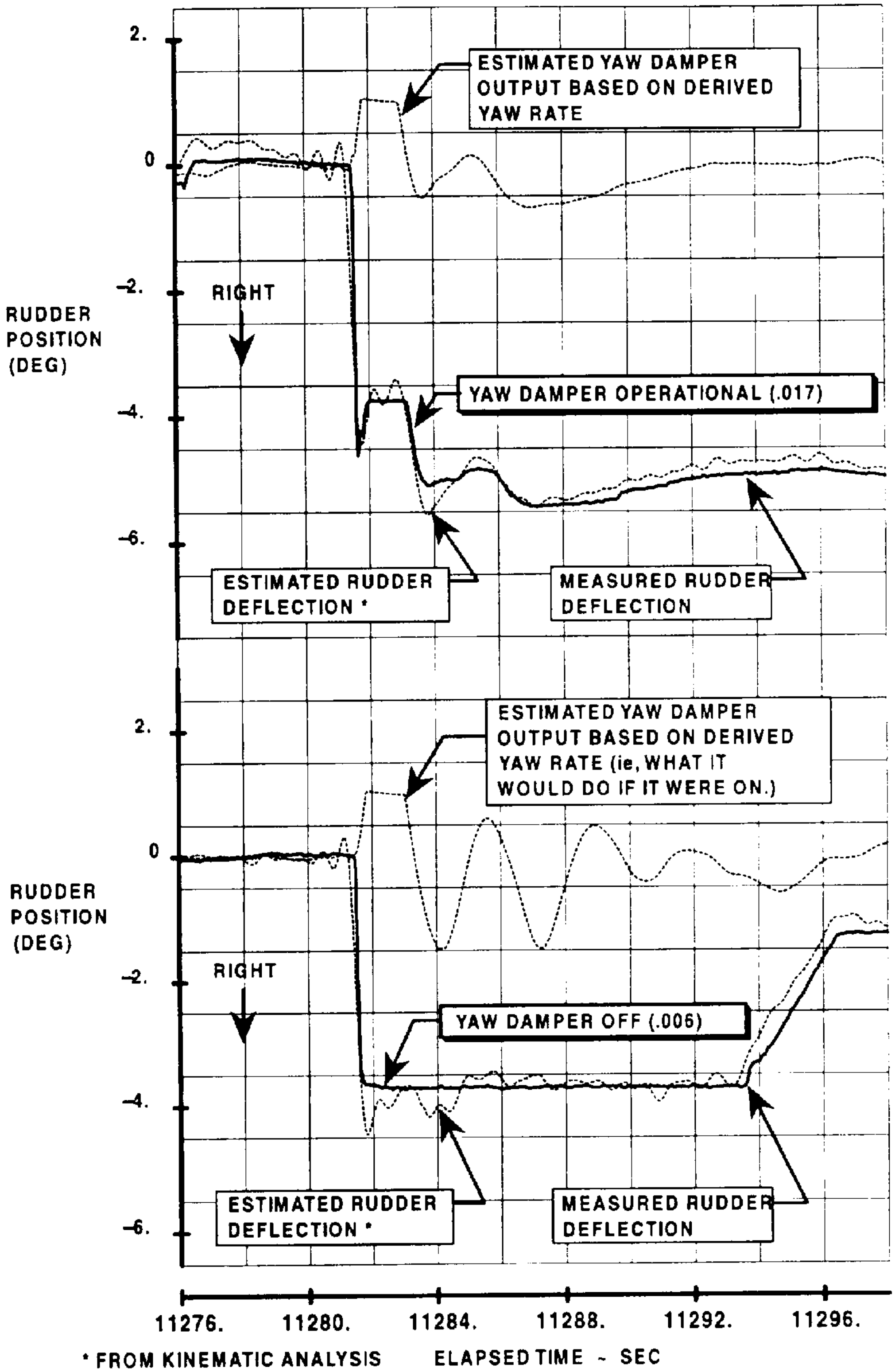


Figure 12

Comparison of Measured Rudder, Kinematically Predicted Rudder and Yaw Damper Response to Yaw Rate

2.3 Postulated Event Scenario Descriptions and Discussions

Of the many scenarios that might explain the Eastwind event, four are considered here as being more consistent with both the flight data recorder information and facts and statements from crew reports of the event. It should be noted that no scenario has been suggested that fits all the statements in the flight crew reports. The scenarios to be considered are listed below. Note that only Scenario 4 has the yaw damper operational following the original upset.

Table I

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Pre-event Condition	Y/D hardover to the left (not functioning) and rudder PCU operational	Y/D and rudder PCU operational	Y/D hardover to the left (not functioning) and rudder PCU operational	Y/D hardover to the right (not functioning) and rudder PCU operational
Event Initiation	Y/D goes hardover 5 degrees to the right	Y/D goes hardover 3.7 degrees to the right	Y/D goes hardover 5 degrees to the right	Y/D becomes operational moving 3.7 degrees to the left
Event	Pilot commands a small amount of additional rudder to the right	Pilot commands rudder to the left and rudder reverses because of a jam in the secondary valve slide	Pilot commands rudder to the left and rudder reverses because of a jam in the secondary valve slide	Pilot correctly commands rudder to the right but leaves rudder in
Post-event Condition	Y/D OFF and operational rudder PCU	Y/D OFF and operational rudder PCU	Y/D OFF and operational rudder PCU	Y/D OFF and operational rudder PCU

2.3.1 Scenario 1: Preexisting Left Yaw Damper Hardover With Subsequent Right Yaw Damper Hardover, Followed by a Small Nose-Right Pedal Input

- When the yaw damper is turned on, the rudder moves to 1.5 degrees left due to the linear variable differential transformer misrig.
- The rudder subsequently moves to 3 degrees left due to a hardover during the ground roll, requiring 3 degrees right trim to compensate.
- At ~11,281.2 seconds, another yaw damper fault produces a right rudder deflection of ~5 degrees (6 degrees commanded, minus the effects of structural compliance). The control wheel *simultaneously* (no pilot response time) begins moving to ~20 degrees left, resulting in a left roll in opposition to the right yaw.
- The pilot responds ~1.5 to 2 seconds later with a rudder pedal input to the right, while increasing control wheel to ~60 degrees left and advancing the right throttle to engine pressure ratio 1.3.

This scenario requires the pilot to react incorrectly to a nose-right yaw damper hardover with a right rudder pedal input. While a rudder and wheel can be calculated to match the corrected flight data recorder heading angle as shown in Figure 13 (page 35), this scenario does not match many of the pilot comments or known conditions for the event. Most significantly, the reported pedal input force should cause a very significant rudder deflection to the full blowdown limit. Rudder during the event did not reach the blowdown limit based on the flight test results and only went a couple degrees beyond the yaw damper authority limit. Also, an input in the same direction as the initiating upset would seem an unlikely pilot response.

Another problem with this scenario is that to match the small but distinct initial roll to the left, the wheel must be deflected to the left simultaneous with the initiating yaw damper hardover, which does not have a logical explanation.

2.3.2 Scenario 2: Right Yaw Damper Hardover With a Secondary-Valve Jam and Reversal

- When the yaw damper is turned on, the rudder moves to 1.5 degrees left due to the linear variable differential transformer misrig, requiring ~1.5 degrees right trim to compensate.
- The event is initiated by a yaw damper fault which produces a rudder deflection of ~3.7 degrees to the right at ~11,281.2 seconds. The control wheel *simultaneously* begins moving to ~20 degrees left, resulting in a left roll in opposition to the right yaw.
- The pilot responds ~1.5 to 2 seconds later with a rudder pedal input to the left, while increasing control wheel to ~60 degrees left and advancing right throttle to engine pressure ratio 1.3.
- Sufficient force is applied to the left pedal (~60 pounds) to overstroke the primary valve. The rudder reverses and moves to ~6 degrees right.

While this scenario matches certain pilot comments and is consistent with the expected rudder blowdown value, the rudder cannot move significantly once the reversal occurs, and it is not possible to get a good match with the corrected flight data recorder heading data as shown in Figure 14 (page 36). The reported rudder pedal deflection and pedal stiffness is also difficult to resolve with known system characteristics once the reversal occurs. In this scenario, the reversal causes the rudder to deflect further in the direction of the initial yaw damper hardover even though the pilot is pushing on the left pedal. This causes the left pedal to push back unrelentingly on the pilot's foot with little or no deflection in the direction of his initial input. This does not match the reported pedal deflection and would not likely be described as a "somewhat stiff" rudder. As in Scenario 1, the wheel required to match the small but distinct initial roll to the left requires an input to the left simultaneously with the initiating yaw damper hardover, which does not have a logical explanation.

2.3.3 Scenario 3: Preexisting Left Yaw Damper Hardover with Subsequent Right Yaw Damper Hardover, Plus a Secondary-Valve Jam and Reversal

- When the yaw damper is turned on, the rudder moves to 1.5 degrees left due to the linear variable differential transformer misrig.

- The rudder subsequently moves to 3 degrees left due to a hardover during the ground roll, requiring 3 degrees right trim to compensate.
- At ~11,281.2 seconds a yaw damper fault produces a right rudder deflection of ~5 degrees. The control wheel *simultaneously* begins moving to ~20 degrees left, resulting in an initial left roll.
- The pilot responds ~1.5 to 2 seconds later with a pedal input to the left, while increasing control wheel to ~60 degrees left and advancing right throttle to engine pressure ratio 1.3.
- Sufficient force is applied to the left pedal (~60 pounds) to overstroke the primary valve. The rudder reverses and moves to ~6 degrees right.

Recent in-service events where a yaw damper was hardover prior to takeoff and went hardover in the other direction in-flight suggest the plausibility of this scenario. This preexisting yaw damper hardover is not obvious to the crew if it occurs during the ground roll and may not be noticeable in-flight if turbulence is light.

This scenario matches certain pilot comments and is consistent with the expected rudder blowdown value. In this case it is possible to get a reasonable match with the corrected flight data recorder heading data because the initial rudder deflection due to the preexisting left yaw damper hardover is more consistent with the event upset as shown in Figure 15 (page 37). Again, however, the reported rudder pedal deflection and pedal stiffness is difficult to resolve with known system characteristics once the reversal occurs. As in Scenario 2, the reversal causes the rudder to deflect further in the direction of the initial yaw damper hardover even though the pilot is pushing on the left pedal. This causes the left pedal to push back unrelentingly on the pilot's foot with little or no deflection in the direction of his initial input. This does not match the reported pedal deflection and would not likely be described as a "somewhat stiff" rudder. Also, as in Scenarios 1 and 2, the wheel required to match the small but distinct initial roll to the left requires an input to the left simultaneous with the initiating yaw damper hardover, which does not have a logical explanation.

2.3.4 Scenario 4: Preexisting Right Yaw Damper Hardover, Subsequently Operational, Followed by Right Pedal Input

- When the yaw damper is turned on, the rudder moves to 1.5 degrees left due to the linear variable differential transformer misrig.
- The rudder subsequently moves to 3 degrees right due to a yaw damper fault during the ground roll, requiring 3 degrees left trim to compensate.
- At ~11,281.2 seconds, the yaw damper fault clears itself, causing the rudder to move suddenly to the left ~3.7 degrees due to the previous left-trim input combined with the misrigging of the linear variable differential transformer.
- The pilot responds correctly with right pedal, commanding the rudder to about 6 degrees right, which causes the airplane to yaw back to the right. The pedal input is maintained to the right and the yaw damper responds appropriately.

- Control wheel is input ~25 degrees to the left about one second after the rudder input, then increases to ~60 degrees left at about the same time the right throttle is advanced to an engine pressure ratio of 1.3. The indication that the yaw damper may have been working properly during the Eastwind event and the previously mentioned in-service event where a yaw damper was hardover prior to takeoff led to this scenario. In this scenario, a yaw damper fault that occurred during the ground roll corrected itself at the initiation of the event.

This scenario matches certain pilot comments and known conditions related to the event. The airplane rolls to the left during the initiation of the event and matches the heading very closely as shown in Figure 16 (page 38). This scenario correlates with the reported nearly simultaneous input of rudder and wheel during the recovery. Rudder pedal deflection would be much closer to the reported 3 to 4 inches, since the pilot would have to overcome a yaw damper hardover to the left as well as put in enough rudder to the right to cause the roll to the right. This usage of a significant rudder input to recover from the initial upset is consistent with the manner in which the pilot used rudder to recover from an unexpected upset created during the flight testing. The stiff rudder comment may have been caused by the lack of expected airplane response to the significant rudder pedal input made by the pilot. The only significant discrepancy with the pilot report is the direction of his pedal command and his report that there was no yaw to the left.

The following additional analyses support this scenario:

- A free response to a hardover to the left is shown in Figure 17 (page 39). This shows in more detail the simulator roll and heading compared to the flight data recorder event data, demonstrating that yaw damper hardover and recovery proposed in Scenario 4 does match the flight data recorder information.
- Figure 18 (page 40) shows the rudder commanded by the Eastwind captain during the post-event flight test compared to the rudder required during the event for Scenario 4. Note that he responded to a hardover of the same magnitude as Scenario 4 with an equivalent rudder input.

2.3.5 Scenario Discussion Summary

A comparison of these four scenarios has been made based on a free response to the theorized control inputs. The errors that result when the corrected flight data recorder heading is subtracted from the heading calculated for the four preceding scenarios are shown in Figure 19 (page 41). These data show that several of the scenarios result in relatively small heading errors.

As shown in Table II, Scenario 4 appears to match more of the crew comments and known airplane conditions than the other scenarios considered. The estimated rudder and wheel for this scenario are shown in Figure 20 (page 42) along with the flight data recorder parameters. The heading trace shown in this figure has been adjusted so that it shows a movement to the left while still going through all the original flight data recorder data points.

Table II

Pro | Con

Pilot Comment/ Known Condition ⇓	**SCENARIO 1** Preexisting left Y/D H/O followed by a nose-right pedal input	**SCENARIO 2** NTSB—right Y/D H/O with a secondary valve jam and reversal	**SCENARIO 3** Preexisting left Y/D H/O, subsequent right Y/D H/O, secondary valve jam and reversal	**SCENARIO 4** Preexisting right Y/D H/O, subsequently operational, followed by right pedal input
Is the recorded roll to left apparent?	Yes, but unreasonable wheel required	Yes, but unreasonable wheel required	Yes, but unreasonable wheel required	Yes, roll agrees with the FDR
Is there a reasonable match with recorded heading?	Yes	No	Yes	Yes
Does the rudder go to the expected blowdown value?	No	Yes, given an assumed secondary valve slide jam	Yes, given an assumed secondary valve slide jam	N/A
Is the pilot input of rudder and wheel nearly simultaneous as reported?	No	No	No	Yes
Does the nose go right as reported?	Yes	Yes	Yes	Yes
Does the pedal go left as reported?	No	Yes	Yes	No
Does the pedal deflect 3–4 in as reported?	No	No	No	Yes
Is there an initial yaw to left (pilot reported no yaw to the left)?	No	No	No	Yes
Would the rudder feel somewhat stiff as reported?	No, normal force to get small rudder deflection	No, distinct pedal pushback and very high forces to deflect pedal	No, distinct pedal pushback and very high forces to deflect pedal	Possibly, since normal forces don't result in expected airplane response
Would there be little trim change before or after event as reported?	No	No	No	No

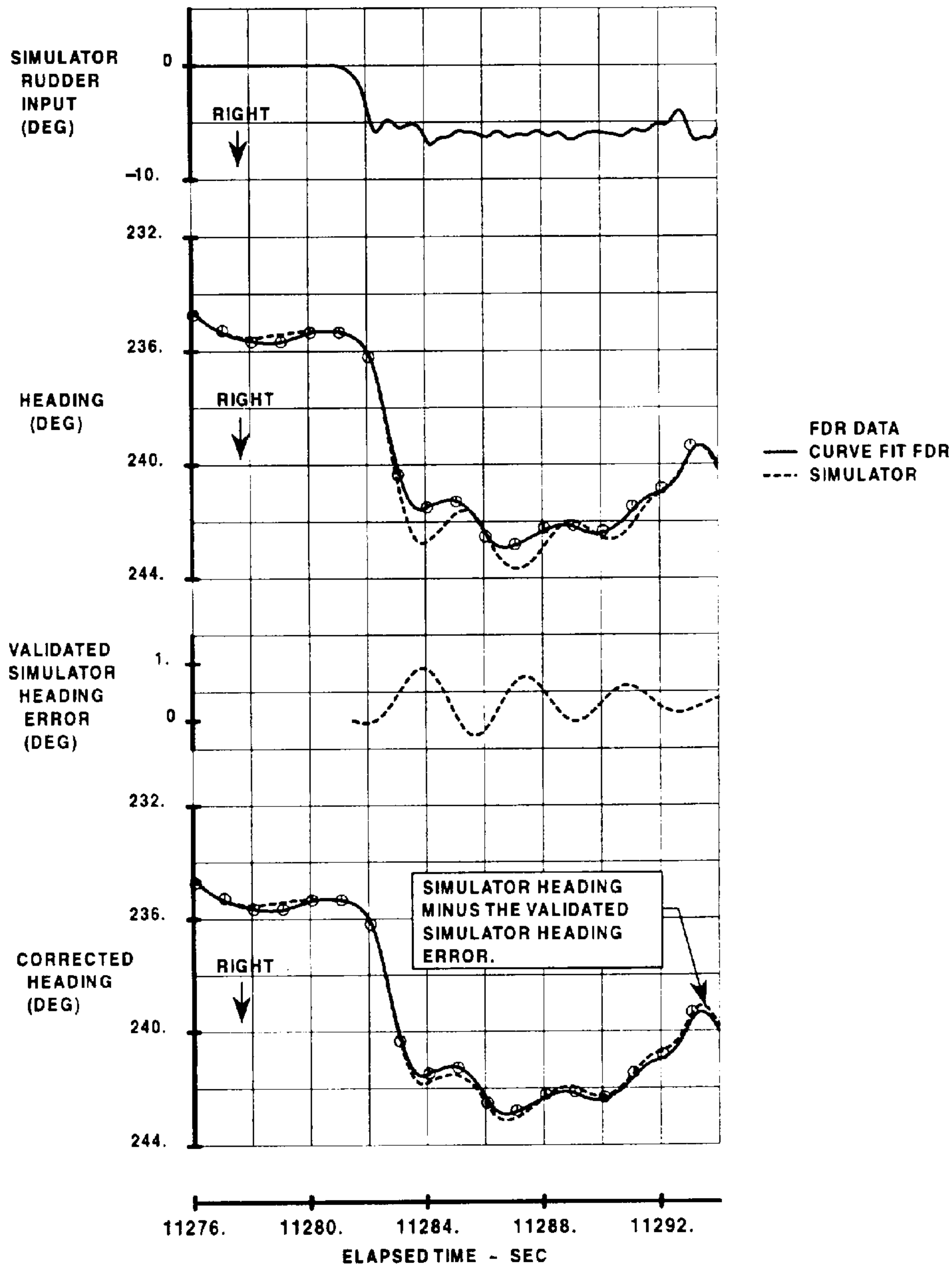


Figure 13

Open-Loop Match For Eastwind Event
Y/D 6 Degree H/O, Pilot Input to Right
(Based on 737-200 Simulation)

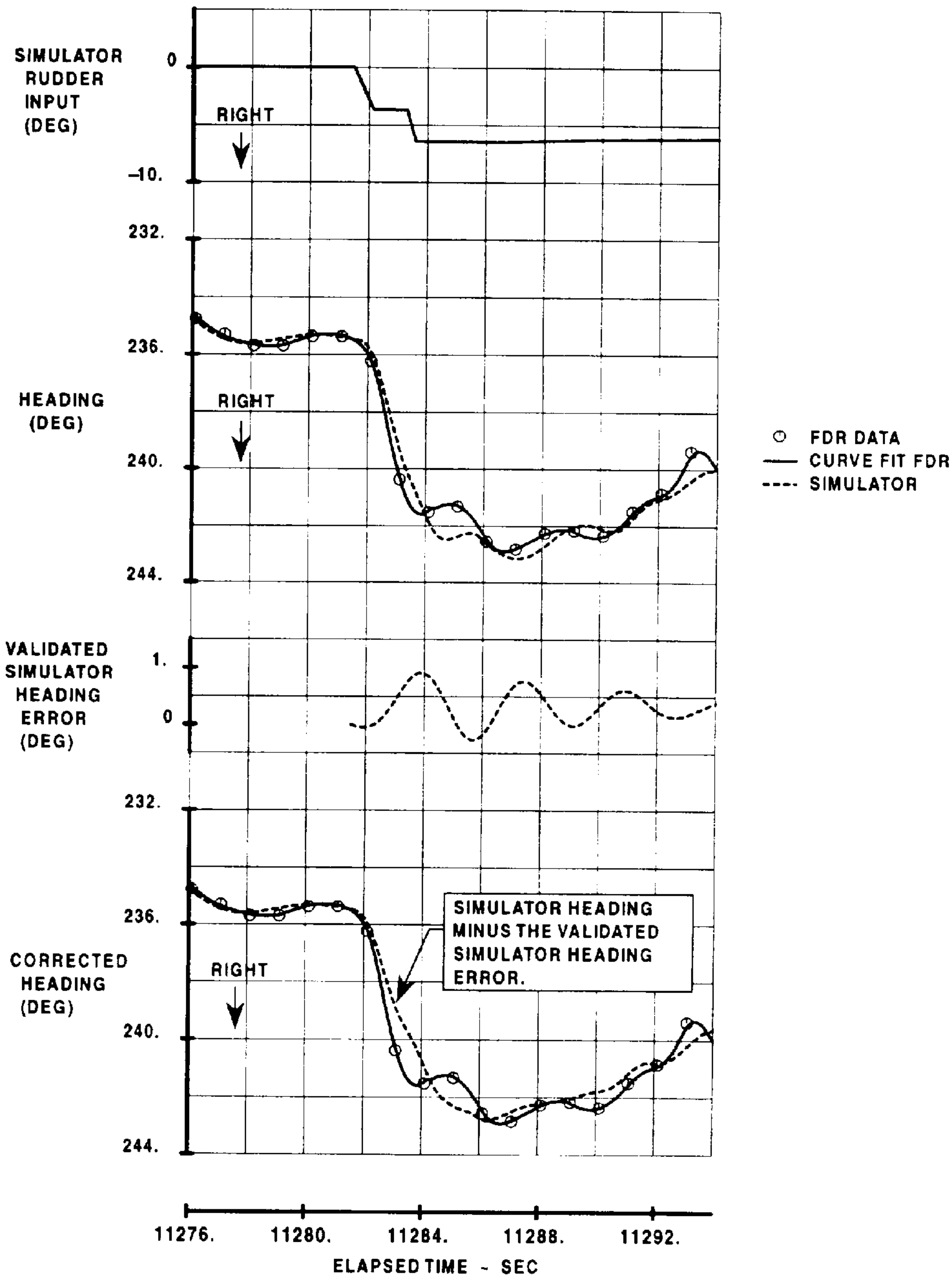


Figure 14

Open-Loop Match For Eastwind Event
Yaw Damper Hardover / 43% Jam / Reversal
(Based on 737-200 Simulation)

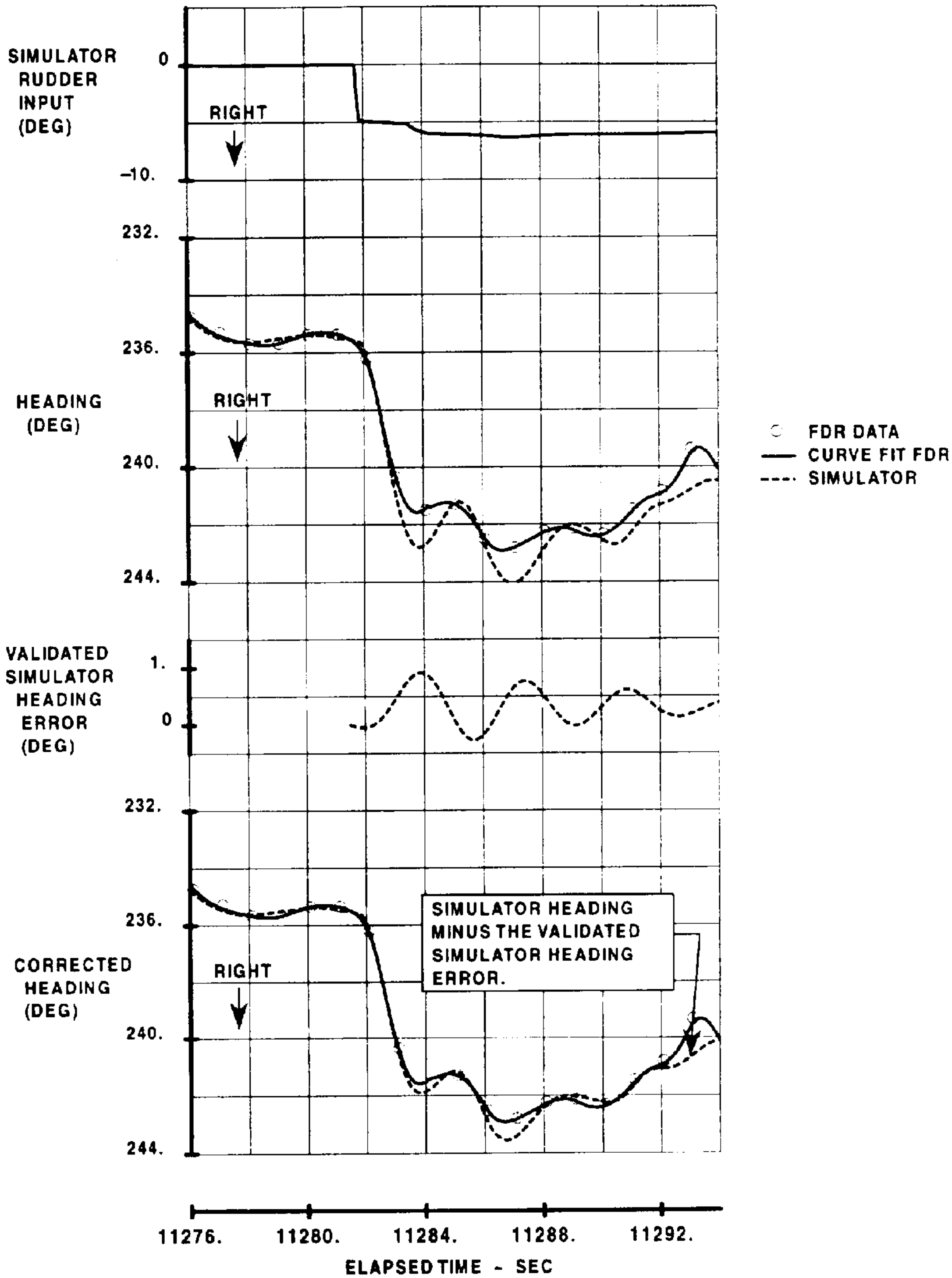


Figure 15

Open-Loop Match For Eastwind Event
Double Y/D Hardover / 39% Jam / Reversal
(Based on 737-200 Simulation)

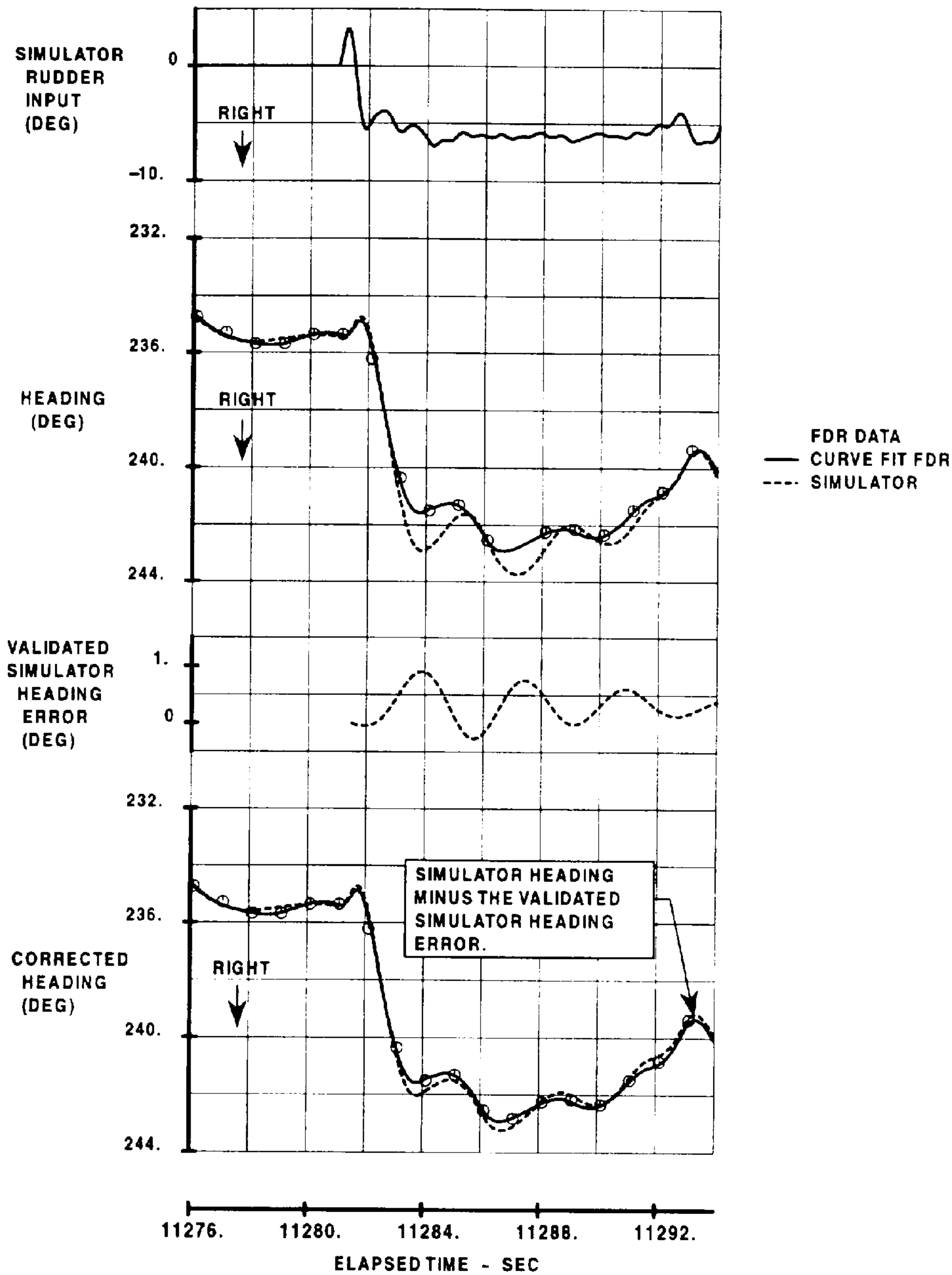


FIGURE 16

Open-Loop Match For Eastwind Event
Y/D H/O Release, Pedal Step, Y/D Working
(Based on 737-200 Simulation)

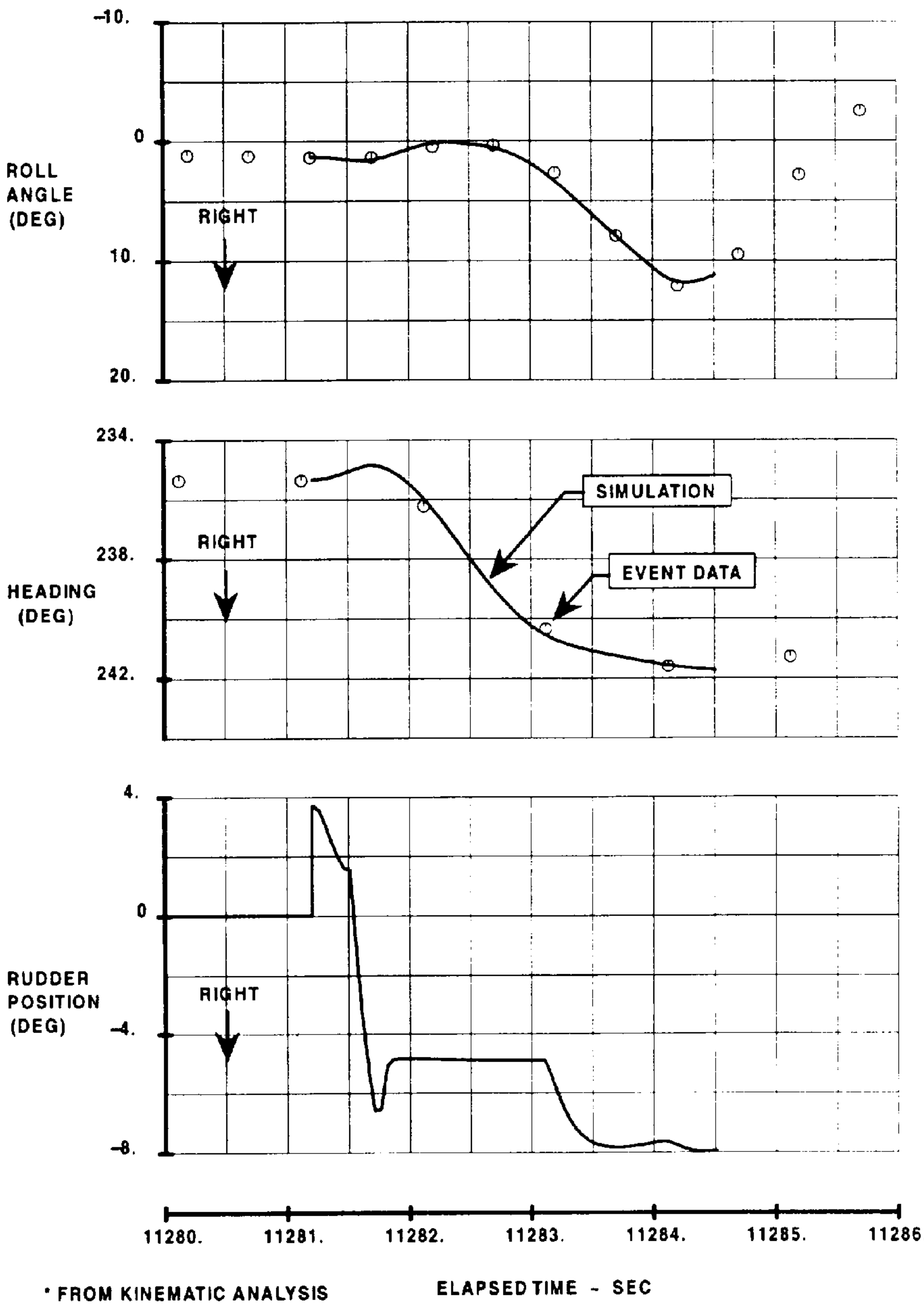


FIGURE 17
Comparison of Airplane Response for the Eastwind Event Vs. Simulated Y/D Hardover-Release

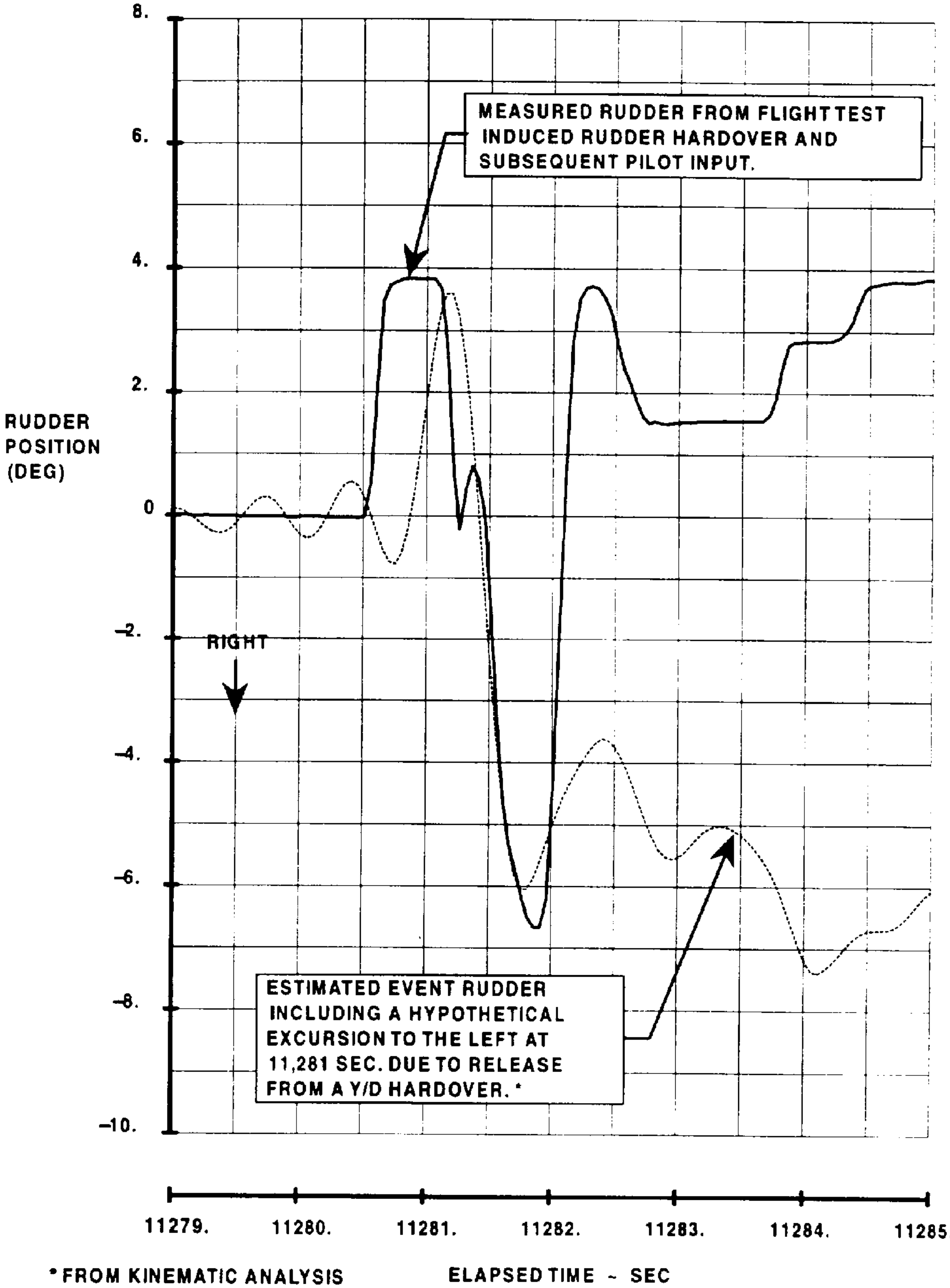


Figure 18

Comparison of Predicted Rudder vs. Flight Test Rudder Data From an Induced Y/D Hardover and Subsequent Pilot Input

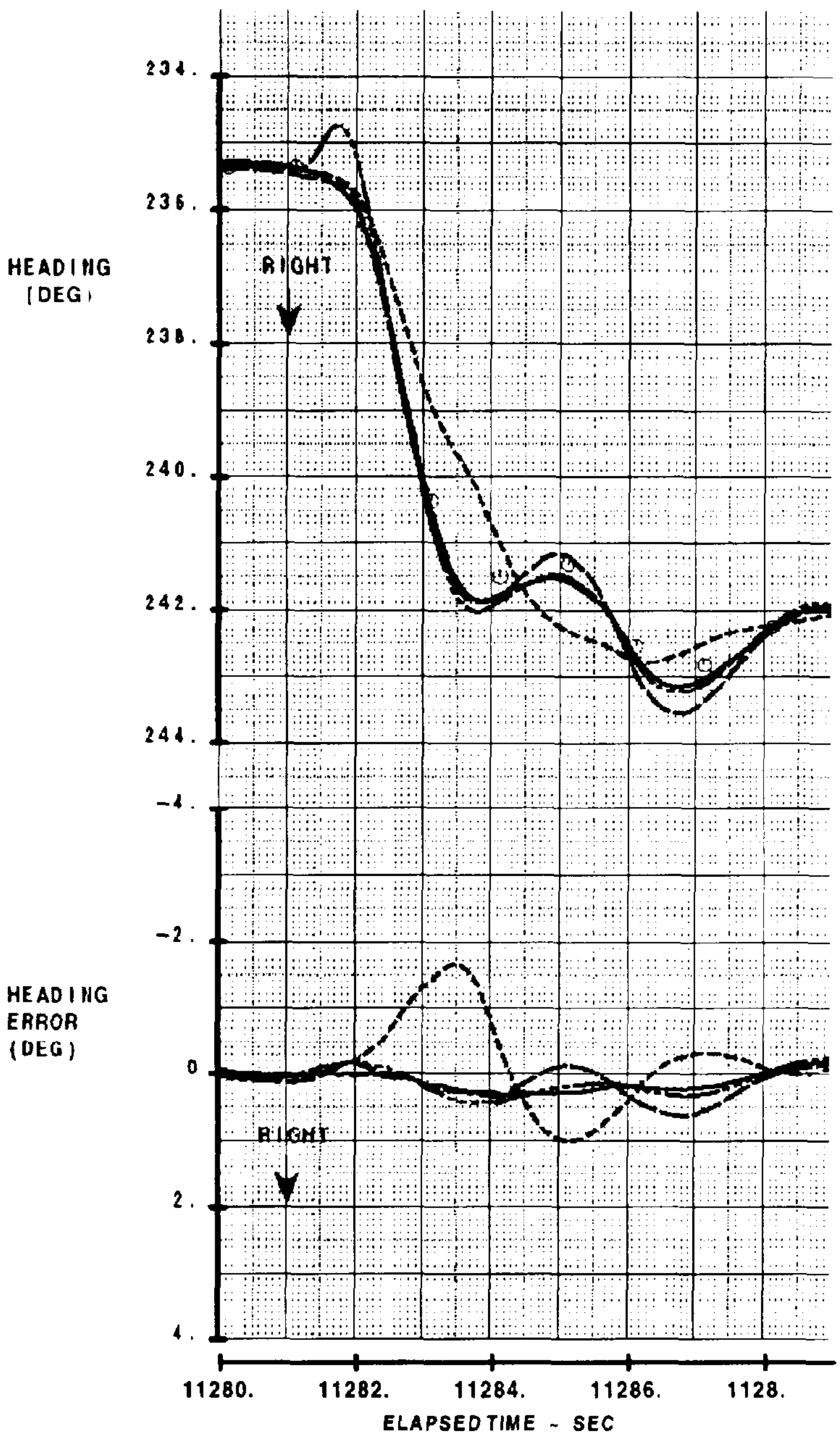


Figure 19

Comparison of Heading Errors for The Various Open Loop Matches (Based on 737-200 Simulation)

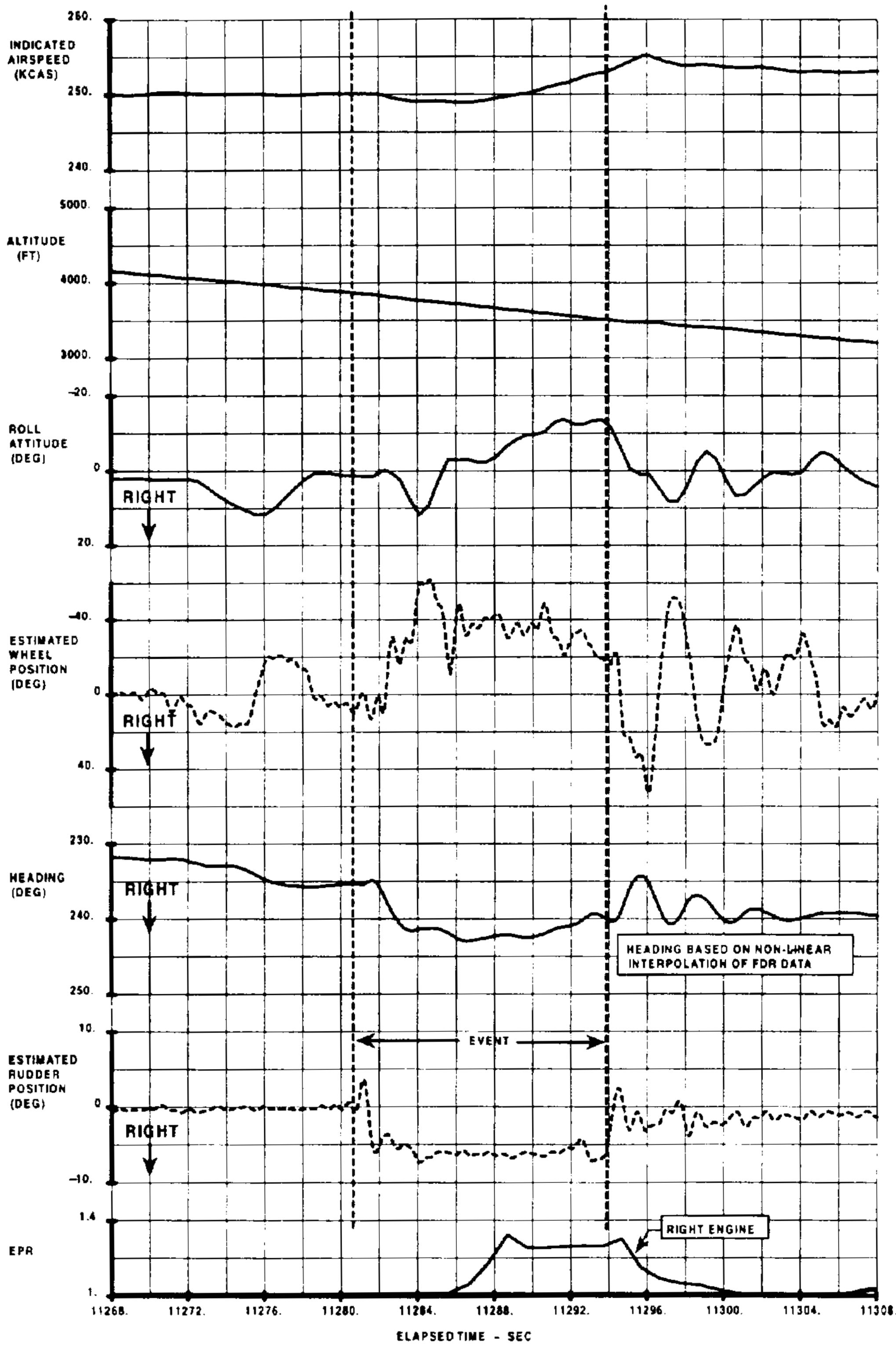


Figure 20

Estimated Control Wheel and Rudder for Eastwind Airlines Yaw/Roll Event June 9, 1996 (Assuming Initial Left Yaw)

2.4 Postulated Airplane Faults

The NTSB led an exhaustive investigation into the 737 rudder system as part of the USAir Flight 427 accident investigation. A systematic study was conducted of failure modes that could produce rudder jams, hardovers, or reversals. Pursued over several years, this intensive investigation revealed that in a laboratory setting in which unrealistic thermal conditions are introduced to a rudder power control unit, a failure effect can occur that may result in a rudder deflection opposite to the direction commanded by the pilot through the rudder pedals. There is no documented case of this reversal condition ever occurring on a 737 airplane in actual operating conditions.

Such a failure effect could only occur if the secondary slide of the rudder power control unit servo valve jammed and was followed by a high-rate or full rudder command from the pilot through the pedals. Pedal forces during this type of failure should be easily recognized by the pilot because of the unrelenting nature of the pushback on the pedals. A hypothetical failure of this nature would not allow the 3 to 4, or even the 1 to 2, inches of left pedal deflection reported by the Eastwind captain in his interviews without an excessive amount of pedal force being applied.

The Eastwind rudder power control unit has been carefully investigated and no evidence of a secondary valve jam was found. There are no investigation findings to suggest that a chip, silting, corrosion, or any other contaminant contributed to anomalous operation of the power control unit.

Three of the scenarios that are being considered involve a preexisting yaw damper fault to the left or to the right followed by subsequent yaw damper activity or a yaw damper fault in the opposite direction. These types of failures have been reported by other operators in the past. The recorded flight data recorder information is insufficient to determine which of these failures occurred. The flight data recorder information does not record rudder deflection, yaw damper command, or rudder pedal inputs. We can only infer these parameters from the recorded data.

An analysis of the yaw damper coupler has been made for the purpose of determining failure modes that could help explain the postulated scenarios. For the purposes of this analysis Scenario 4 was viewed as the likely candidate. In this scenario:

1. The yaw damper goes hardover to the right (about 3 degrees) on the ground and becomes inoperative.
2. After takeoff, the pilot trims out the rudder offset.
3. At some later time during flight, the yaw damper suddenly becomes operative, giving a rudder kick to the left, followed by active damping.
4. The fault returns and the yaw damper again goes hardover to the right.

The analysis simply looked for failures within the yaw damper coupler that could cause an intermittent hardover such that the airplane could take off with a yaw damper hardover, then at some later stage the yaw damper become functional. The yaw damper coupler does exhibit single failures that could explain the anomalies seen in the Eastwind event. There are known and documented yaw damper failure modes that can produce the intermittent-type failure postulated in Scenario 4. These failure modes initially involve an open-circuit-type failure often caused by dry solder joints. Frequently, intermittent failures of this nature result in a statement of "no fault found" when the yaw damper coupler is returned to the factory for testing.

2.5 Boeing Conclusions

It is clear that rudder movement was the cause of the upset in the Eastwind event. However, the events that led to the rudder deflection are not so clear.

1. Multiple scenarios have been identified that match at least some of the data and crew reports from the Eastwind 517 event. None of the scenarios fully match all the data, kinematic analysis, and crew reports.
2. The NTSB has recognized that a theoretical explanation for an accident/incident can only be elevated to the "probable cause" of the accident/incident when there is "conclusive" and "decisive" evidence to support that explanation. In Boeing's view, under the standards developed by the NTSB, there is insufficient evidence to reach a conclusion as to the probable cause of the rudder deflection. The following factors are significant to reaching this conclusion.
   - No data indicates that a rudder power control unit failure occurred during the event sequence. To the contrary, the event and flight test data indicate that the yaw damper *was functioning* as the event progressed. If so, a rudder reversal could not have occurred because the yaw damper system cannot affect rudder position during a rudder reversal. (See Section 2.2.7)
   - The extremely cold environmental conditions and hydraulic system failure necessary for a thermally produced secondary slide jam were not present on Eastwind Flight 517. (See Section 2.4)
   - Inspection results of the power control unit servo valve showed no physical indications of jams to the primary or secondary slide. No known or reasonably hypothesized mechanism can result in a rudder PCU jam for approximately 12 seconds and subsequently clear without leaving witness marks. (See Sections 2.2.2, 2.2.4, and 2.4)
   - The pilot reports of pedal travel and pedal forces are not consistent with a rudder reversal scenario. (See Section 2.4)
   - There is no recorded data that indicates the flight crew was responsible for the right rudder deflection sustained for 12 seconds. However, a scenario that includes a pilot input of right rudder matches the data from both the flight data recorder and the kinematic analysis more closely than any other scenario identified. (See Sections 2.2.1, 2.2.8, 2.3, and 2.4)
   - The application of kinematic analysis, as employed in the four scenarios discussed in this submission, is not exact. All four evaluated scenarios produce results reasonably close to the event's recorded data. However, without additional parameter recordings or higher data sampling rates, it is not appropriate to draw definite conclusions about the event from kinematic analysis alone. (See Sections 2.2.5, 2.2.6, and 2.3)
3. All parties generally agree that the initiation of the Eastwind event involved some form of activity from the yaw damper system. This resulted in an airplane upset and flight crew inputs to the flight control system to regain control. Thereafter, either a rudder system fault, additional crew inputs to the rudder, or unknown factors generated a final

rudder deflection of approximately 6 degrees to the right, which is required for the magnitude of heading change recorded. (See Sections 2.2.2, 2.2.4, and 2.3)

4. The most likely explanation for the Eastwind event involves a preexisting yaw damper fault that subsequently cleared itself. This scenario is most consistent with the physical evidence, pilot reports, and kinematic analysis. The yaw damper system includes a yaw damper coupler (electronic box) with a mechanical rate gyro, which senses yaw motion. The coupler sends a variable electrical current to the electro-hydraulic servo valve on the rudder PCU which commands movement of the rudder PCU up to the yaw damper authority. In-service experience has shown that intermittent yaw damper system faults can occur and subsequently clear and not be duplicated during shop testing. (See Sections 2.2.7 and 2.4)

5. There is no data to indicate that the Eastwind Flight 517 event, the United Flight 585 accident, and USAir Flight 427 accident were caused by a common airplane malfunction.

The following table summarizes Boeing's findings as discussed in this document.

Table III

Hypothetical scenarios for rudder deflection	Arguments for	Arguments against	Document section
Scenario 1: • Pre-existing Y/D hardover 3 deg to the left, which is trimmed out • Y/D moves rudder 5 deg to the right, initiating event • Small crew input to right pedal increases rudder to 6 deg right • Crew turns Y/D OFF and rudder is operational	• Potentially fits kinematic analysis	• The crew reported stepping on the left rudder pedal • Pedal force and deflection required to match the data does not agree with crew comments • Wheel time history to match roll does not correlate with crew comments • No apparent reason for a right rudder input • Y/D appears to be working during the event	**Section 2.3.1**
Scenario 2: • 3.7-deg Y/D hardover to the right initiates event • Jam in the rudder PCU secondary valve slide • Approx. 60-pound crew input to the left rudder pedal • Rudder reverses and moves to 6 deg right • Crew turns Y/D OFF and rudder is operational	• The crew reported stepping on the left rudder pedal	• Does not adequately match airplane heading response • PCU secondary slide can shear all chips • No evidence of PCU secondary slide jam • No reasonable mechanism has been identified for causing PCU jam • No crew comments to indicate a rudder reversal • Wheel time history to match roll does not match crew comments • Pedal forces would feel different than "somewhat stiff" • An active Y/D signifies no reversal	**Section 2.3.2**
Scenario 3: • Pre-existing 3-deg left Y/D hardover • Jam in rudder secondary valve slide • Y/D fault produces 5-deg right rudder, initiating the event • Approx. 60-pound crew input to the left rudder pedal • Rudder reverses, goes to 6 deg right • Crew turns Y/D OFF and rudder is operational	• Potentially fits kinematic analysis • The crew reported stepping on the left rudder pedal	• PCU secondary slide can shear all chips • No evidence of PCU secondary slide jam • No reasonable mechanism has been identified to cause PCU jam • No crew comments to indicate a rudder reversal • Wheel time history to match roll does not match crew comments • Pedal forces would feel different than "somewhat stiff" • An active Y/D signifies no reversal	**Section 2.3.3**
Scenario 4: • Pre-existing 3-deg Y/D hardover to the right • Y/D becomes operational, moving the rudder 3.7 deg to the left • Crew puts in and maintains a 6-deg right rudder input, Y/D is operational • Crew turns Y/D OFF and rudder is operational	• Potentially fits kinematic analysis • Crew reported pedal force fits the scenario • The amount of crew-reported pedal deflection fits the scenario • Wheel time history to match roll agrees with crew comments • Rudder reached during the upset is a reasonable pilot response to a Y/D hardover (it matches this pilot's recorded response during flight test) • Y/D appears to be working during the event	• Crew reported stepping on the left rudder pedal • Crew reported no yaw to the left	**Section 2.3.4**

Based on knowledge gained during the course of the Flight 427 investigation, Boeing, the aviation industry, and the U.S. government have already implemented a number of improvements to the 737 design, flight operations procedures, and flight crew training. Already in place, these improvements address the postulated Eastwind failure conditions. The actions taken include:

- The rudder power control unit for the 737 has been revised to eliminate the highly unlikely potential for a rudder reversal.
- The yaw damper computer for the 737 is being replaced with a new design that incorporates significantly improved system redundancy. Overall system reliability will be significantly improved, and failure modes of the yaw damper computer that lead to yaw damper hardover commands to the rudder will be nearly eliminated.
- A hydraulic pressure reducer has been added to the 737 to improve the match between rudder deflection capability and airplane control requirements. This will reduce airplane reactions to large or fast rudder deflections at some flight conditions, no matter what the cause, simplifying flight crew recovery techniques.
- A 737 flight crew operations procedure has been published which provides a means to minimize the effects of any system malfunction that may affect rudder operation.
- Industrywide upset-recovery training programs are being implemented.

As noted in the USAir Flight 427 submission, Boeing believes actions addressing all significant improvement opportunities have been taken. No additional recommendations for design, procedure, or training changes are recommended as a result of the Eastwind investigation.

3.0 Servo Value Inspection Findings, UAL Flight 585

The NTSB examined several main rudder power control unit dual concentric servo valves. Included in this examination was the dual concentric servo valve (P/N 68010-5003, S/N 1091) removed from the UAL Flight 585 main rudder power control unit.

The examination documented the location of witness marks created as a result of the heating of the phosphate ester–based hydraulic fluid (BMS 3-11) during the post-crash fire. When BMS 3-11 fluid is heated to temperatures above approximately 270°F, the esters breakdown to form phosphoric acid, which will chemically attack, or etch, metals. The reaction is accompanied by the formation of a porous, gummy residue that adheres tenaciously to the affected surfaces. Also, the pores act as reservoirs to hold small quantities of the acid. In the case of the slides, the reaction generated circular and rectangular witness marks that indicated the relative positions of the slides at various points in time.

The outside diameters of the primary and secondary slides provided the best history of the location of the slides during and after the post-crash fire. The inside diameters of the secondary slide and housing were also examined and determined to have witness marks in agreement with those present of the outside diameters. For purposes of clarity only the outside diameters of the primary and secondary slides will be discussed from this point forward.

Multiple sets of witness marks are currently present on both the primary and secondary slides. Optical and SEM examination was used in conjunction with photographs obtained during the fall 1992 NTSB investigation to place the witness marks into three distinctive chronological categories:

Category 1: Original Post-Crash Fire

These witness marks were created during the post-crash fire and are characterized by a film of phosphorous-rich deposits and aggressive etching of the slide surface within the marks. These features are consistent with the high temperature decomposition of BMS 3-11 as described above.

Category 2: Storage 1

These witness marks were created while the valve was in storage between the fall 1992 NTSB investigation and the examination by plaintiffs' experts in January 1998. These marks appear darker in color than those that formed during the fire. They are characterized by little to no deposit formation and only slight etching of the metal, giving the marks a stained appearance. Before the components were stored they were coated with MIL-H-5606 hydraulic fluid. During the storage period, the acid contained in the pores of the deposits leached out into the hydraulic fluid, thereby creating a corrosive environment within the ports. Exposure to this solution caused light etching on the surfaces of the slides that were coincident with the ports, and created the second set of witness marks.

Category 3: Storage 2

These witness marks were created while the valve was in storage between January 1998 and the recent NTSB examination documented by Report No. 98-116. These marks were subtle in appearance compared to the first two sets of marks, but they exhibited characteristics very similar to those created during Storage 1. The features were less distinct due to the shorter exposure time.

The original post-crash witness marks of the secondary slide indicate the slide was in the neutral position during the entire fire. This position is best confirmed by Figure 31 of NTSB Report No. 98-116. This figure shows the entire "return" metering port to be etched onto the land of the secondary slide, indicating that the slide completely covered the port (neutral position).

The secondary slide is spring-detented to the neutral position and is not directly connected to the input linkage (a deadband exists between the secondary slide and secondary input lever). Without any large rudder rate commands present, the secondary slide will remain in the detented position, even without hydraulic pressure being supplied to the power control unit.

In contrast to the secondary slide, the primary slide is not spring-detented and it is directly connected to the input linkage. As a result, the primary slide contains multiple witness marks created during the post-crash fire. As the wreckage shifted and crumpled, the primary slide was repositioned multiple times and multiple witness marks were created.

Of special interest are the six equally spaced, semicircular "original post-crash fire" witness marks created on one of the lands on the primary slide during the post-crash fire. The circular marks overlap the land of the primary slide by 0.019 inches. Examination of the internal diameter of the secondary slide determined the edge of the circular holes to be 0.039 inches from the metering port. Therefore, in order for the primary slide land to be covering the hole by 0.019 inches, the slide had to have moved 0.0596 inches relative to the secondary slide (0.019 + 0.039 + 0.0016 nominal underlap).

Normal travel of the primary slide is limited to 0.045 inches relative to the secondary slide. Although witness marks would indicate that the primary slide may have traveled beyond its normal limits during the post-crash fire, its maximum traveled position as indicated by the witness marks is 0.033 inches short of that required to produce a completely overstroked condition.

Also, given the unknown trauma that the power control unit was subjected to during impact, the subsequent post crash fire, fire control efforts, rescue efforts, and wreckage removal activity, no realistic correlation can be drawn from these witness marks and the position of the primary slide prior to impact.

However, the following scenario is the most probable sequence of events leading up to the creation of these witness marks, which indicated 0.0596 inches of travel.

After impact with the ground, the wreckage momentarily comes to rest and the post-crash fire begins to heat the airplane structure as well as the main rudder power control unit dual concentric servo valve. At this point the hydraulic fluid within the servo valve begins to etch the surface of the components and create witness marks.

Continued heating causes some of the airplane structure, as well as the rudder power control unit input control rod, to melt and collapse. By this time the extreme heating of the dual concentric servo valve causes the secondary slide to become "thermally" seized within the servo valve body. Collapsing of the airplane structure loads the input lever to the main rudder power control unit. Because the secondary slide is thermally jammed, the compliance of the internal summing levers allows the primary slide to travel slightly beyond its normal limits.

As noted in the Flight 427 submission and in the Eastwind discussion presented earlier, Boeing believes actions addressing all significant improvement opportunities have been taken. No additional recommendations for design, procedure, or training changes are recommended as a result of the additional UAL Flight 585 servo valve investigation.

4.0 Status of Rudder System Improvement Program

Changes will be made to the rudder control system to address two airworthiness directives: AD 97-14-03 and AD 97-14-04.

AD 97-14-04: Requires retrofit of the servo valve in the main rudder power control unit, and replacement of the control rod and dual-load-path bolt.

- The dual-load-path bolts connect the control rod to the power control unit. The current bolt can develop cracks under normal operation. The bolt has been redesigned to alleviate this failure mode.
- Changes were incorporated into production in July 1997, and retrofit kits were made available at the same time.

AD 97-14-03: Requires retrofit of the yaw damper coupler and the addition of a rudder pressure reducer. Incorporation of these changes requires additional wiring modification to the airplane.

- Wiring kits are currently being provided to the airlines to allow early incorporation of the wiring changes.
- The yaw damper coupler and rudder pressure reducer will be incorporated into production in October 1998, with retrofit kits being made available at that time.

The detailed status of each retrofit program is provided in the body of this report.

737-100/-200/-300/-400/-500 Rudder Power Control Unit Retrofit Status (AD 97-14-04)

	Airplanes	Power control units
To be modified	2,776 [(1)]	3,187
Modified	230 [(2)]	1,211 [(3)]

(1) Number of 737s (from L/N 1-2914) currently in service; based on Boeing database information.

(2) This number is based on responses received from operators.

(3) 549 rudder power control units modified by Parker, plus 596 kits shipped, plus 66 valves available at Parker CSO to be shipped upon request.

Reference: Power Control Unit Retrofit documented in Boeing Service Bulletin 737-27A1202, Rev 3.

737-100/-200/-300/-400/-500 Control Rod and Dual-Loadpath Bolts Retrofit Status
(AD 97-14-04)

Airplanes to be modified	2,776 [1]
Airplanes modified	338 [2]
Kits shipped from Boeing	2,255

[1] Number of 737s (from L/N 1-2914) currently in service; based on Boeing database information.

[2] This number is based on responses received from operators.

Reference: Control Rod and Dual-Loadpath Bolt Retrofit documented in Boeing Service Bulletin 737-27A1202, Rev 3.

737-300/-400/-500 Yaw Damper Coupler Wiring Kits Status
(AD 97-14-03)

Airplanes to be modified	1,736 [1]
Airplanes modified	65 [2]
Kits shipped from Boeing	530 [3]

[1] All 737-300/-400/-500 airplanes currently in service; based on Boeing database information.

[2] This number is based on responses received from operators.

[3] 530 kits shipped plus 138 available to ship upon request.

Reference: Yaw Damper Coupler Wire Kits retrofit documented in Boeing Service Bulletin 737-22-1124.

737-100/-200 Yaw Damper Coupler Wiring Kits Status
(AD 97-14-03)

Airplanes to be modified	1,038 [1]
Airplanes modified	0 [2]
Kits shipped from Boeing	50 [3]

[1] All 737-100/-200 airplanes currently in service; based on Boeing database information.

[2] This number is based on responses received from operators.

[3] Kits became available in July 1998.

Reference: Yaw Damper Coupler Wire Kits retrofit documented in Boeing Service Bulletin 737-22-1127.

5.0 Document References

Ref. 1: "Systems Group Chairman's Factual Report of Investigation," DCA-96-IA-061, National Transportation Safety Board, June 11, 1997.

Ref. 2: "737-200 (Eastwind) Unexpected Yaw Event Investigation Flight Test – FT," T.I. B1.38.0173, Boeing D6-38554, June 20, 1996.

Ref. 3: "737-200 (Eastwind) Yaw Damper Hardover Test – FT," T.I. B1.38.0174, Boeing D6-38554, June 20, 1996.

Ref. 4: "737-200 (Eastwind) Yaw Damper (-901) Ground Test – GT," T.I. B1.38.0175, Boeing D6-38554, June 20, 1996.

Ref. 5: "737-200 (Eastwind) Yaw Damper (-901) Ground Test – GT," T.I. B1.38.0176, Boeing D6-38554, June 20, 1996.

Ref. 6: "Human Performance Group Chairman's Factual Report of Investigation," DCA-96-IA-061, National Transportation Safety Board, July 29, 1996.

Ref. 7: NTSB Addendum to Specialist's Sound Spectrum Study, Eastwind Cabin Sounds, Cockpit Voice Recorder, January 24, 1997.

Ref. 8: "N221US—Examination of Removed Components," Equipment Quality Analysis Report, EQA No. 7175R, Boeing, October 28, 1996.

Ref. 9: "Directional, Vertical, and Rate Gyro Test Factual Report," DCA-96-IA-061, Office of Research and Engineering, National Transportation Safety Board, June 16, 1997.