NATIONAL TRANSPORTATION SAFETY BOARD
Office of Research and Engineering
Washington, DC

February 26, 1999

Addendum to Rudder Jam Simulation Study

By Dennis Crider

A. ACCIDENT DCA-94-MA-076

Location: Aliquippa, Pennsylvania
Date: September 8, 1994
Time: 1904 Eastern Daylight Time
Aircraft: Boeing 737-300, N513AU

B. GROUP IDENTIFICATION

There was no group participation in this study.

C. SUMMARY

On September 8, 1994 at 1904 Eastern Daylight Time, USAir Flight 427, a Boeing 737-3B7, N513AU, crashed while maneuvering to land at Pittsburgh International Airport, Pittsburgh, Pennsylvania. The airplane was being operated on an instrument flight rules (IFR) flight plan under the provisions of Title 14, code of Federal Regulation (CFR), Part 121, on a regularly scheduled flight from Chicago O'Hare International Airport, Chicago, Illinois, to Pittsburgh. The airplane was destroyed by impact forces and fire near Aliquippa, Pennsylvania. All 132 persons on board the airplane were fatally injured.

D. DETAILS OF INVESTIGATION

Overview

The Rudder Jam Simulation Study used data from the August 1997, systems group tests on the USAir427 PCU to see how consistent a secondary slide jam was with Flight Data Recorder (FDR) data. This study documents the present state of the USAir427 simulation incorporating the following changes.

- The initial 3 degrees rudder before the application of the jammed secondary slide rudder has been eliminated.
- A revision of the Cockpit Voice Recorder (CVR) transcript has eliminated the sound of the stabilizer early in the departure sequence. Accordingly, the stabilizer change in the original report has been eliminated and replaced with a change to the lift and pitching moment wake increments.
- In October of 1998, a discrepancy was discovered in the rudder blow-down table Boeing originally provided. Further investigation into this matter revealed that the effect of pedal force on rudder blow-down was not as trivial as thought. Accordingly, the lookup table method of establishing rudder blow-down was replaced with a rigorous simulation that accounted for pressure and flow rates through the valve. The code deviated from the Boeing equations slightly to allow for the input of pedal force for the jammed secondary slide condition.
- NTSB human performance staff determined that the pilot's response to the 20 degrees left bank at 19:02:59 should be between 40 and 60 degrees of wheel. The roll wake affect has been reduced to be consistent with the upper end of this range.
- A change to the FDR altitude trace (a barometric correction) was made. This addendum uses this revised altitude.

Procedure

The simulation was conducted using the Safety Board's 737-300 simulation. For investigation of a jammed rudder, the user inputs the hydraulic load (which varied with position of the jam) and an orifice coefficient (for USAir

427, a value of .098 was used). This modification was used to model the degradation in available rudder hinge moment measured for a jammed secondary slide. Rudder traces were input directly from a file (and overridden by the simulation when they reached the blow-down limit). Pedal Force, Wheel and elevator controls were input as time histories from a file.

The simulation was started at time = 19:02:52.9. At this point flight 427 was in a turn at a changing flight state. Accordingly, the simulation was trimmed to the following dynamic condition.

Airspeed = 189.835 KCAS
Altitude = 5992.8 ft
Heading = 106.75 degrees
Pitch Angle = 7.22 degrees (nose up)
Bank Angle = -13.89 degrees (left wing down)
Control column = 0.4 degrees (nose up)
Pitch Rate = 0.2 degrees/sec (nose up)
Yaw Rate = -1.17 degrees/sec (nose left)
Roll Rate = 0.45 degrees/sec (right wing down)

Except for the angular rates, these conditions came from the FDR. The angular rates were iterated from their initial estimated values to match the initial portion of the flight path. Thrust was developed from Engine Pressure Ratio (EPR) recorded on the FDR. Elevator was obtained from the FDR column.

Wake Modeling

The Safety Board 737-300 simulation inputs wake as a time history of changes in the aerodynamic coefficients. The original study used the wake estimates developed by Boeing. Briefly, except for the change in yawing moment coefficient, a Rankine vortex was used to determine a flow field. Aerodynamics coefficients were then obtained using strip theory. The change in yawing moment coefficient was obtained empirically as a function of position relative to the wake vortex core from the September 1995 wake vortex flight test. Since control column and engine N1 were available from the FDR, the longitudinal motion of the airplane was specified, except for external forces (the wake). Accordingly, the wake

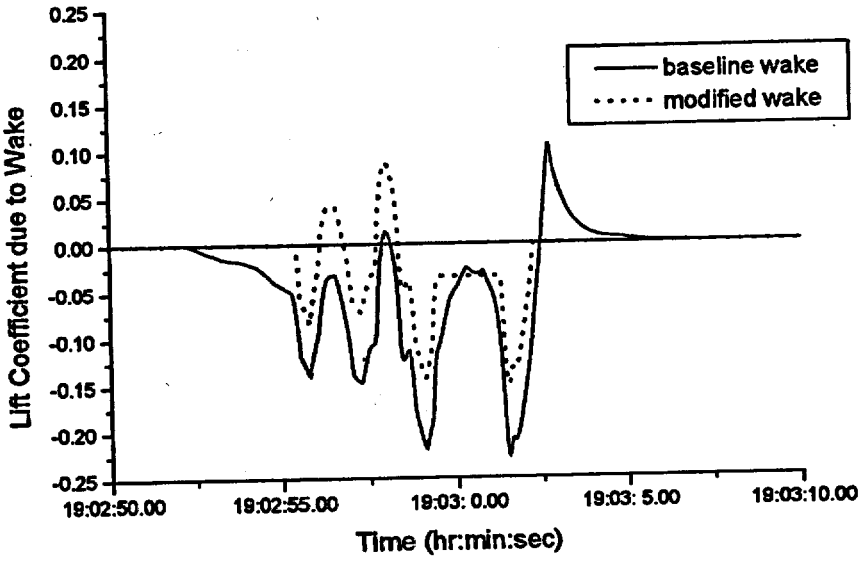
was positioned to account for the difference between the no wake aircraft longitudinal motion and the recorded airplane longitudinal motion.

The original Jam study used a stabilizer movement early in the departure sequence to match the recorded longitudinal motion. As mentioned above, a revision of the CVR transcript has eliminated the sound of the stabilizer during this time period. Since the stabilizer change was no longer available as a mechanism to account for the excess pitching moment, the effect of the wake on lift and pitching moment were revised.

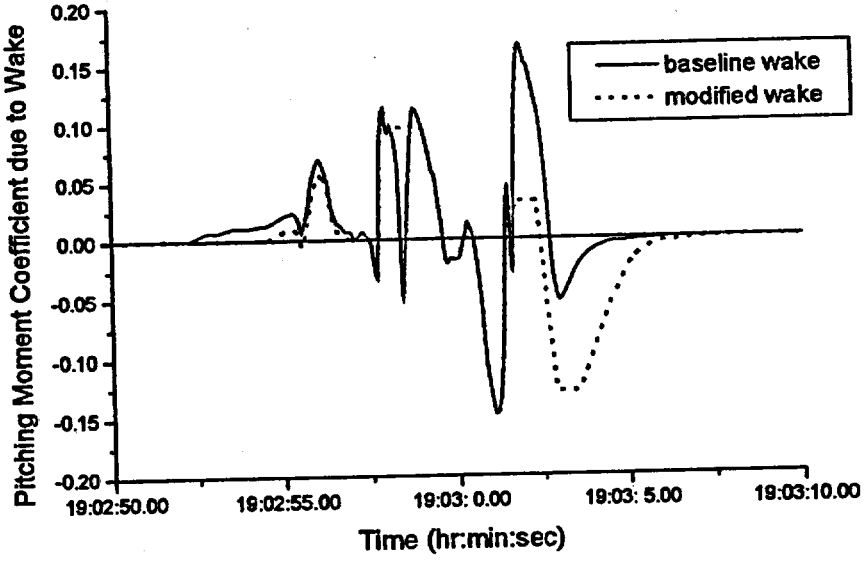
All previous work has shown full opposing wheel in response to the 20 degrees left bank at 19:02:59. NTSB Human Performance and Operations staff determined that this pilot response to a 20 degree bank was excessive and specified a wheel range of 40 to 60 degrees as appropriate for this stimulus. Accordingly the roll component of the wake was reduced, targeting a 60 degree wheel in this area.

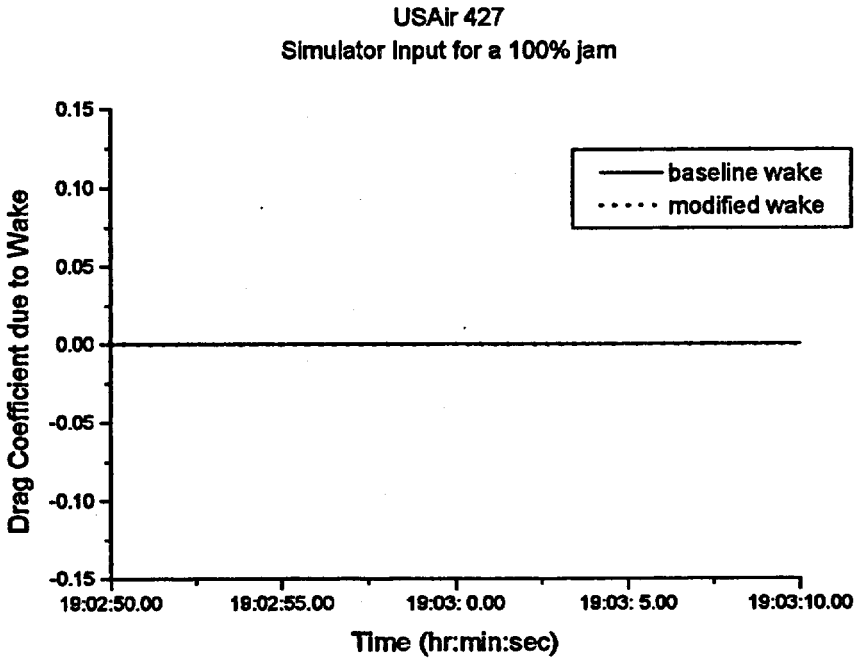
In addition, the wake yawing moment wake component beginning at 19:05:58 was extended 0.15 sec for a fraction of a degree improvement in the heading match early in the departure. The wake yawing moment component beginning at 19:03:02 was extended 0.45 sec to improve the pitch match later in the sequence. These changes corresponded to extending the time the vertical tail was in proximity to the wake core. The modified wake yawing moment is compared to the original in the following plots.

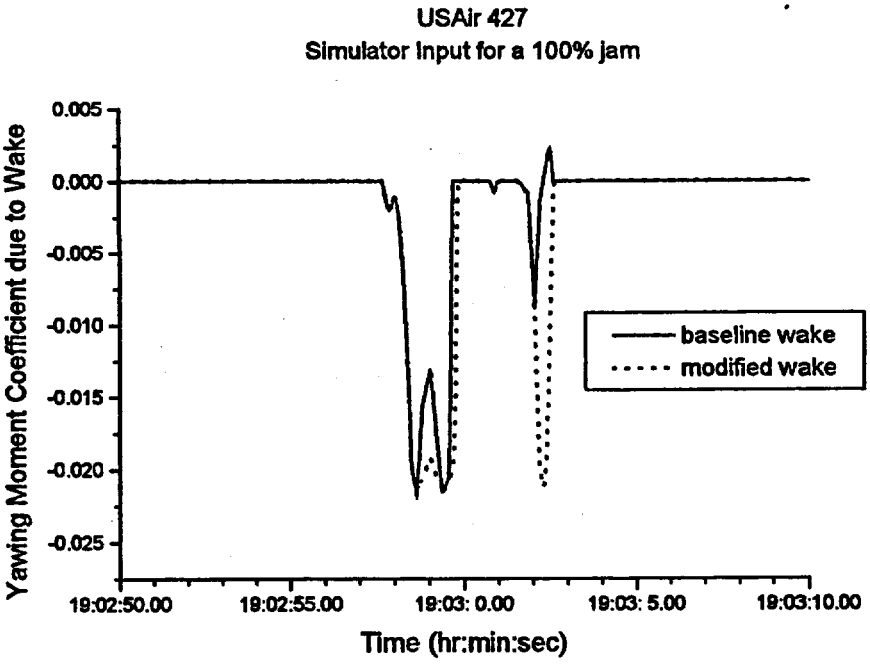
USAir 427
Simulator Input for a 100% jam

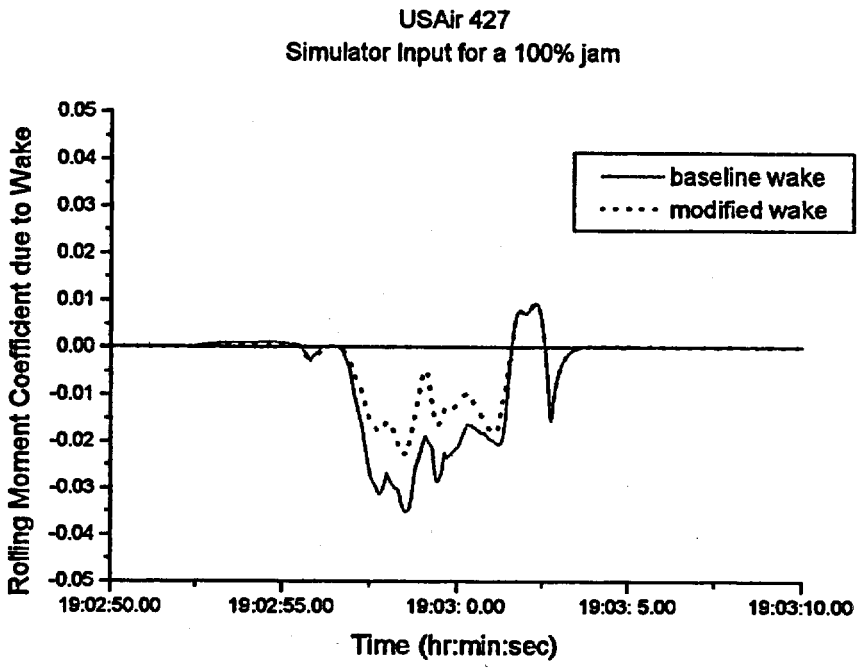


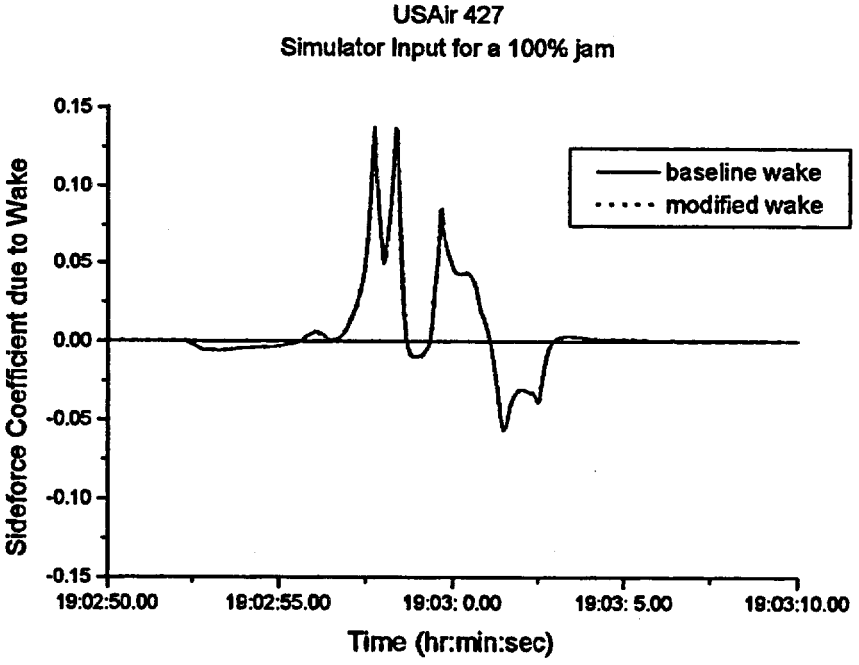
USAir 427
Simulator Input for a 100% jam




USAir 427
Simulator Input for a 100% jam
Drag Coefficient due to Wake
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
baseline wake
modified wake
19:02:50.00
19:02:55.00
19:03: 0.00
19:03: 5.00
19:03:10.00
Time (hr:min:sec)

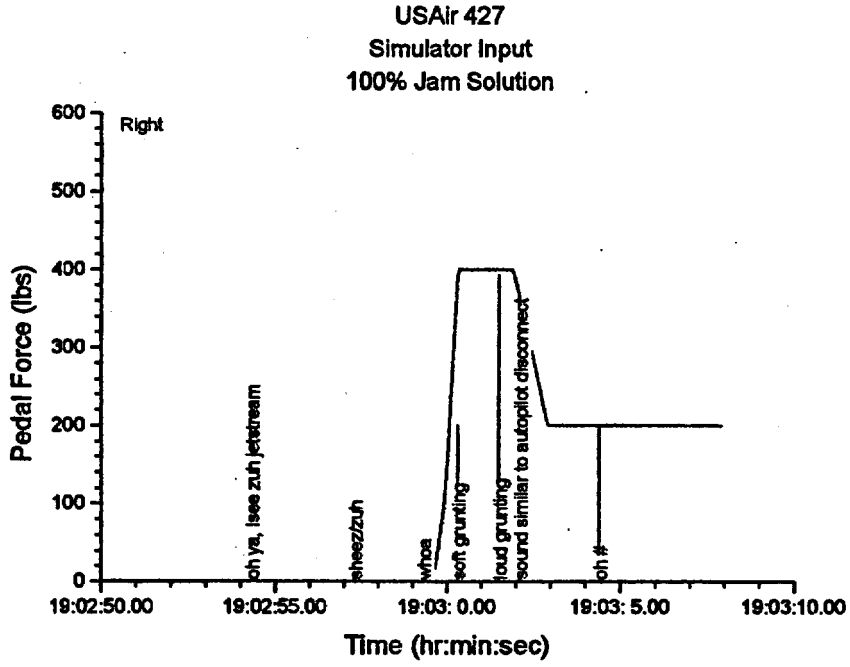

USAir 427
Simulator Input for a 100% jam
Yawing Moment Coefficient due to Wake
0.005
0.000
-0.005
-0.010
-0.015
-0.020
-0.025
baseline wake
modified wake
19:02:50.00
19:02:55.00
19:03: 0.00
19:03: 5.00
19:03:10.00
Time (hr:min:sec)


USAir 427
Simulator Input for a 100% jam
Rolling Moment Coefficient due to Wake
0.05
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
baseline wake
modified wake
19:02:50.00
19:02:55.00
19:03: 0.00
19:03: 5.00
19:03:10.00
Time (hr:min:sec)

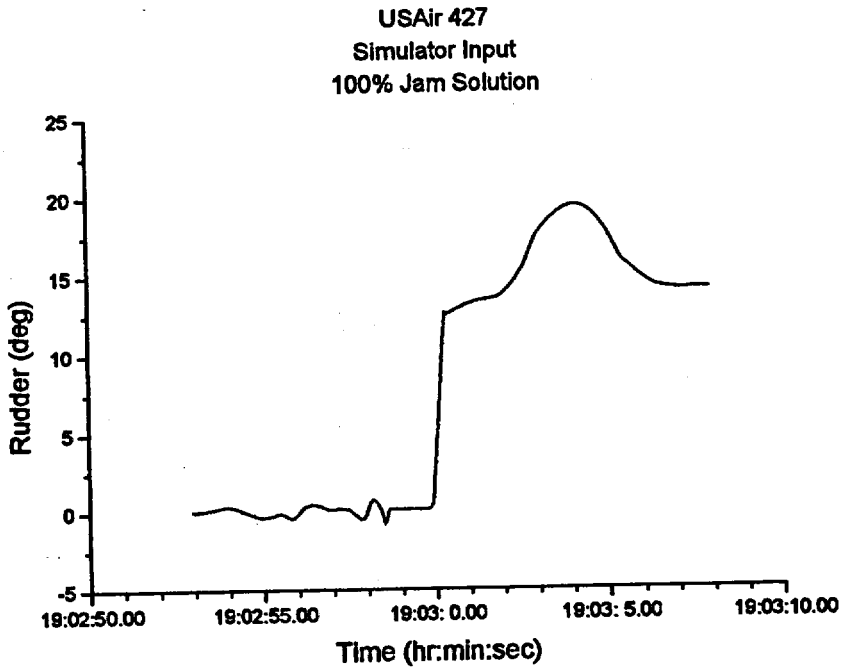

USAir 427
Simulator Input for a 100% jam
Sideforce Coefficient due to Wake
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
baseline wake
modified wake
19:02:50.00
19:02:55.00
19:03: 0.00
19:03: 5.00
19:03:10.00
Time (hr:min:sec)

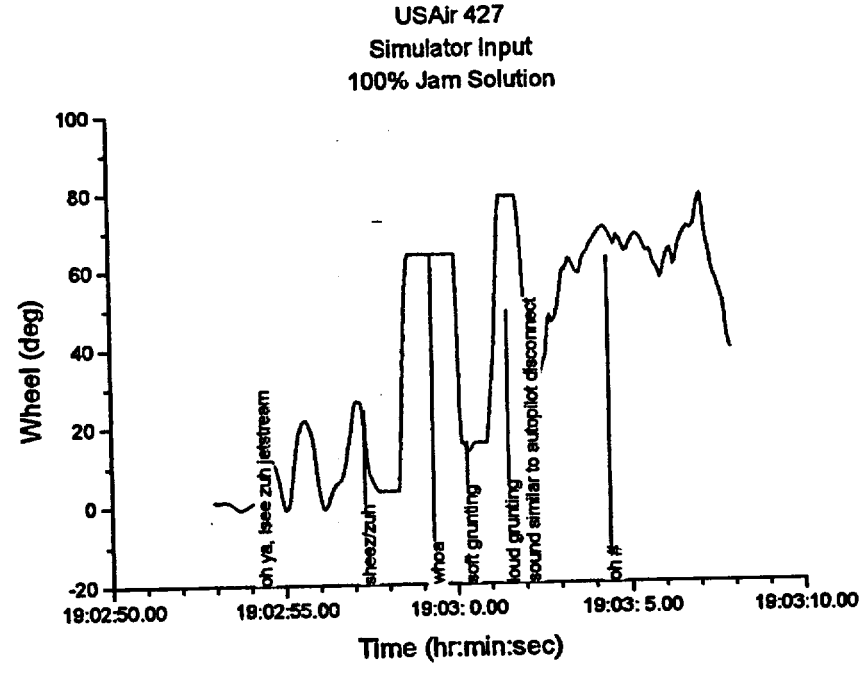
100% Jam Solution

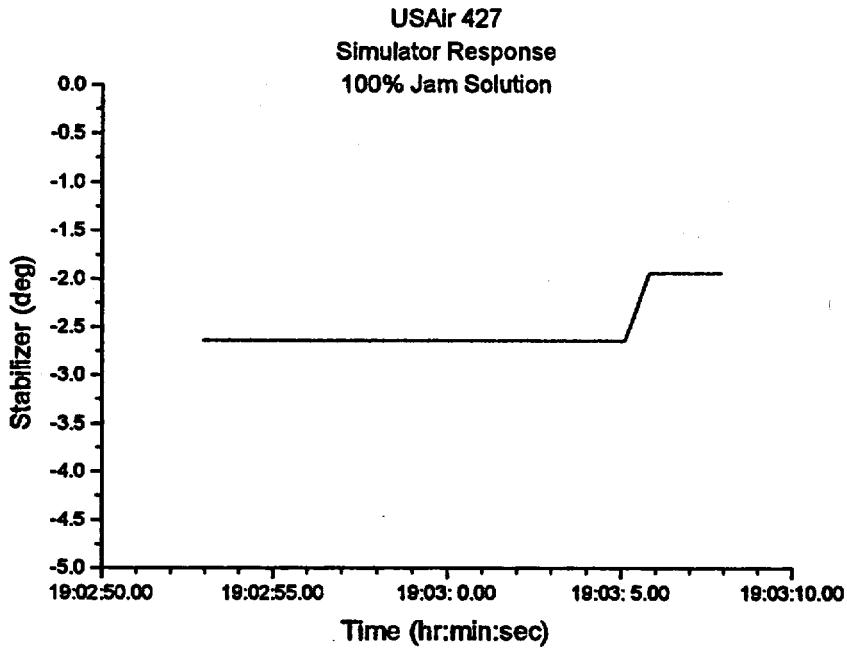
Plots of control input[1] and the resulting FDR match are shown below for a 100% jam using a hydraulic pressure of 2891 psi. The pedal force time history was developed with the help of NTSB human performance staff.

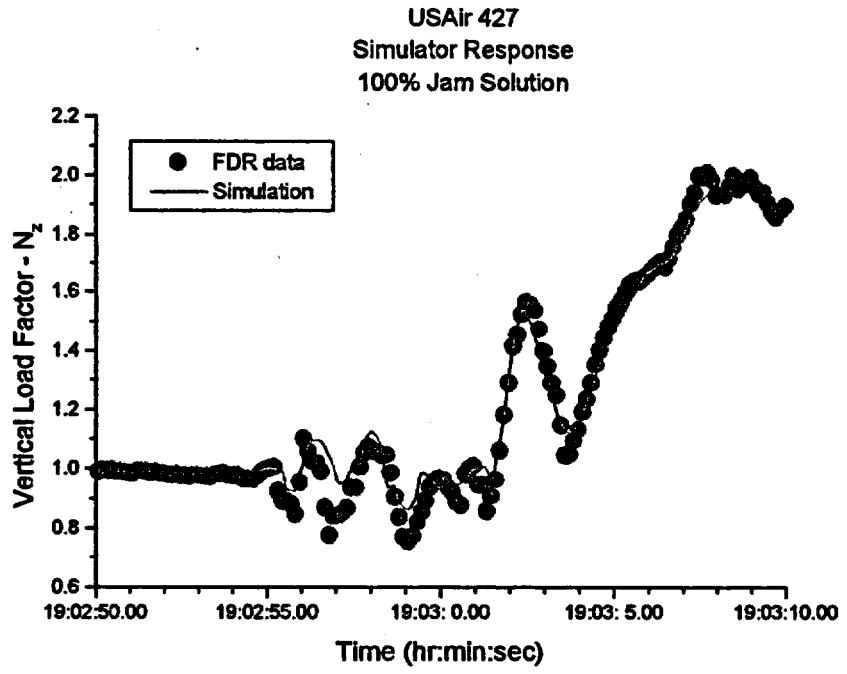


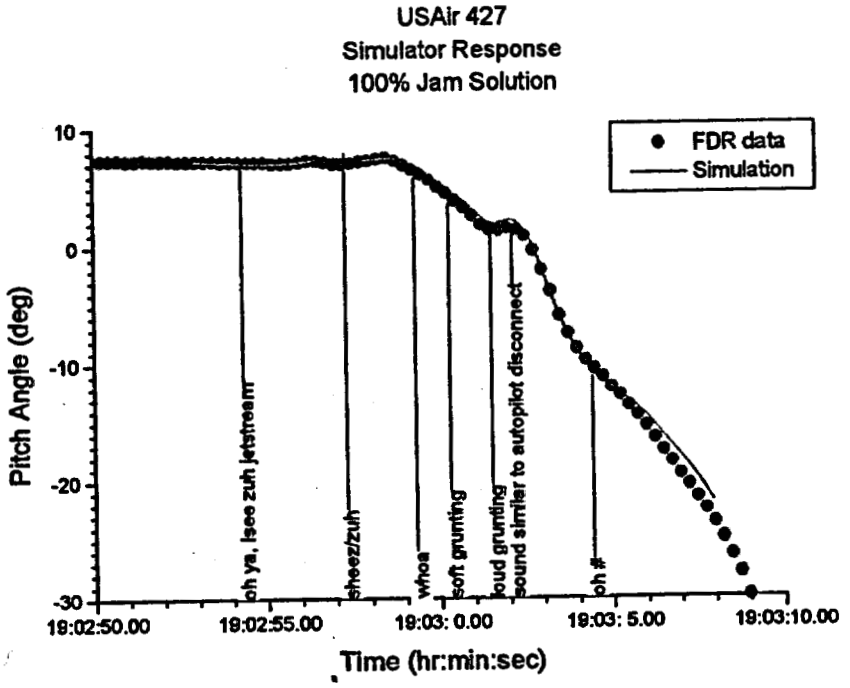
[1] Stabilizer was used late in the sequence to provide a small pitching moment change to facilitate the match. There is no evidence on the CVR of a stabilizer movement at this time. However, at this point in the event, the aircraft is past the wake and rapidly approaching stall in a full rudder sideslip. This is outside the normal flight envelope where one would expect the fidelity of the aerodynamic model to be degraded.

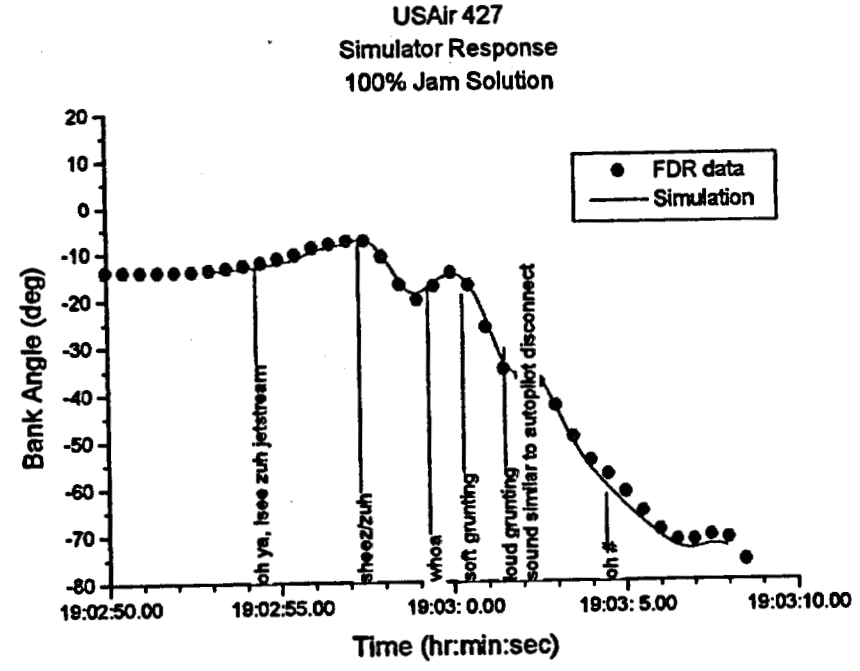

USAir 427
Simulator Input
100% Jam Solution
Rudder (deg)
25
20
15
10
5
0
-5
19:02:50.00
19:02:55.00
19:03: 0.00
19:03: 5.00
19:03:10.00
Time (hr:min:sec)

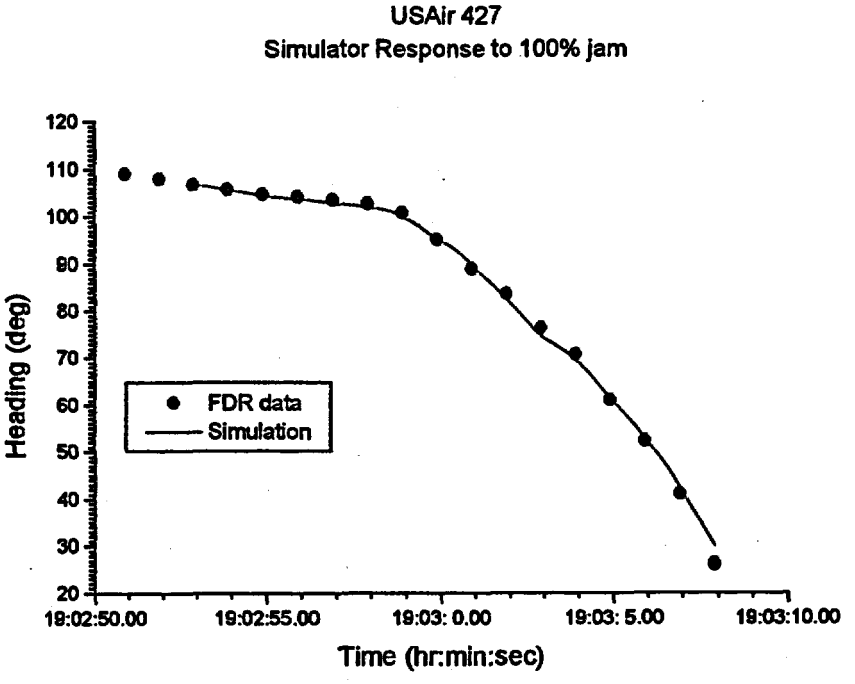

USAir 427
Simulator Input
100% Jam Solution
Wheel (deg)
100
80
60
40
20
0
-20
oh ya, ksee zuh jetstream
sheez/zuh
whos
soft grunting
loud grunting
sound similar to autopilot disconnect
oh #
19:02:50.00
19:02:55.00
19:03: 0.00
19:03: 5.00
19:03:10.00
Time (hr:min:sec)


USAir 427
Simulator Response
100% Jam Solution
Stabilizer (deg)
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-4.5
-5.0
19:02:50.00
19:02:55.00
19:03: 0.00
19:03: 5.00
19:03:10.00
Time (hr:min:sec)


USAir 427
Simulator Response
100% Jam Solution
FDR data
Simulation
Vertical Load Factor - Nz
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
19:02:50.00
19:02:55.00
19:03: 0.00
19:03: 5.00
19:03:10.00
Time (hr:min:sec)


USAir 427
Simulator Response
100% Jam Solution
FDR data
Simulation
Pitch Angle (deg)
10
0
-10
-20
-30
oh ya, lsee zuh jetstream
sheez/zuh
whoa
soft grunting
loud grunting
sound similar to autopilot disconnect
oh #
19:02:50.00
19:02:55.00
19:03: 0.00
19:03: 5.00
19:03:10.00
Time (hr:min:sec)


USAir 427
Simulator Response
100% Jam Solution
FDR data
Simulation
Bank Angle (deg)
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
oh ya, lsee zuh jetstream
sheez/zuh
whoa
soft grunting
loud grunting
sound similar to autopilot disconnect
oh #
19:02:50.00
19:02:55.00
19:03: 0.00
19:03: 5.00
19:03:10.00
Time (hr:min:sec)



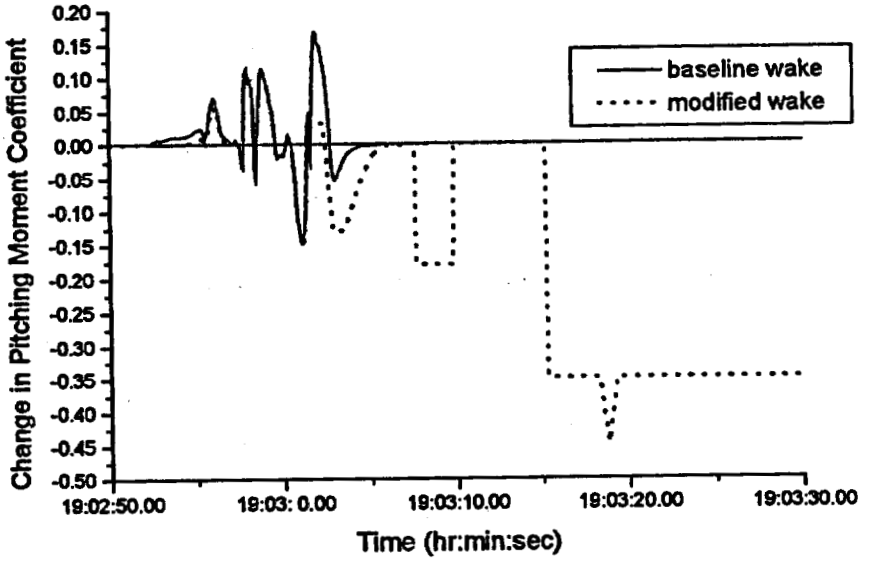
Conclusions

An updated solution has been obtained with the changes outlined in the overview. Including pilot pedal force in the rudder blow down modeling has resulted in an increase in the hinge moment (and thus jam position) required to match the data.

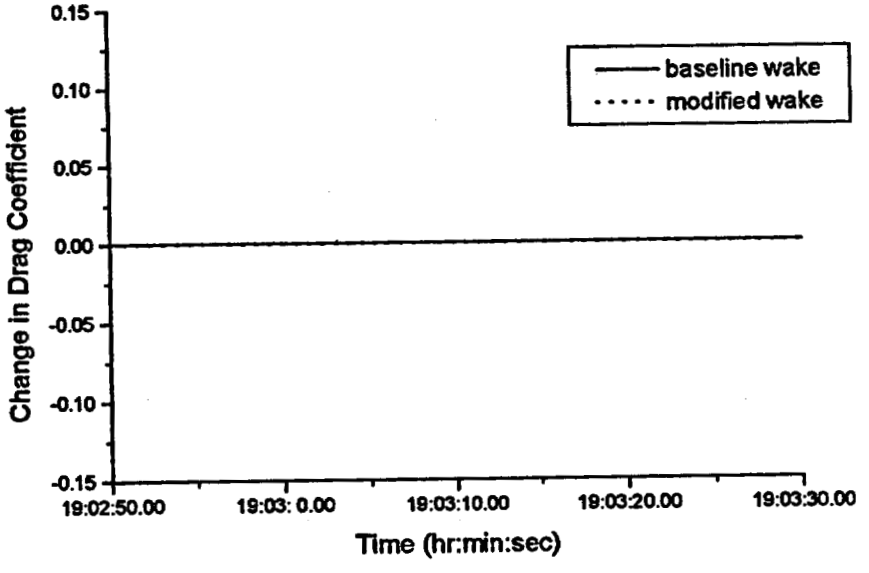
[redacted]

Dennis Crider
Aerospace Engineer

USAir 427
Aerodynamic change due to wake and stall

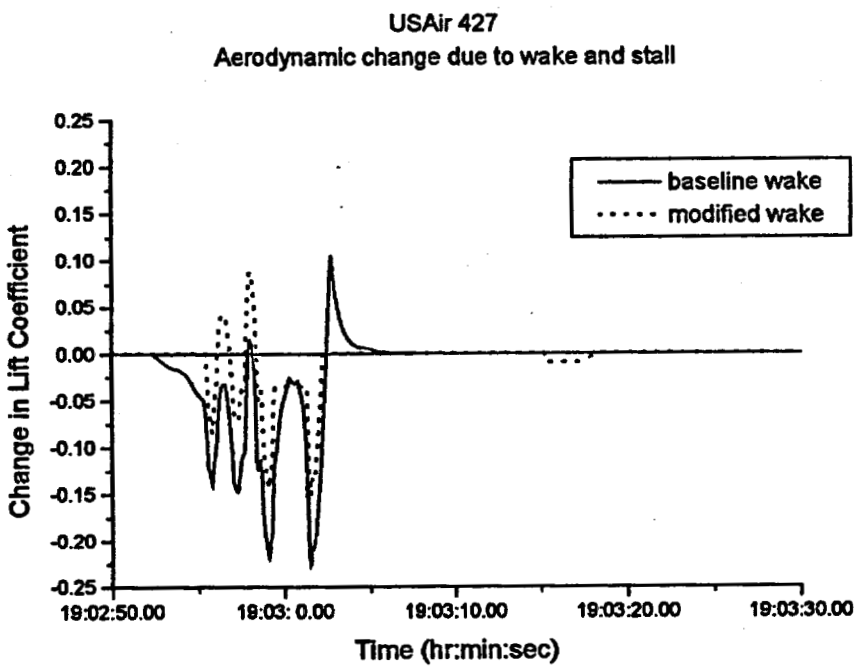


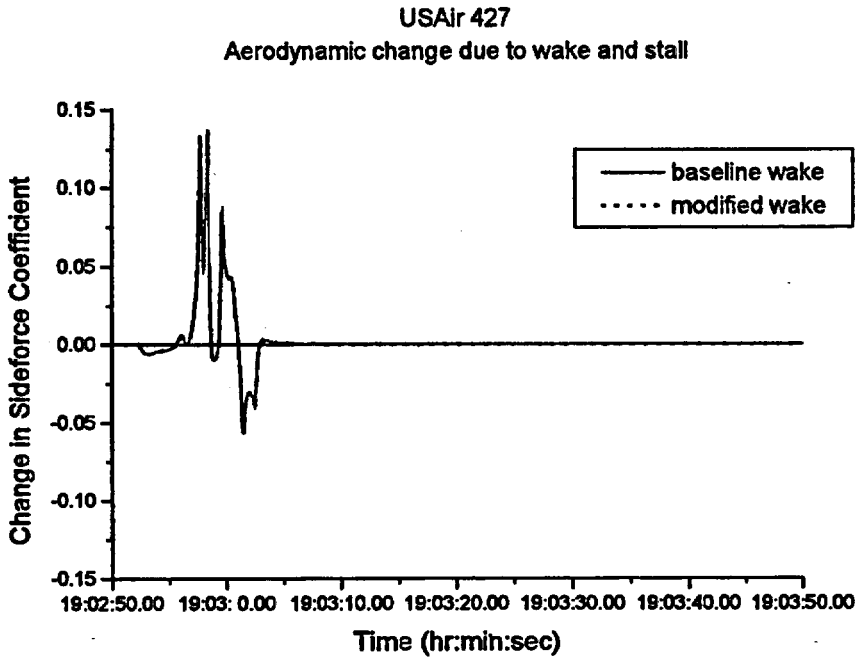
USAir 427
Aerodynamic change due to wake and stall

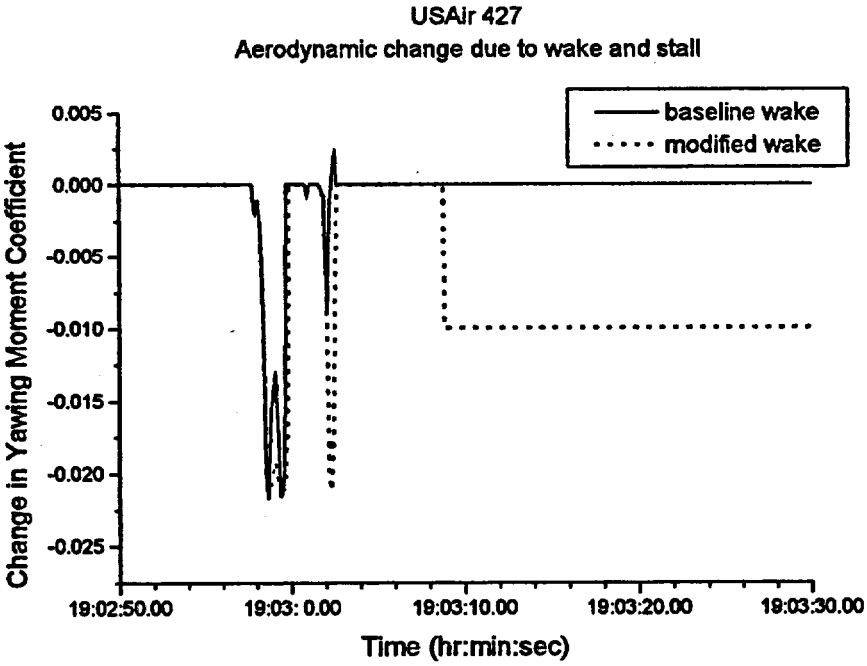


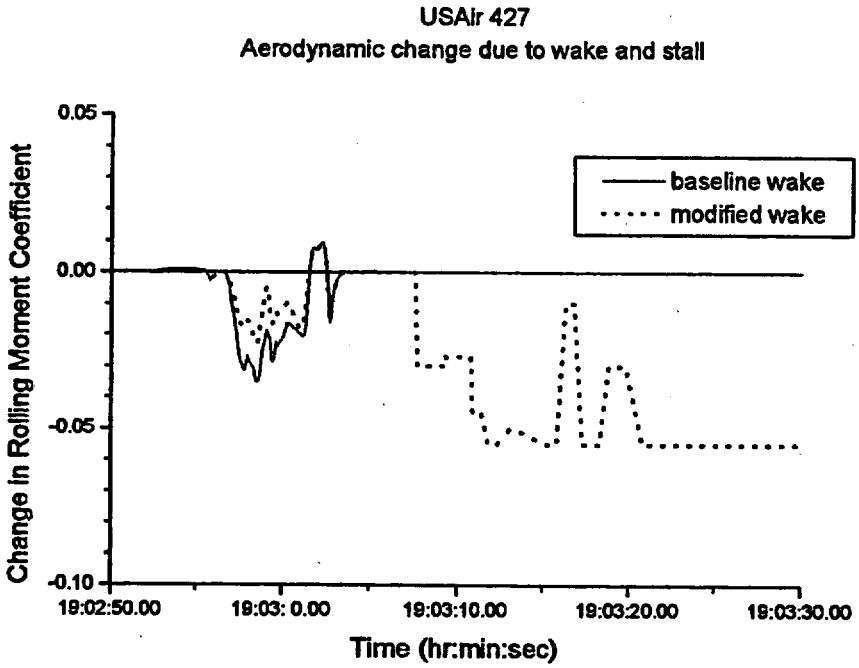
Appendix A

This appendix continues the simulation documented in this addendum to the ground in support of the 427 animation. The aerodynamic model becomes unreliable near stall (about 19:03:08). Accordingly, the delta aerodynamic coefficient time histories were used to control the simulation. Wheel was assumed to remain full in against the departure while rudder continued at blow down.

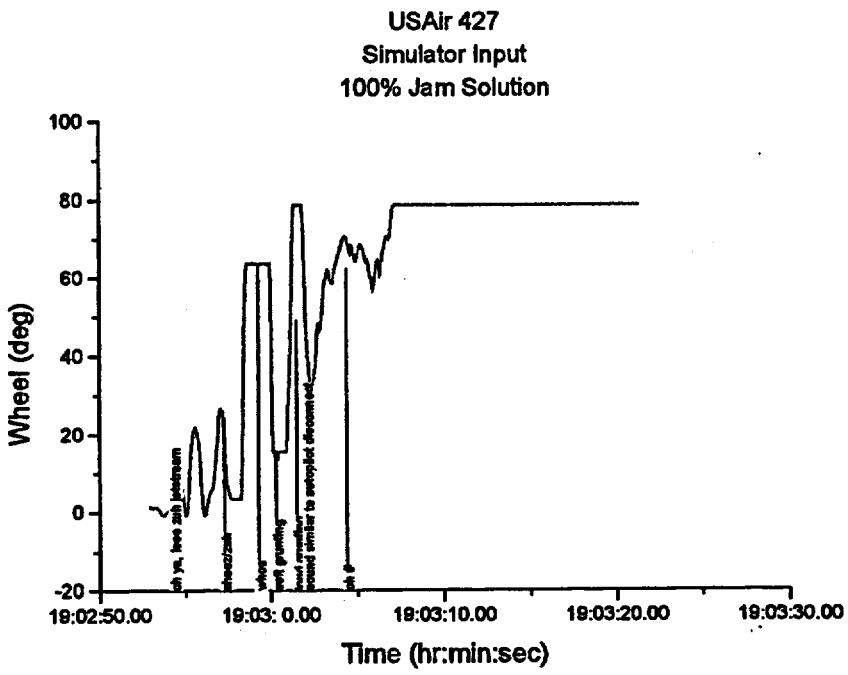


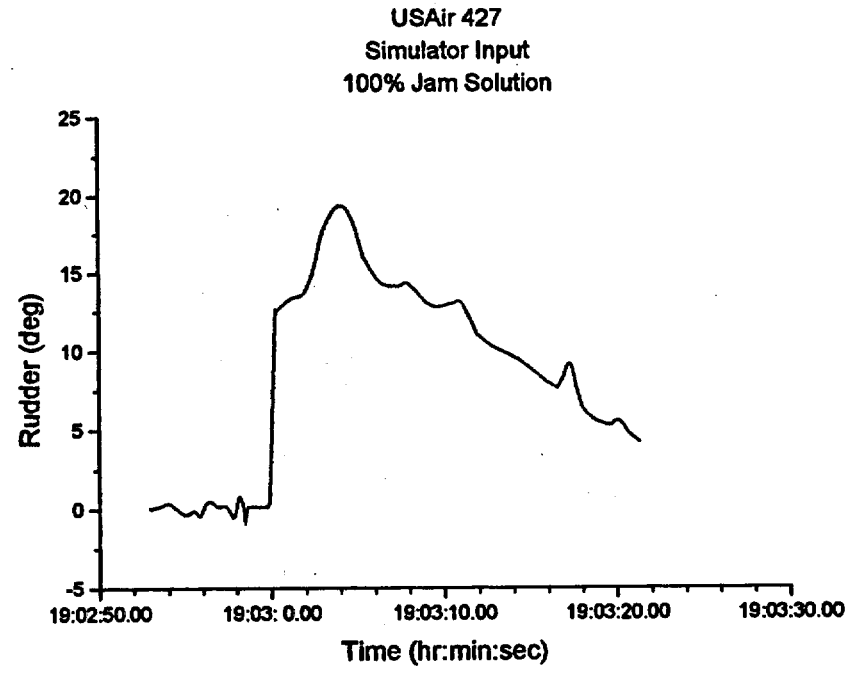

USAir 427
Aerodynamic change due to wake and stall
baseline wake
modified wake
Change in Sideforce Coefficient
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
19:02:50.00
19:03: 0.00
19:03:10.00
19:03:20.00
19:03:30.00
19:03:40.00
19:03:50.00
Time (hr:min:sec)


USAir 427
Aerodynamic change due to wake and stall
baseline wake
modified wake
Change in Yawing Moment Coefficient
0.005
0.000
-0.005
-0.010
-0.015
-0.020
-0.025
19:02:50.00
19:03: 0.00
19:03:10.00
19:03:20.00
19:03:30.00
Time (hr:min:sec)

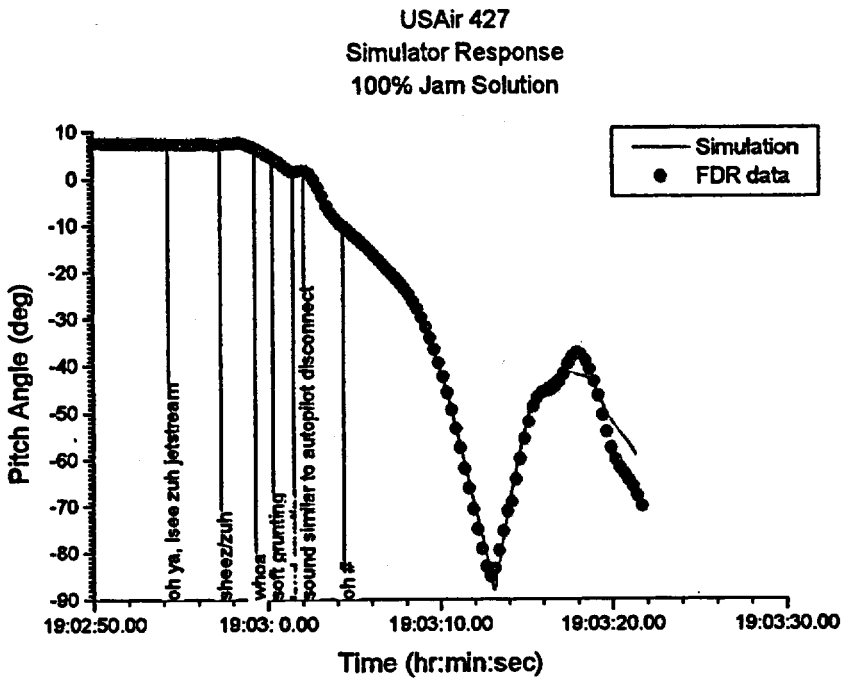


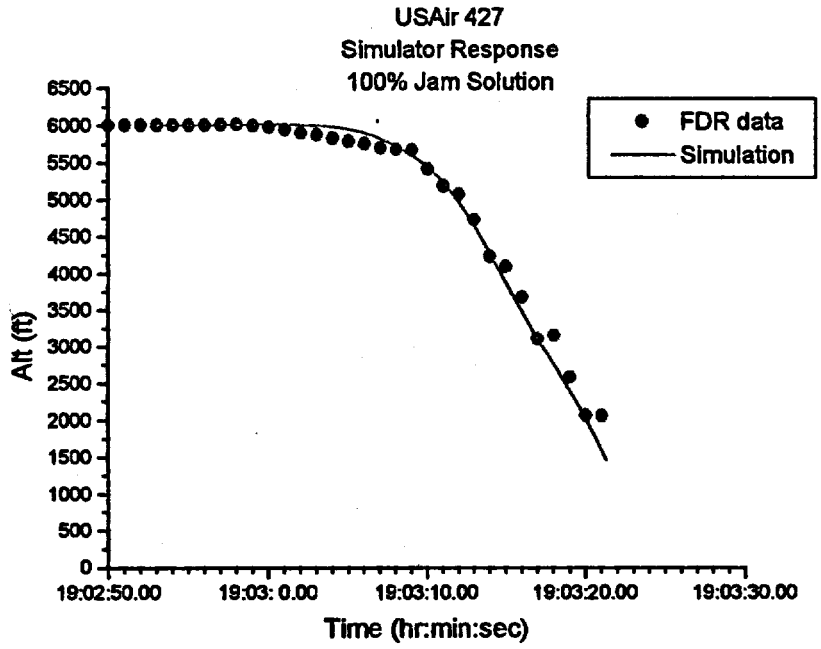
The control input for the simulation is given below. The pedal force maintains 200 lb to the end of the simulation. Control column is from the FDR.

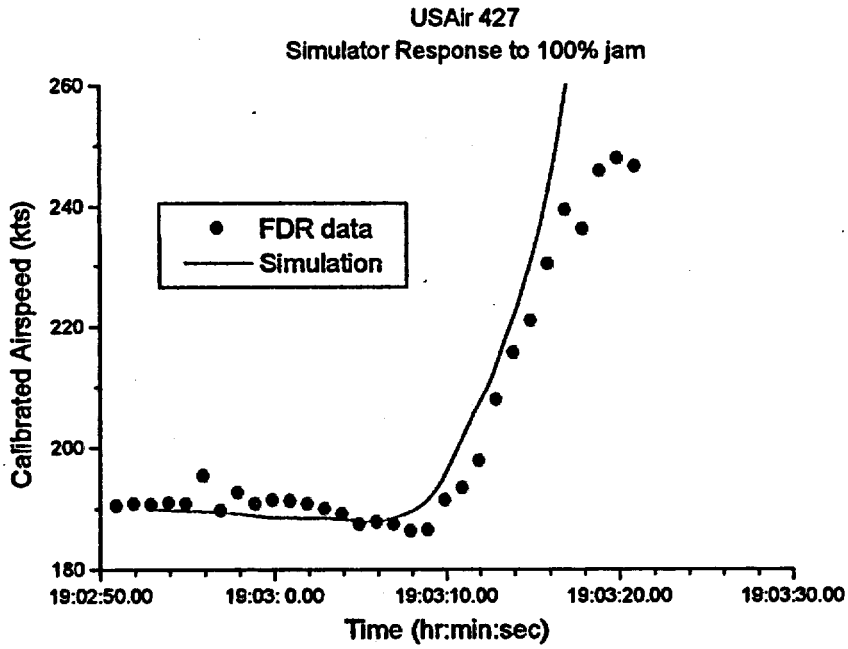

USAir 427
Simulator Input
100% Jam Solution
Wheel (deg)
100
80
60
40
20
0
-20
19:02:50.00
19:03: 0.00
19:03:10.00
19:03:20.00
19:03:30.00
Time (hr:min:sec)

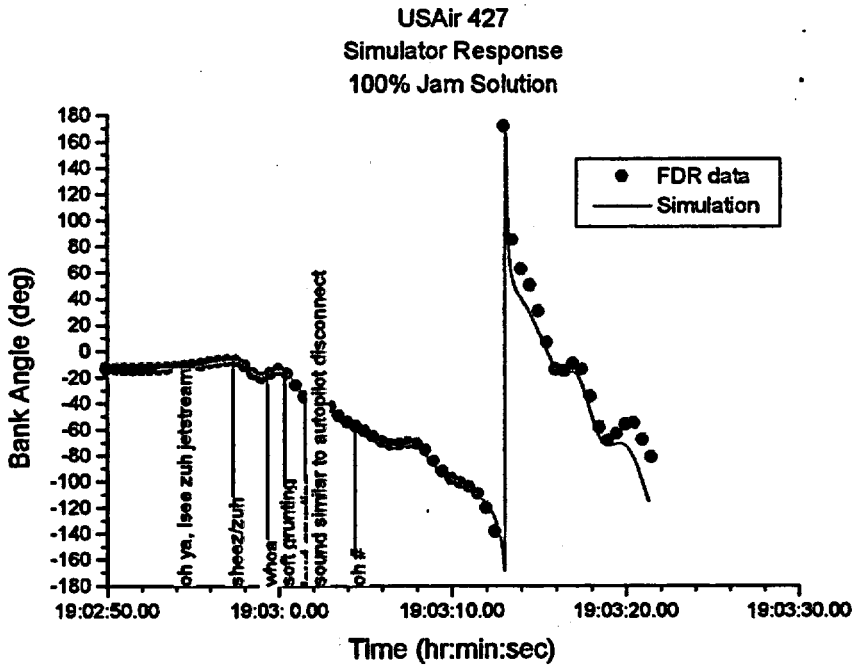

USAir 427
Simulator Input
100% Jam Solution
Rudder (deg)
25
20
15
10
5
0
-5
19:02:50.00
19:03: 0.00
19:03:10.00
19:03:20.00
19:03:30.00
Time (hr:min:sec)

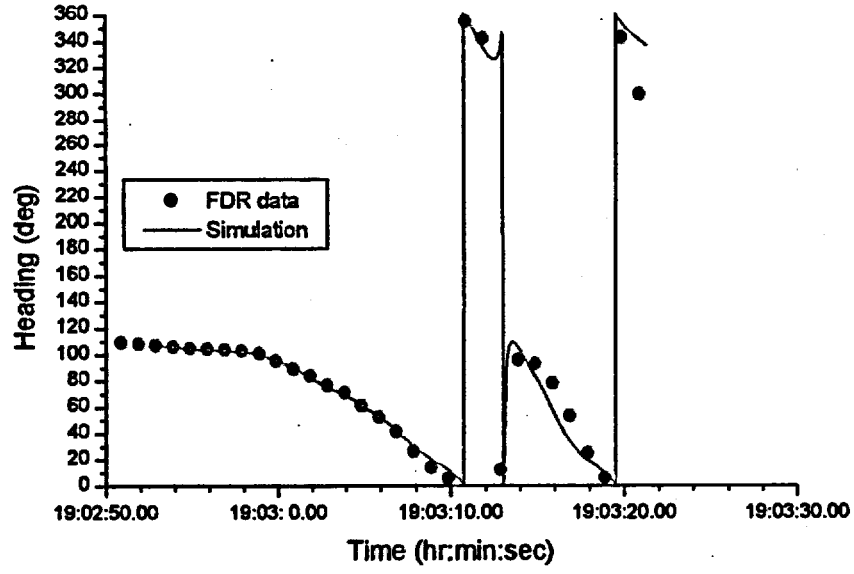
The simulation results are compared to the FDR data in the following plots. Note that tolerances for the match were relaxed after stall.




USAir 427
Simulator Response
100% Jam Solution
FDR data
Simulation
Alt (ft)
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
19:02:50.00
19:03: 0.00
19:03:10.00
19:03:20.00
19:03:30.00
Time (hr:min:sec)


USAir 427
Simulator Response to 100% jam
FDR data
Simulation
Calibrated Airspeed (kts)
260
240
220
200
180
19:02:50.00
19:03: 0.00
19:03:10.00
19:03:20.00
19:03:30.00
Time (hr:min:sec)


USAir 427
Simulator Response
100% Jam Solution
FDR data
Simulation
Bank Angle (deg)
oh ya, lsee zuh jetstream
sheez/zuh
whoa
soft grunting
sound similar to autopilot disconnect
oh #
19:02:50.00
19:03: 0.00
19:03:10.00
19:03:20.00
19:03:30.00
Time (hr:min:sec)


USAir 427
Simulator Response to 100% jam
FDR data
Simulation
Heading (deg)
19:02:50.00
19:03: 0.00
19:03:10.00
19:03:20.00
19:03:30.00
Time (hr:min:sec)