Appendix A
Kinematic Analysis of Flight 427 DFDR

This appendix describes the processes used to derive Flight 427's lateral and directional control positions—two parameters not recorded by the Flight 427 DFDR—during the accident sequence. To understand the wake upset, and the flight crew's subsequent response to this startling event, it was first necessary to determine the effects of a 727 wake on a 737, and introduce these effects into the kinematic analysis.

A flight test program, conducted by the NTSB Performance Group at the FAA Flight Test Center near Atlantic City,[29] used an FAA 727 and a USAir 737-300, to acquire the required information. The process used during this analysis has been validated by Dennis Crider of the NTSB and is documented in an NTSB report.[30]

The first step in determining lateral and directional control positions was to expand the basic 11 parameters recorded on the DFDR by deriving the angular rates and accelerations from the Euler angles, and integrating the linear accelerations to determine a flight trajectory. Comparisons of derived and measured data were performed to achieve a final converged solution, from which angle-of-attack and sideslip angle were derived.

The next step was to use Newton's second law to obtain the total aerodynamic forces and moments acting on the aircraft using the derived and measured angular and linear accelerations. Next, the aerodynamic forces arising from known or derived effects—such as those due to angle-of-attack, sideslip, elevator position, engine rpm, and so on—were computed using the 737-300 engineering simulator database.

[29] *Wake Vortex Flight Test,* NTSB Factual Report, to be issued.
[30] *Kinematic Validation Study,* NTSB Study, February 15, 1997.

These effects were then subtracted from the total, leaving behind the sum of all unknown aerodynamic effects. This sum includes the effects of wake turbulence, lateral and directional control-surface deflections, DFDR processing errors, possible structural damage, and deficiencies in the simulator aerodynamics math model.

The magnitude of any DFDR processing errors was shown to be very small by the inertial reference unit (IRU) platform testing undertaken by the NTSB Performance Group in February 1995 at the Honeywell facility in Clearwater, Florida.[31] The 737-300 engineering simulator aerodynamic math model is a proven, valid model of the aircraft, with a very small magnitude of error in the aerodynamic data throughout the normal flight envelope. The model was updated to an even higher degree of accuracy using the data obtained in the NTSB flight testing conducted as part of this investigation.

Once the examination of the aircraft structure eliminated structural damage[32] as a potential cause, only the effects of wake turbulence, and the lateral and directional control positions, were of a magnitude significant for further consideration. The wake flight test program conducted in Atlantic City provided the data necessary to locate the 727 wake relative to the 737 during the accident sequence. The flight test data also allowed the mathematical model of the wake to be verified and improved based on actual data. This process is documented in an NTSB report.[33]

The results of the kinematic analysis provide significant information as to the control activity during the accident sequence. It is important to note that the wheel time history derived using the kinematic process was consistent with those derived during the NTSB validation of the Boeing kinematic process.

[31] *Honeywell Tilt Table Test,* NTSB Factual Report, to be issued.
[32] NTSB Structures Factual Report, Dec. 13. 1994.
[33] *Kinematic Study Update: Derivation of Lateral and Directional Control Surface Positions,* NTSB Study, June 11, 1997.

Obtaining the rudder time history from available DFDR data is more challenging because airplane heading—the primary parameter for determining rudder position—was recorded on the DFDR only once every second, whereas roll angle—the primary parameter for determining wheel position—was recorded twice every second. When the heading data is sampled at less than twice a second, the rudder position derived using kinematics becomes contaminated with an overlying "noise" signal that shows up as an oscillation in derived rudder, with a period of about 0.75 seconds and a peak-to-peak amplitude that can exceed ten degrees. Proper interpolation of the heading data can reduce the "noise," providing more reliable information on rudder movement.

In regions of the flight envelope where the rudder position is known or can be inferred (such as when the rudder is believed to be at its blowdown limit), it is possible to derive a continuous heading trace between the low-sample-rate data points that are known from measurement. This heading trace accurately represents the airplane heading during the period of time where rudder position is known or can be inferred.

The end result of this effort is an improved knowledge of the boundary conditions of the heading trace at the edges of the adjoining regions where rudder position is not known or cannot be inferred. Applying these new boundary conditions, while maintaining a smooth continuous heading trace that goes through all known heading data points, resulted in an improved representation of the airplane's heading from time 133 to 140. This new heading-trace interpolation has been used, along with the derived wake-induced yawing moment, to derive a final, best estimate of rudder position.

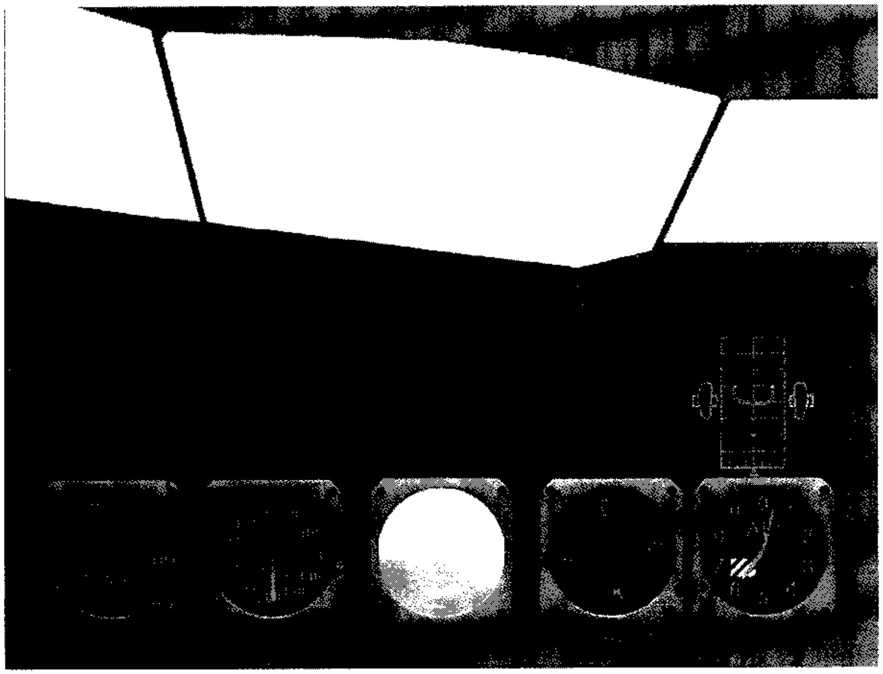
This is not the only method of interpolating the heading trace. The NTSB Performance Group looked at several other methods of interpolation and the results are discussed in the NTSB Study.[30]

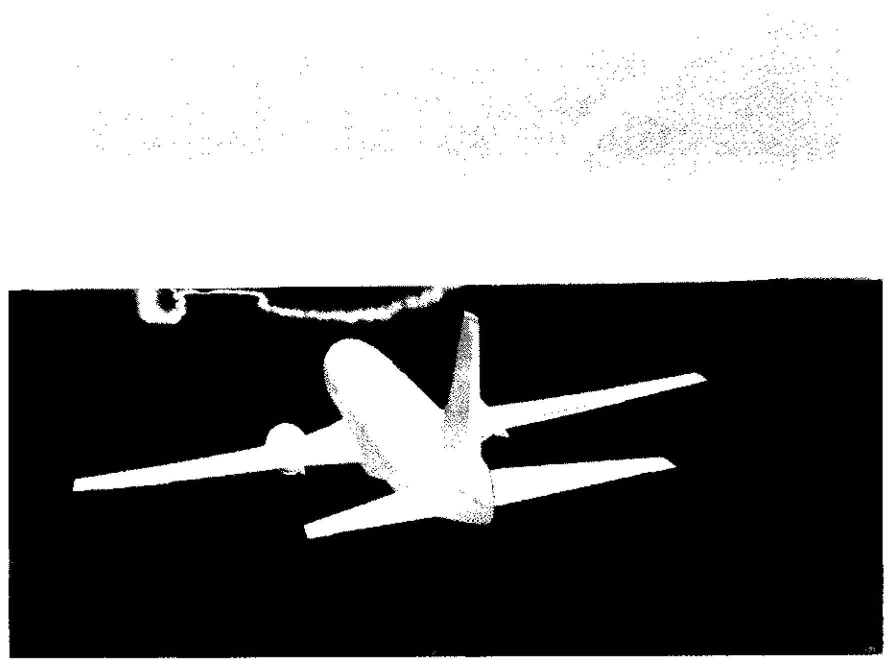
Figures A1 to A14 show an animation of the accident sequence[34] with the following information:

- Animated following view of the accident aircraft.
- Animated cockpit view from the accident aircraft.
- Estimated wake location.
- Derived roll and yaw accelerations and rates.
- DFDR recorded roll and heading angles.
- DFDR recorded column position.
- Estimated wheel and rudder deflections.
- CVR comments/sounds.
- General comments.

[34] First presented in *Boeing Contribution to the USAir Flight 427 Accident Investigation Board,* Sep. 25, 1996.

TIME = 134.3





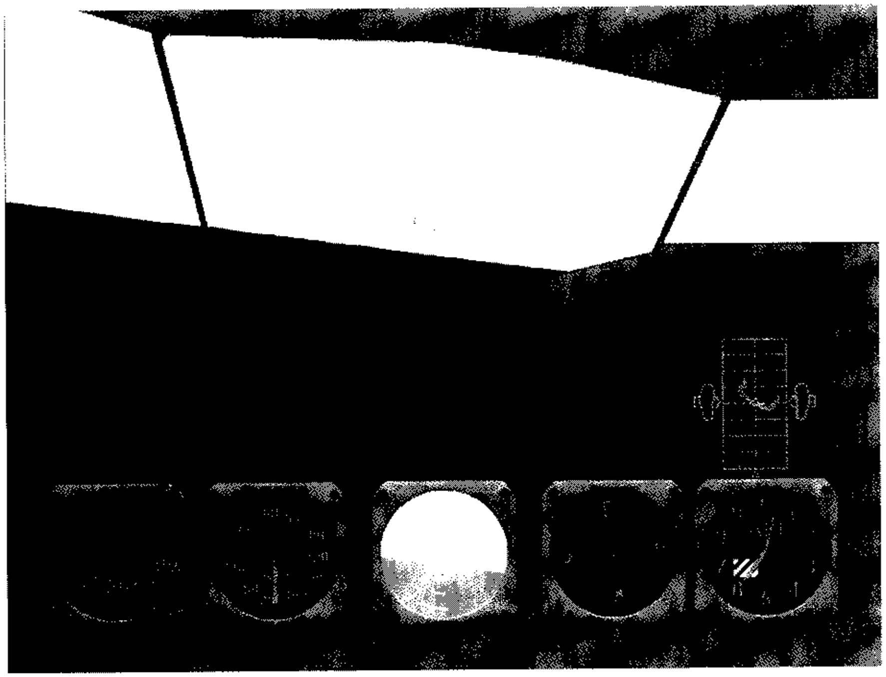
Roll acceleration	=	**4 deg/sec/sec - left**
Roll rate	=	**1 deg/sec - right**
Roll angle	=	**7 deg - left**
Yaw acceleration	=	**0 deg/sec/sec**
Yaw rate	=	**1 deg/sec - left**
Heading angle	=	**103 deg**
Wheel angle	=	**1 deg - right**
Rudder angle	=	**1 deg - right**
Column angle	=	**0 deg**
Normal load factor	=	**0.88 g's**

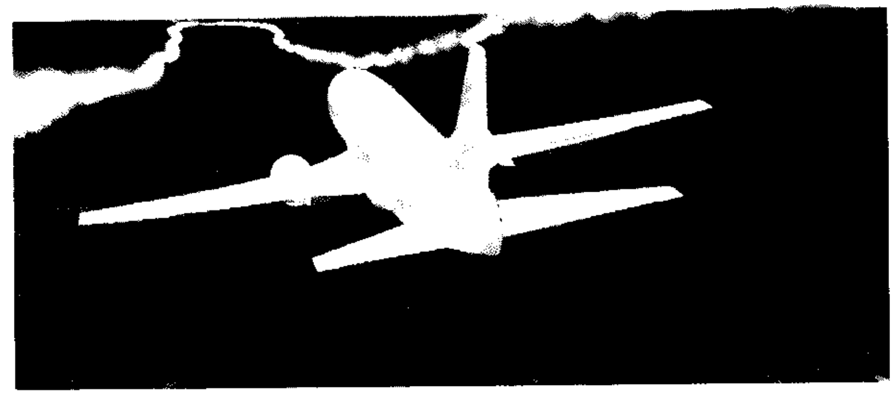
CVR time	**CVR comments/sounds**
133.55-.85	**"bumps" – (cockpit area mic)**
134.10	**"electrical click" – (Captain)**

Comments:
The aircraft is rolling toward wings level from a left bank, but stops short as a result of the wake encounter. There are several vertical bounces that may be noticed by the crew. The airplane is just starting to accelerate to the left, which causes the autopilot to begin commanding right wheel.

Figure A1

TIME = 134.7





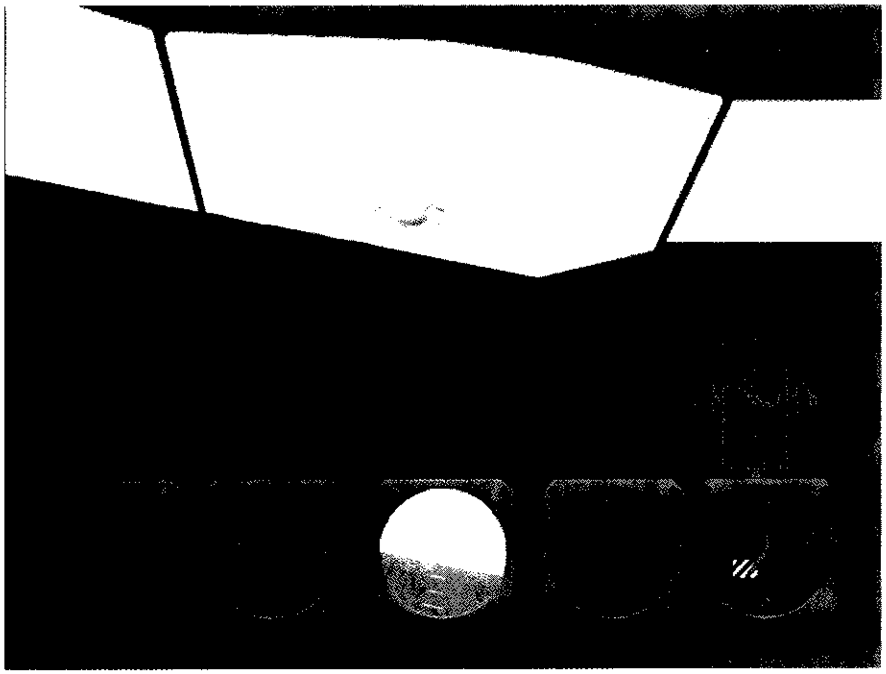
Roll acceleration	=	**16 deg/sec/sec - left**
Roll rate	=	**3 deg/sec - left**
Roll angle	=	**8 deg - left**
Yaw acceleration	=	**0 deg/sec/sec**
Yaw rate	=	**1 deg/sec - left**
Heading angle	=	**103 deg**
Wheel angle	=	**29 deg - right**
Rudder angle	=	**1 deg - right**
Column angle	=	**0 deg**
Normal load factor	=	**0.99 g's**

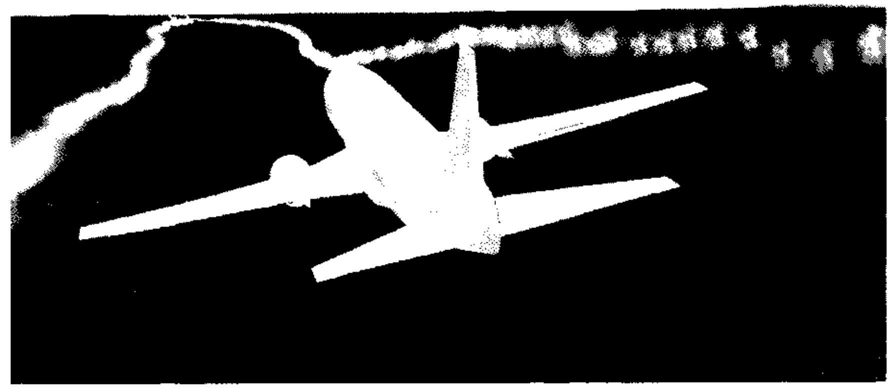
CVR time	**CVR comments/sounds**
134.45	**"exhale/inhale" – (Captain)**
134.65	**"zuh" – (First Officer)**
134.75	**"Sheez" – (Captain)**

Comments:
The airplane is now rolling left and still accelerating to the left, at accelerations 8 times greater than the autopilot commands. The autopilot response is to put in full autopilot authority wheel to the right.

Figure A2

TIME = 135.2





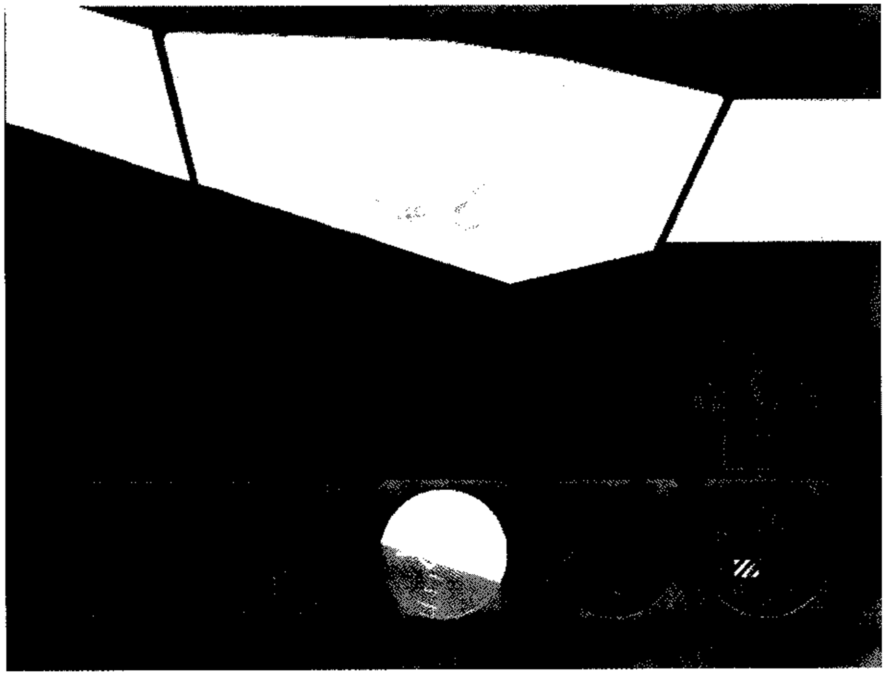
Roll acceleration	=	**8 deg/sec/sec - left**
Roll rate	=	**11 deg/sec - left**
Roll angle	=	**11 deg - left**
Yaw acceleration	=	**0 deg/sec/sec**
Yaw rate	=	**1 deg/sec - left**
Heading angle	=	**102 deg**
Wheel angle	=	**29 deg - right**
Rudder angle	=	**1 deg - right**
Column angle	=	**0.5 deg - nose down**
Normal load factor	=	**1.11 g's**

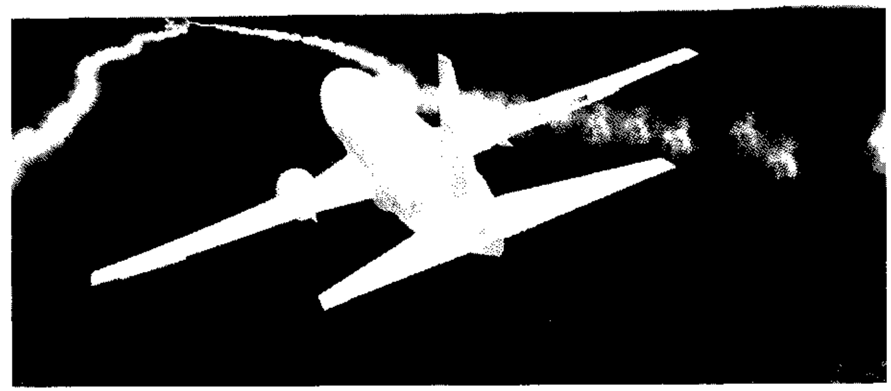
CVR time	**CVR comments/sounds**
134.45	"exhale/inhale" – (Captain)
134.65	"zuh" – (First Officer)
134.75	"Sheez" – (Captain)
135.20	**"thump/thump" – (cockpit area mic)**

Comments.
A loud thump is heard on the CVR, caused by the wake vortex hitting the fuselage. The First Officer manually continues the right wheel motion, overriding the autopilot roll mode with 10 pounds of force.

Figure A3

TIME = 135.8





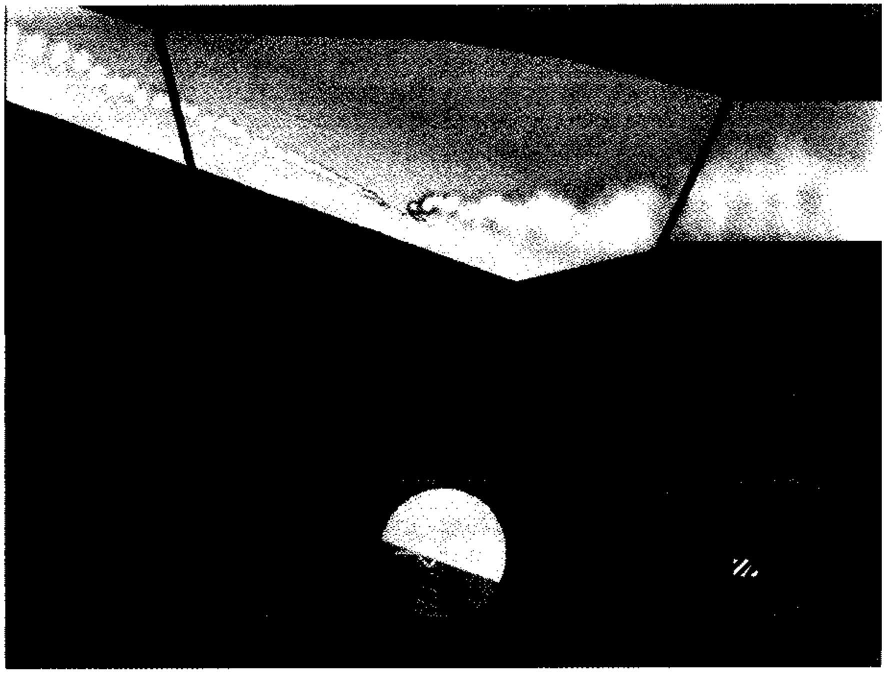
Roll acceleration	=	**18 deg/sec/sec - right**
Roll rate	=	**10 deg/sec - left**
Roll angle	=	**18 deg - left**
Yaw acceleration	=	**7 deg/sec/sec - left**
Yaw rate	=	**3 deg/sec - left**
Heading angle	=	**102 deg**
Wheel angle	=	**73 deg - right**
Rudder angle	=	**1 deg - left**
Column angle	=	**2 deg - nose down**
Normal load factor	=	**0.96 g's**

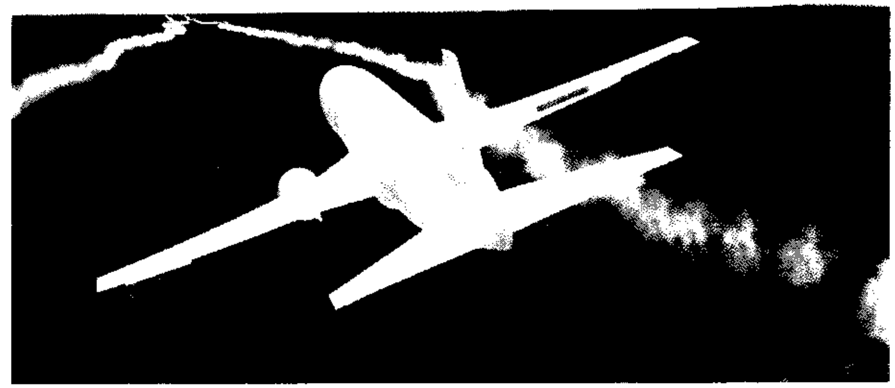
CVR time	**CVR comments/sounds**
135.20	"thump/thump" – (cockpit area mic)
135.60	**"inhale/exhale" – (Captain)**

Comments:
The First Officer is applying right wheel at a rate exceeding 60 deg/sec. The large wheel input reverses the roll acceleration, and the airplane starts to roll back to the right. The roll acceleration is now 18 deg/sec/sec to the right, rapidly changing the left roll rate.

Figure A4

TIME = 136.1





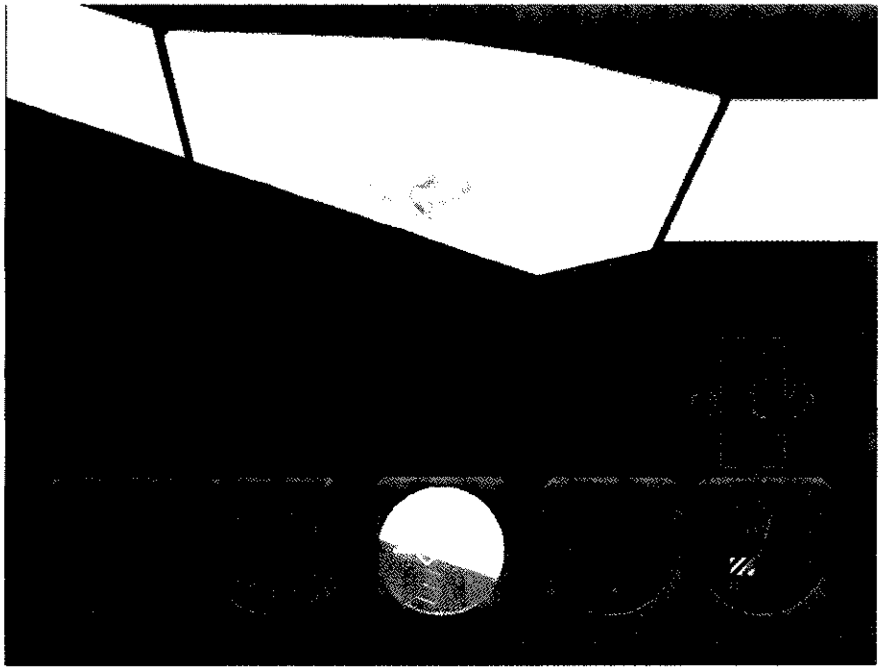
Roll acceleration	**=**	**36 deg/sec/sec - right**
Roll rate	**=**	**1 deg/sec - left**
Roll angle	**=**	**20 deg - left**
Yaw acceleration	**=**	**3 deg/sec/sec - left**
Yaw rate	**=**	**4 deg/sec - left**
Heading angle	**=**	**101 deg**
Wheel angle	**=**	**85 deg - right**
Rudder angle	**=**	**1 deg - left**
Column angle	**=**	**1 deg - nose down**
Normal load factor	**=**	**0.75 g's**

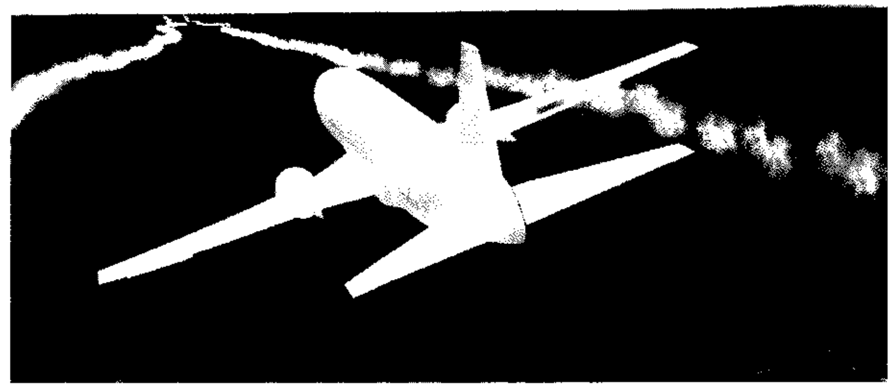
CVR time	**CVR comments/sounds**
135.60	"inhale/exhale" - (Captain)

Comments:
The wheel probably hits the physical limit of the control system at 136.2 seconds, with the roll acceleration to the right peaking at 36 deg/sec/sec, a change in roll acceleration of 54 deg/sec/sec in a period of 1.8 seconds. By itself, the 36 deg/sec/sec roll acceleration is 18 times greater than an autopilot rate.

Figure A5

TIME = 136.5





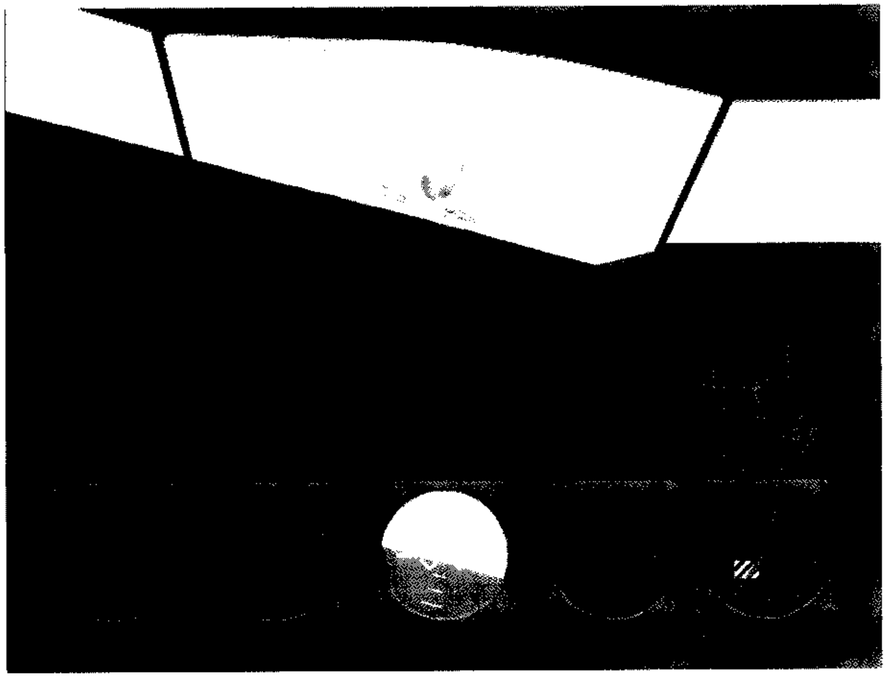
Roll acceleration	=	**3 deg/sec/sec - right**
Roll rate	=	**8 deg/sec - left**
Roll angle	=	**18 deg - left**
Yaw acceleration	=	**3 deg/sec/sec - left**
Yaw rate	=	**5 deg/sec - left**
Heading angle	=	**99 deg**
Wheel angle	=	**85 deg - right**
Rudder angle	=	**0 deg**
Column angle	=	**1 deg - nose down**
Normal load factor	=	**0.83 g's**

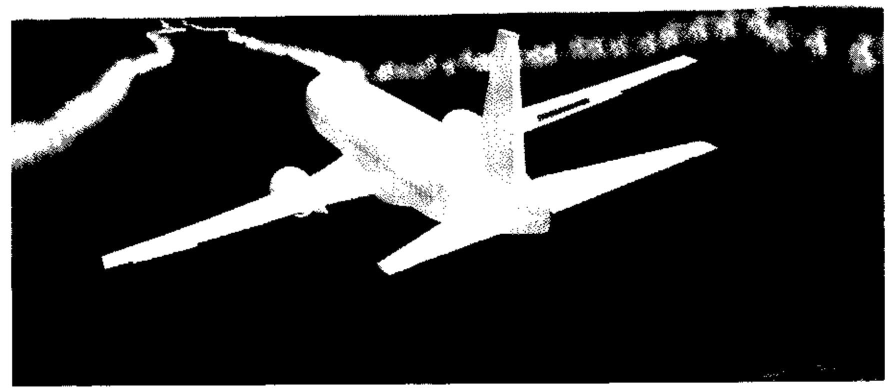
CVR time	CVR comments/sounds
135.60	"inhale/exhale" (Captain)
136.45	**"whoa" – (Captain)**

Comments.
The Captain comments "whoa". The rudder pedals start to go left – reaching about 3 inches of pedal travel at FDR time 136.9

Figure A6

TIME = 137.0





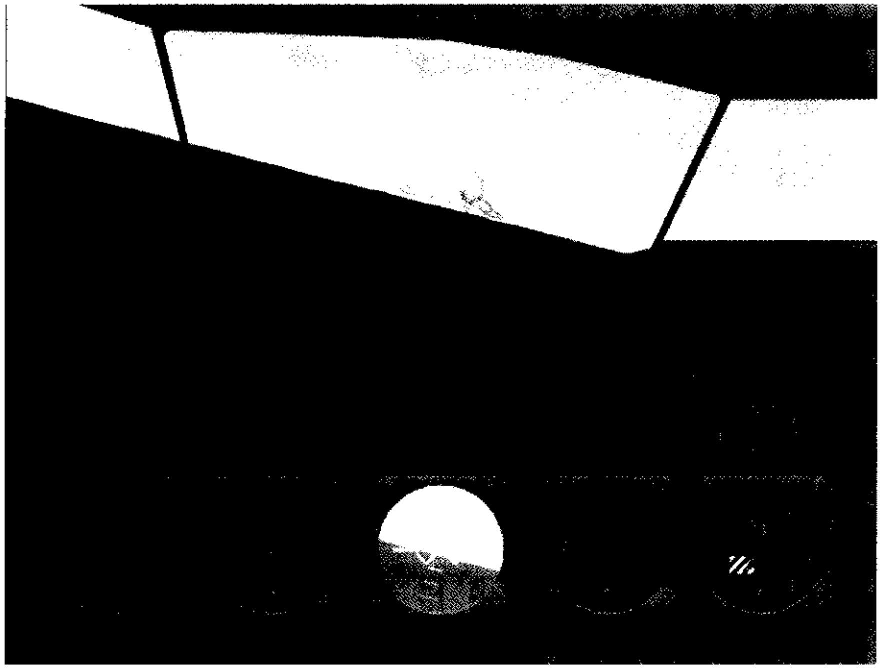
Roll acceleration	=	**10 deg/sec/sec - left**
Roll rate	=	**6 deg/sec - right**
Roll angle	=	**15 deg - left**
Yaw acceleration	=	**6 deg/sec/sec - left**
Yaw rate	=	**8 deg/sec - left**
Heading angle	=	**96 deg**
Wheel angle	=	**80 deg - right**
Rudder angle	=	**12 deg - left**
Column angle	=	**0 deg**
Normal load factor	=	**1.00 g's**

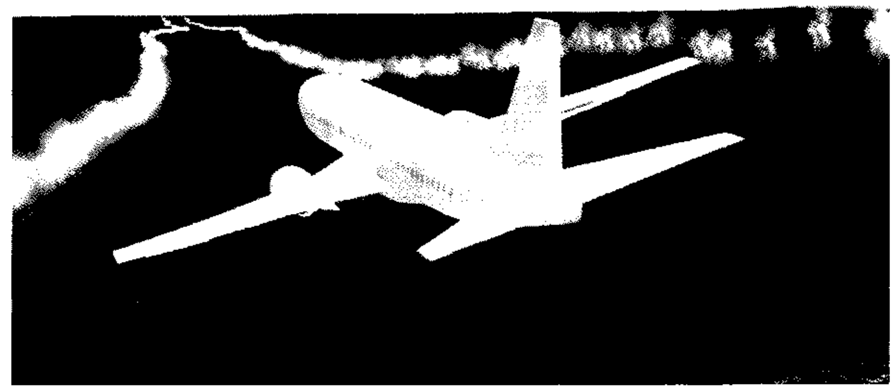
CVR time	**CVR comments/sounds**
136.45	"whoa" - (Captain)

Comments:
The full right wheel and near full left rudder inputs are now being returned toward a neutral position – which in normal flight will allow the airplane to come to zero roll rate at some small bank angle. However, the airplane is still in the effect of the wake which is rolling the aircraft to the left.

Figure A7

TIME = 137.4





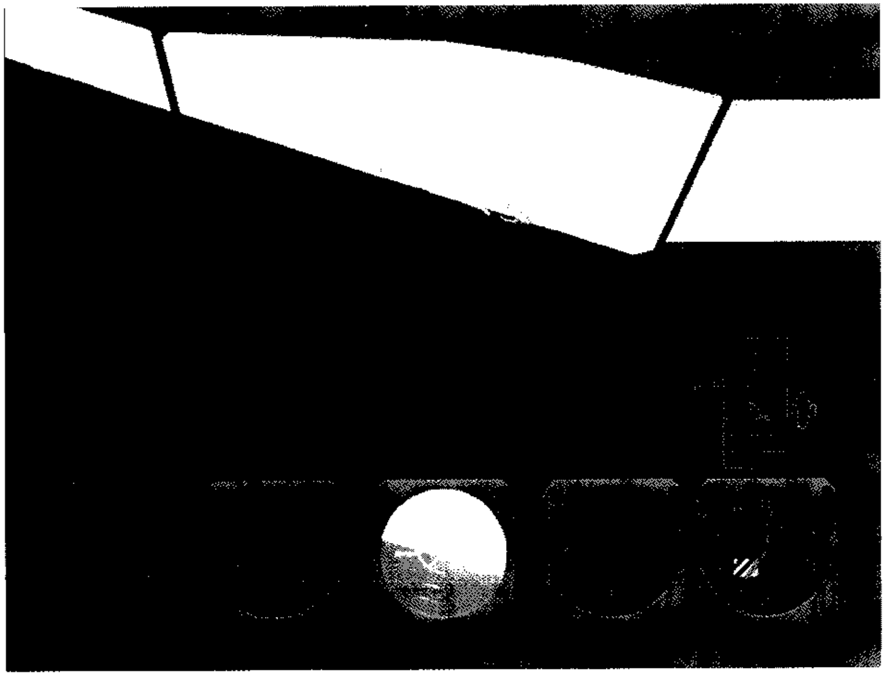
Roll acceleration	=	**38 deg/sec/sec - left**
Roll rate	=	**4 deg/sec - left**
Roll angle	=	**14 deg - left**
Yaw acceleration	=	**5 deg/sec/sec - right**
Yaw rate	=	**8 deg/sec - left**
Heading angle	=	**93 deg**
Wheel angle	=	**44 deg - right**
Rudder angle	=	**5 deg - left**
Column angle	=	**1 deg - nose up**
Normal load factor	=	**1.04 g's**

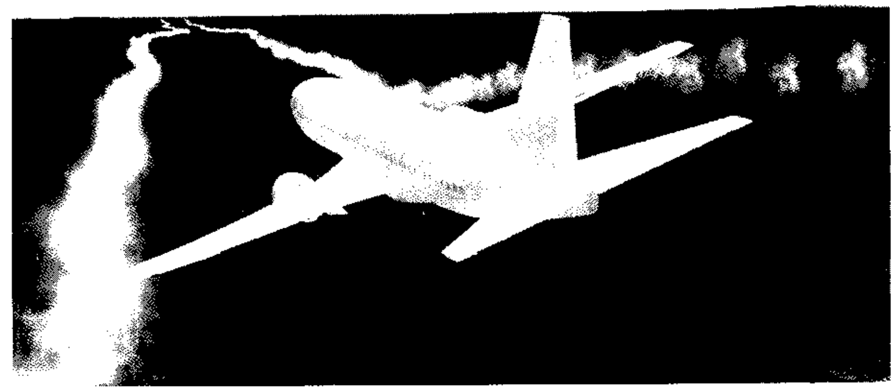
CVR time **CVR comments/sounds**

Comments:
The airplane, in the influence of the right side core, has a large left rolling moment. The left roll acceleration peaks at 38 deg/sec/sec, a change of almost 74 deg/sec/sec in a period of 1 second

Figure A8

TIME = 137.7





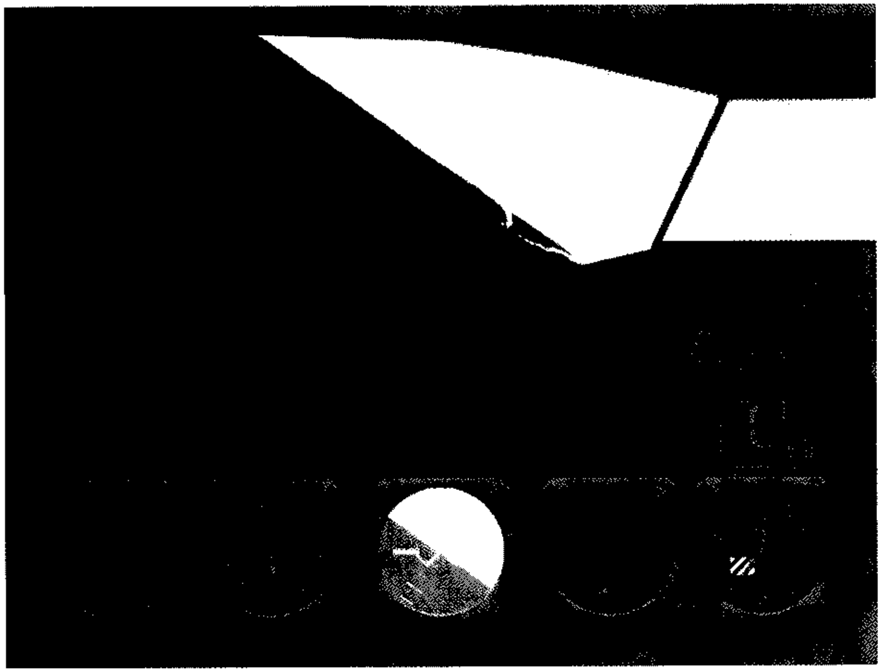
Roll acceleration	=	**23 deg/sec/sec - left**
Roll rate	=	**14 deg/sec - left**
Roll angle	=	**17 deg - left**
Yaw acceleration	=	**10 deg/sec/sec - right**
Yaw rate	=	**6 deg/sec - left**
Heading angle	=	**90 deg**
Wheel angle	=	**48 deg - right**
Rudder angle	=	**3 deg - left**
Column angle	=	**2 deg - nose up**
Normal load factor	=	**0.95 g's**

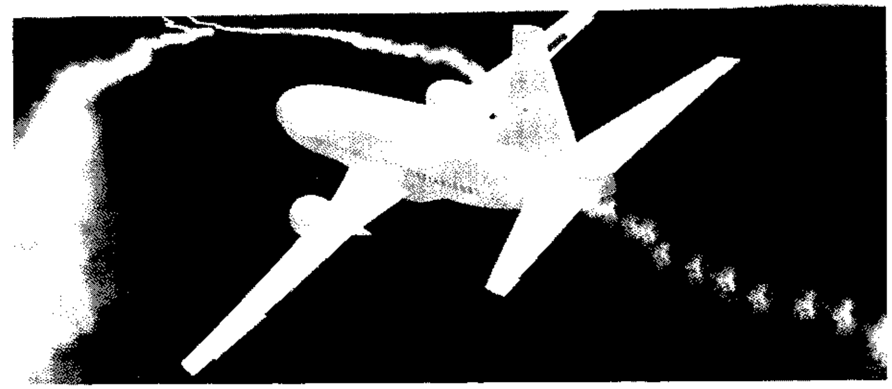
CVR time	**CVR comments/sounds**

Comments:
The airplane is now rolling rapidly left and accelerating to an even faster rate -- all away from wings level. Right wheel and left rudder inputs are made. Throttles are advanced. These three inputs are all made at about the same time.

Figure A9

TIME = 138.7





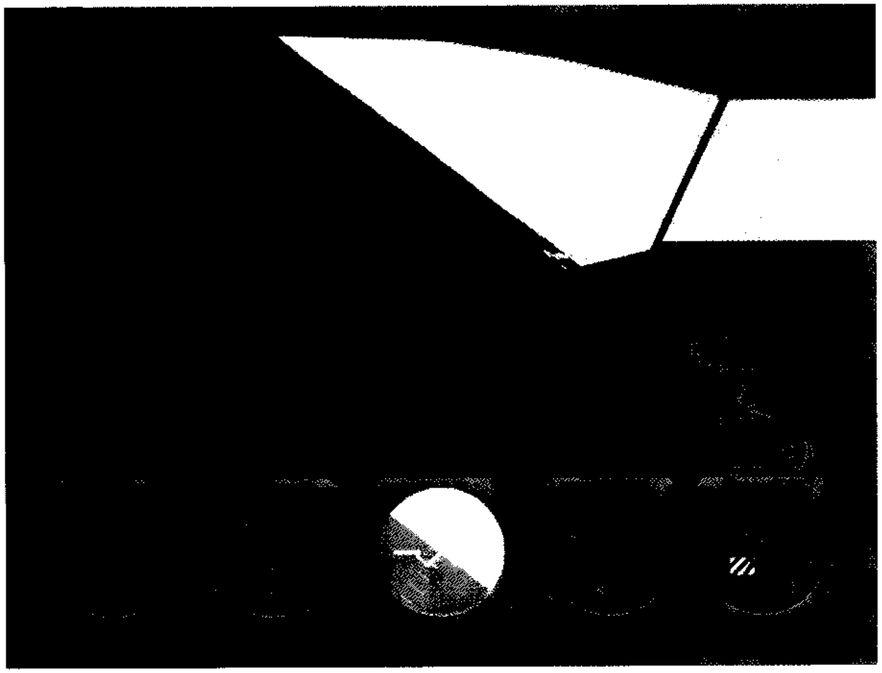
Roll acceleration	=	**39 deg/sec/sec - right**
Roll rate	=	**9 deg/sec - right**
Roll angle	=	**35 deg - left**
Yaw acceleration	=	**1 deg/sec/sec - left**
Yaw rate	=	**5 deg/sec - left**
Heading angle	=	**86 deg**
Wheel angle	=	**85 deg - right**
Rudder angle	=	**16 deg - left**
Column angle	=	**5 deg - nose up**
Normal load factor	=	**0.88 g's**

CVR time	CVR comments/sounds
138.25	**"hang on" – (Captain)**
138.85	**"grunt" – (First Officer)**

Comments.
The right roll acceleration peaks at 40 deg/sec/sec and the airplane stops rolling at 35 deg left wing down. The First Officer starts to remove the full right wheel input but does not remove the rudder input.

Figure A10

TIME = 139.5



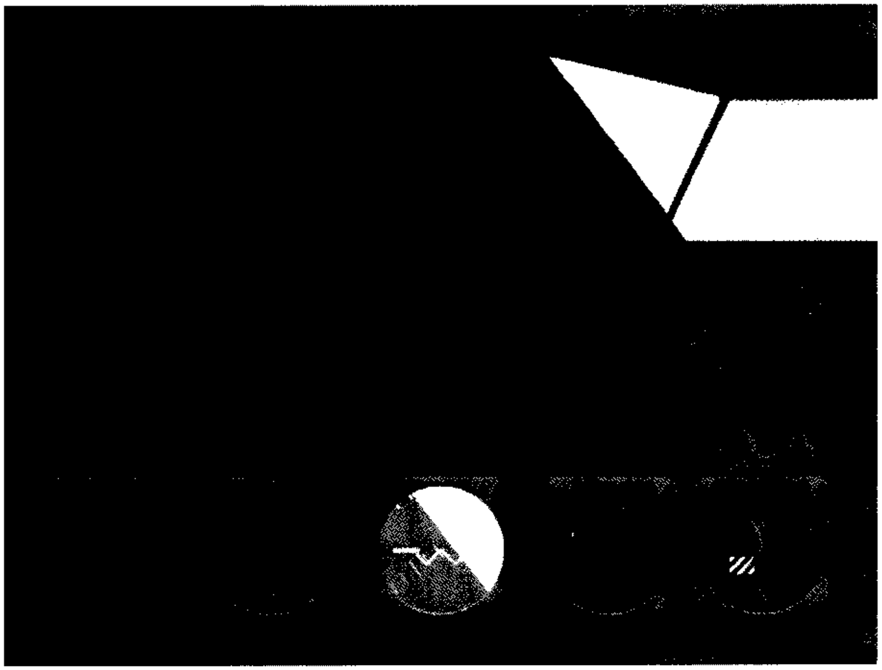
Roll acceleration	=	**15 deg/sec/sec - left**
Roll rate	=	**4 deg/sec - left**
Roll angle	=	**37 deg - left**
Yaw acceleration	=	**3 deg/sec/sec - left**
Yaw rate	=	**8 deg/sec - left**
Heading angle	=	**81 deg**
Wheel angle	=	**25 deg - right**
Rudder angle	=	**16 deg - left**
Column angle	=	**2 deg - nose up**
Normal load factor	=	**1.56 g's**

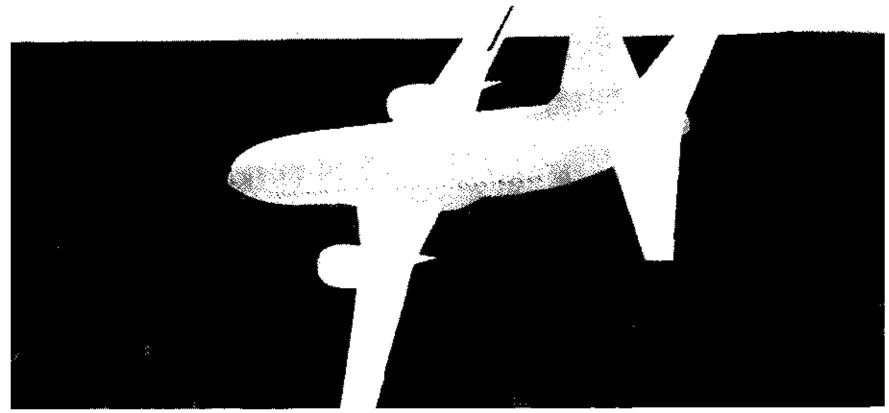
CVR time	**CVR comments/sounds**
138.85	"grunt" (First Officer)
139.05	**"hang on" – (Captain)**
139.25	**"autopilot disconnect" – (cockpit area mic)**

Comments:
The airplane is now nearly clear of the effects of the wake vortex
The wheel is returned toward neutral, to 20 degrees right.

Figure A11

TIME = 141.0





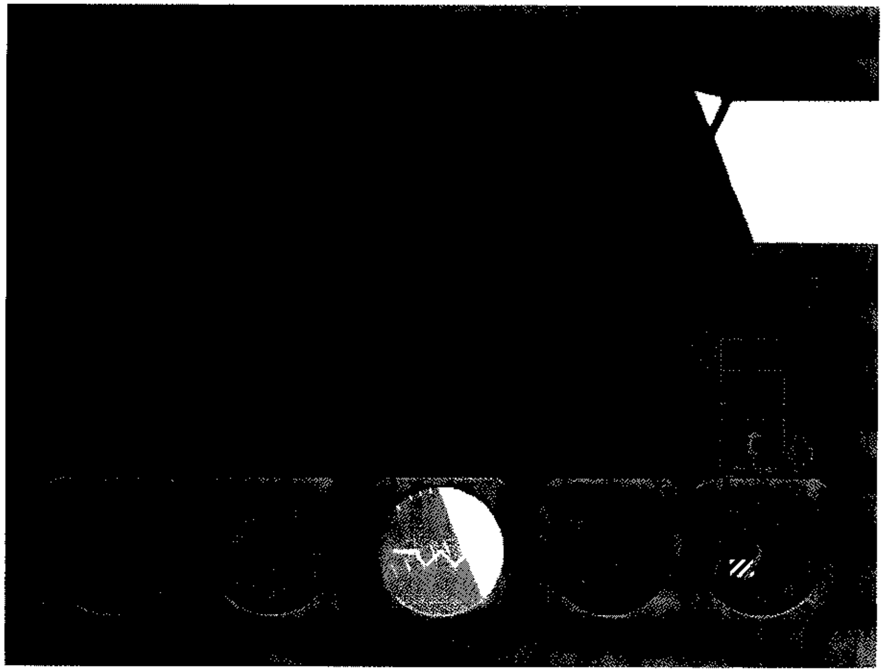
Roll acceleration	=	**7 deg/sec/sec - right**
Roll rate	=	**10 deg/sec - left**
Roll angle	=	**53 deg - left**
Yaw acceleration	=	**1 deg/sec/sec - right**
Yaw rate	=	**8 deg/sec - left**
Heading angle	=	**72 deg**
Wheel angle	=	**68 deg - right**
Rudder angle	=	**21 deg - left**
Column angle	=	**9 deg - nose up**
Normal load factor	=	**1.10 g's**

CVR time	**CVR comments/sounds**
140.65	**"hang on" – (Captain)**
141.50	**"oh shit" – (First Officer)**

Comments:
The First Officer reapplies right wheel, which slows the left roll rate down to 10 deg/sec. The Captain makes the third of four "hang on" comments. The column has moved aft to nearly three-quarters of its nose up authority. The throttles have been retarded towards idle.

Figure A12

TIME = 143.0



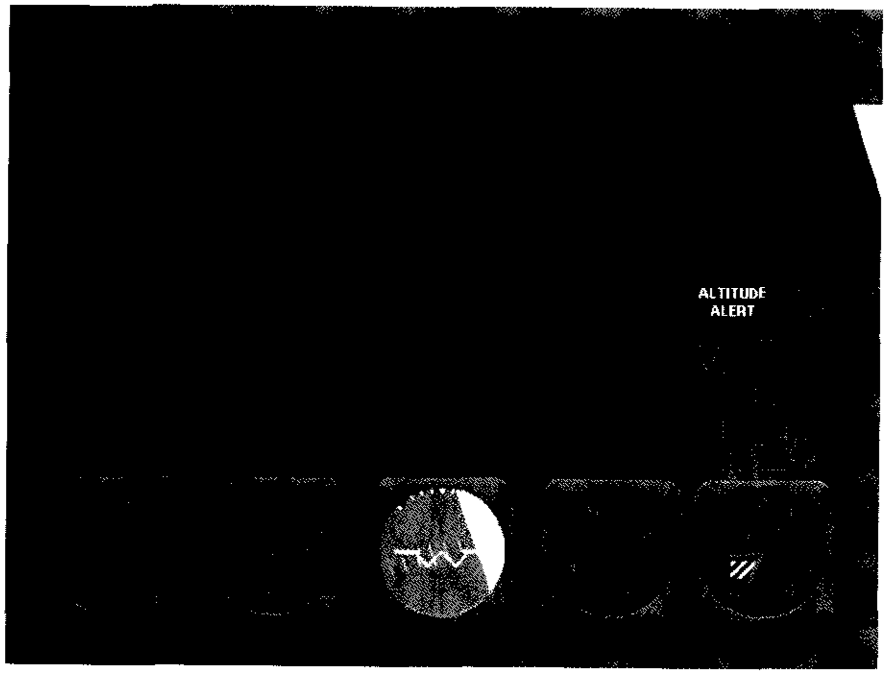
Roll acceleration	=	**4 deg/sec/sec - right**
Roll rate	=	**10 deg/sec - left**
Roll angle	=	**68 deg - left**
Yaw acceleration	=	**0 deg/sec/sec**
Yaw rate	=	**7 deg/sec - left**
Heading angle	=	**53 deg**
Wheel angle	=	**71 deg - right**
Rudder angle	=	**20 deg - left**
Column angle	=	**10 deg - nose up**
Normal load factor	=	**1.66 g's**

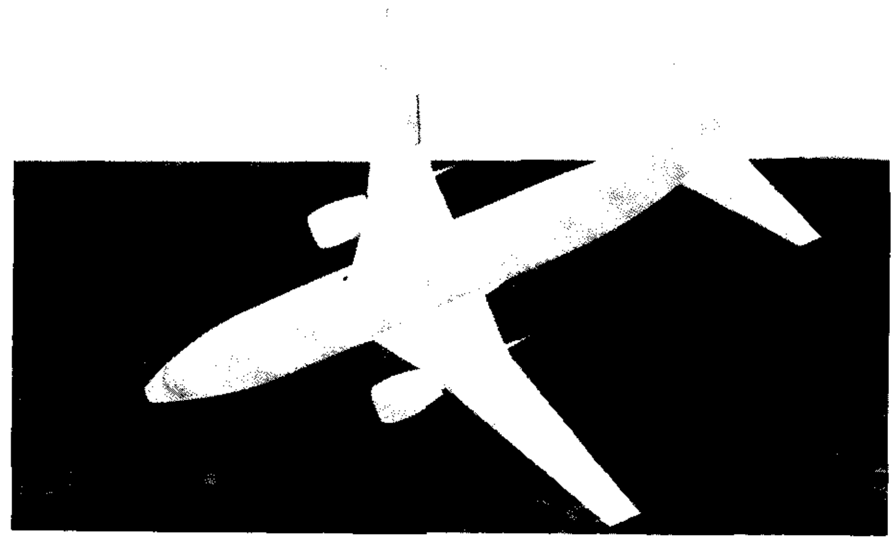
CVR time	CVR comments/sounds
142.25	**"hang on" – (Captain)**

Comments:
The crew now increases the wheel to a full right command, which reduces the left roll rate. More aft column is used. The Captain says again to "hang on"

Figure A13

TIME = 145.0





Roll acceleration	=	**16 deg/sec/sec - left**
Roll rate	=	**8 deg/sec - left**
Roll angle	=	**70 deg - left**
Yaw acceleration	=	**1 deg/sec/sec - left**
Yaw rate	=	**9 deg/sec - left**
Heading angle	=	**28 deg**
Wheel angle	=	**85 deg - right**
Rudder angle	=	**22 deg - left**
Column angle	=	**12 deg - nose up**
Normal load factor	=	**2.05 g's**

<u>CVR time</u>	**<u>CVR comments/sounds</u>**
145.05	**"stall warning" – (cockpit area mic)**
145.10	**"What the hell is this" – (Captain)**

Comments:
The roll rate is decreased to near zero – full wheel overpowers full rudder. The column is essentially full aft. The crew's action of trying to change pitch attitude prior to rolling wings level results in an aerodynamic stall, loss of roll control, and a stalled aircraft until ground impact.

Figure A14