NATIONAL TRANSPORTATION SAFETY BOARD
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Kinematics Validation 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

This study was conducted under the Aircraft Performance Group. However, group participation was limited to the curve fit activities.

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

N513AU was equipped with a Flight Data Recorder (FDR) which did not record any information for either yaw or roll controls. Control column position was, however, recorded providing some pitch control information. In order to determine the yaw and roll control position time histories for the accident, the vehicle performance group initiated a kinematics study. In this case kinematics refers to the process by which forces and moments acting on an aircraft are determined from the motion of the aircraft. With forces and moments known, the control surface positions (rudder, aileron, spoiler, elevator) required to produce these forces and moments are determined from aerodynamics.

In the case of USAir427, the kinematics study is further complicated by the presence of a wake vortex generated by a Boeing 727 on approach to Pittsburgh. The wake vortex is accounted for by adding wake effects to the aerodynamics model. Thus, the kinematics efforts, which were done by Boeing, can be divided into a) modeling the vortex encounter, and b) processing the FDR data through the kinematics process with the vortex effects accounted for in the aerodynamic model.

Tools for kinematics were developed at the Safety Board in order to validate the results of the Boeing developed kinematics. The kinematics process used by Boeing was validated using these tools and by on site investigation. The vortex modeling was validated by the author spending time at Boeing to understand the modeling, the resulting computer code, and the vortex matching process in detail.

Kinematics at the Safety Board

Kinematics as done at the Safety Board follows the following process (the Boeing process is outlined in the next section of this report).

1. Adjust the FDR data to common times corrected for word slot location.
2. Determine the forces and moments on the airplane required to produce the FDR-recorded motion.
3. Get the required aerodynamic coefficients.

4. Remove the vortex effect from the required aerodynamic coefficients.
5. Get the control deflections required to produce the aerodynamic coefficients.

Programs Columnar, FDRPlus and CoSurf have been written to perform the Kinematics steps. Step one is done with the Columnar program. Steps two and three are done with the FDRPlus program. Steps four and five are done with the CoSurf program.

A simulation program was also developed to aid in the study. Boeing 737-300 aerodynamics, engine and simplified controls were modeled and installed in program CoSurf and in the simulation using Boeing-supplied data tables. The aerodynamics model had the capacity to add a time history of aerodynamic coefficient deltas to the basic aerodynamic coefficients it calculates. This was used to input the vortex effects. Validation of the kinematics codes was completed and is outlined in attachment 1.

Kinematics at Boeing

The kinematics process used by Boeing was reviewed at Boeing's Renton Washington facility during the weeks of December 2nd and 9th of 1996. The process used for USAir427 is summarized below. Several steps in the procedure refer to KINESIS macros. Program KINESIS is a superset of FORTRAN which among other things is particularly adept at handling arrays. In KINESIS, each time history is a vector which is operated on as a whole. A KINESIS macro (a set of KINESIS instructions) is run through KINESIS to produce a standard FORTRAN source which is compiled and linked into an executable program.

1. The FDR binary data is converted to an ASCII file in engineering units. This is done with the program MAGS which is an off-the-shelf program developed by Aaco. Input to the program is a binary FDR data file and a data frame definition file.
2. Time history data files are created with the UNIX Script FDRSCEW. Input to the script is the FDR data file output from MAGS and a file with parameter word slot locations. Output from the script is time history files. The script does no interpolation. Each parameter has its own output file with unique time values.

3. The tool set program ADAPT is then used to linearly interpolate the data files to 40 points/sec. The files are then merged with one common time using another tool in ADAPT.
4. At approximately 150 sec there is a singularity point in the FDR Euler angles when the airplane pitches down near -90 degrees. A KINESIS macro is run iteratively to derive smooth Euler rate curves that when integrated match the Euler angles on the other side of the singularity.
5. The data is then processed with the USAIR427FLT.MTX KINESIS macro. Input to the macro is the semi raw FDR data. Output from the macro is conditioned longitudinal and vertical load factors, angle of attack, corrected altitude, conditioned Euler angles, body axis rates and body axis accelerations. The functions of the USAIR427FLT.MTX macro are summarized as follows.
   - The FDR pressure altitude (recorded assuming a 29.92 altimeter setting) is corrected for the altimeter setting reported by the field and for the effect of non-standard temperature lapse. The lapse rate was recorded by a weather balloon.
   - Conservatively, the airspeed system data is considered to be reliable until the absolute value of roll angle exceeds 20 degrees or the absolute value of roll rate exceeds 5 degrees/sec (about 134.8 seconds for USAir 427). Up to this point, the pressure altitude is compared to the altitude time history derived by integrating N_z and N_x. The difference is used to get the N_z offset. The body axis longitudinal airspeed component derived from airspeed is compared with the body axis longitudinal airspeed component derived from N_x and wind. The difference is used to get the N_x offset. From the final inertial altitude, a corrected static pressure time history is derived. A corrected airspeed is then obtained with this corrected static pressure assuming that the total pressure was accurate in the recorded airspeed. Altitude and airspeed derived from N_x and N_z are then used for the remaining calculations.
   - The body axis rates are then computed. The angular rates derived in step 4 are spliced in near the singularity.
   - The body axis rates are then filtered with a fast Fourier transform. The filtered rates are then differentiated to derive the accelerations.

- The heading was edited between 138.2 and 147.2 seconds to match the rudder trace. At the start of the rudder movement, the curve was edited to match the rudder which would have been produced by the yaw damper. At the end of the rudder event, the heading curve was edited so that the rudder trace would follow the rudder blow-down angle. This heading still produced some low amplitude yaw acceleration oscillations . These were manually smoothed, maintaining the same area under the curve, and placed into the edited yaw acceleration table. When the flag UseEditedRdot is set to "True," the macro will splice in the edited yaw acceleration into the data. This is re-integrated to get yaw rate and heading. The final integrated heading is compared to the original. The difference is run through a low pass filter and then added back on to the integrated heading. This provides a smooth transition between the edited area of the heading time history and the remaining unedited heading time history.

6. The KINESIS Simulation macro 737300SIM.MTX is then run iteratively as follows
   - For iteration 0 the flight control surface deflections are zero. The delta aerodynamic coefficients required to match the acceleration time histories are computed and estimated sideslip and control surface time histories are derived.
   - Subsequent iterations use the sideslip and control time histories computed in the previous iteration. Generally six iterations are required for convergence.
   - The wake aerodynamic deltas are added as time histories. The new control deflections are calculated linearly based on the appropriate required aerodynamic delta (for example rud = rud0 + delta C_n / $C_{n\ rud}$)

The sideslip angle obtained from step 6 is then fed back into step 5. Step 5 and 6 are run iteratively until sideslip converges (in 3 iterations). After January 13^{th}, 1997 the USA427FLT.MTS KINESIS macro and the 737300SIM.MTX macro were combined into the "big macro" USA427FLT_SIM.MTX. This effectively combined steps 5 & 6 above into one macro.

USAir427 Kinematics Validation

Steps one through four and part of step five of the Boeing process simply apply reasonable corrections to the FDR data. The "conditioned" FDR parameters are compared to the FDR parameter time histories used at the Safety Board in attachment 2. With the exception of altitude, which is calculated by FDRplus, The Safety Board FDR parameters were obtained by the procedure outlined in the "Data Preparation" section below. As can be seen in attachment 2, the Safety Board data is very similar to Boeing's data. The slight difference in altitude is largely due to the fact that, while both Boeing's and Safety Board's software account for non-standard surface pressure, the Safety Board's software uses a standard temperature lapse rate while Boeing's uses a measured temperature lapse from weather balloon data.

Boeing conditioned data was run through the Safety Board's Kinematics process and compared to Boeing results. These plots are presented in attachment 3. Several plots show noise in the Safety Board's kinematics results when compared to the Boeing results. Noise is introduced when position time histories are differentiated to get rates and again to a greater extent when these noisy rates are differentiated to get accelerations. Boeing applies a Fast Fourier Filter to reduce the noise in the rate time histories before differentiating to get accelerations. This significantly reduces the noise in accelerations and in acceleration dependent quantities (aerodynamic coefficients, control surface deflections, etc.). The Safety Board data was not filtered.

As a further check, the Safety Board's CoSurf program was run using Boeing-derived inputs (aerodynamic coefficients, rates etc.). The resulting control surface deflections are compared to the Boeing control results in attachment 4. It should be noted here that the aerodynamic coefficients input into CoSurf are derived from filtered rates and thus are smoother than the control surface deflections presented in attachment 3.

Safety Board Kinematics Solution

The Safety Board's kinematics process was applied to the Safety Board's FDR data independent of Boeing's data conditioning. The input does however include the Boeing-derived wake aerodynamic delta time histories and also uses the Boeing-derived sideslip (the reason for this is outlined in the next section).

Data Preparation

The Flight Data Acquisition Unit (FADU) instrumentation feeding into the FDR does not handle extreme pitch angles well. When the absolute value of pitch angle exceeds 85 degrees, the system holds the last heading and the last roll angle. USAir flight 427 exceeded -85 degrees pitch angle in the neighborhood of 149 sec to 151 sec.

Honeywell provided corrected data for pitch, roll, and heading angles in a December 2, 1994 memo from K. D. Vanderwert to Lou Taylor. Data from this memo was faired into the raw FDR data replacing raw FDR data in the following slots.

Subframe	Pitch Data Slot	Roll Data Slot	Heading Data Slot
149	none	1 2	1
150	1 2 3 4	1 2	1
151	1	none	none

The FDR data with Honeywell corrections was then fed into program COLUMNAR which corrected the data times for word slot locations and interpolated the data to common time breakpoints. The cubic spline option was chosen for the interpolation. The raw Honeywell data had an error in pitch when pitch hit zero. This was corrected. In addition, the signs of roll angle and control column were switched to match convention.

Results

The common time break-pointed data was run through programs FDRPlus and CoSurf. The results are presented and compared to Boeing's results in attachment 5. As mentioned previously, these results do not include any noise filtering.

Noise is introduced when position time histories are differentiated to get rates and again to a greater extent when these noisy rates are differentiated to get accelerations. Because of the noise, iteration for sideslip angle proved difficult (if not impossible). Accordingly, the Boeing derived sideslip angle was used.

USAir427 Vortex Encounter Validation

The wake vortex model was validated by the author by close inspection of the math model and associated code and by interviews with the responsible Boeing engineer. The validation took place during the weeks of December 1st and December 7th , 1996 at Boeing's Renton Washington facility.

Math Model Validation

The wake of the Boeing 727 ahead of USAir427 is modeled using a Rankine vortex model. The flow field from this vortex model is used to determine local delta alpha and delta beta for input into a strip theory aerodynamic model for all aerodynamic coefficients except yaw. Yawing moment coefficient is determined using empirical data from the September 1995 wake vortex flight test. The model is described in Boeing letter # B-B600-15828-ASI (Oct 25, 1996) included as an attachment to the Vehicle Performance Report. The derivation of the equations was validated by going through them one by one with the cognizant Boeing engineer. A sign error was found in the wake model documentation, but this error was not in the computer code.

Computer Code Validation

The computer code for the wake flow field itself is in subroutine WAKE27. This is called by subroutine DBEXEC which contains the strip theory aero wake delta code. A version of DBEXEC exists as a subroutine to PSIM. The version which was used to produce the aero delta's is a KINESIS macro. The computer code was reviewed section by section and was found to faithfully implement the math model.

Boeing's Code Validation

Boeing validated the WAKE27 subroutine which calculates the wake vortex induced wind velocity at a given location by going through a calculation on paper and comparing the results to the computer calculations. The wake program DBEXEC was validated using a test mode which, instead of the wake flow field calculated by subroutine WAKE27, calculates a flow field that would be produced by perturbing sideslip, angle of attack, yaw rate or roll rate at angle of attacks of 0, 4, 8 and 12 degrees. These perturbations allowed the derivation of $C_{L\alpha}$, $C_{m\alpha}$, C_{lp}, $C_{n\beta}$, and $C_{m\alpha H}$. These derivatives were compared to the derivatives from the simulator to validate the model.

Empirical delta $C_{n\ wake}$ Derivation

The empirical $C_{n\ wake}$ was calculated using the following equation.

$$C_{nwake} = C_{NWKFTD} * K_{NWKFTD}$$

The terms $C_{NWKFTD} * K_{NWKFTD}$ were obtained from wake encounter flight test data using the following procedure.

1. The aerodynamic derivatives in excess of that from controls and flight state (ie due to the wake) were derived using kinematics for each flight test wake encounter.
2. One-hundred and fifty wake encounter cases were examined to find those with clean yaw hits and with wake position readily determinable from the video. This resulted in 21 cases.
3. The videos for these 21 cases were examined to get the position of the wake for the time segment with the wake yawing moment. The term C_{NWKFTD} is a function of lateral position and circulation. To obtain this function, maximum $\Delta C_{N\ wake}$ was plotted as a function of circulation with circulation obtained from maximum $\Delta C_{L\ wake}$ and bank angle. This data was used at the lateral position of maximum wake effect to define the circulation dependence in the C_{NWKFTD} term. The shape of the C_{NWKFTD} as a function of lateral position is determined from a comparison of the lateral position from the video against ΔC_{Nwake} and the fact that ΔC_{Nwake} should be zero at y = 0. The term K_{NKWFTD} accounts for the effect of vertical wake position on $\Delta C_{N\ wake}$. Examination of the video with the ΔC_{Nwake} plots showed that $\Delta C_{N\ wake}$ is constant with position at the tip, mid and base positions on the vertical. Below the horizontal observed ΔC_{Nwake}, and hence K_{NKWFTD}, drops to zero. Above the vertical observed ΔC_{Nwake} drops off rapidly driving the shape of K_{NKWFTD}. The shape of the K_{NKWFTD} was verified by the author who watched the videos and compared ΔC_{Nwake} to the wake position on the video.

Wake Encounter Description

The first cut at the wake position time history at the wing consisted of straight lines 300 ft below the path of the wake generating 727. From this initial baseline, the wake's vertical position (hwake), lateral position of the wake center point (ywake) and distance between the vortex cores (bwake) was adjusted to match lift. The magnitude of the lift peak/trough was determined by circulation, hwake and spoiler (from wake induced roll). The position of the wake peak/trough was determined by ywake and bwake.

The position of the wake was moved North from its initial position to match wake lift loss. At time = 133 sec , the lift loss from the wake with the wake positioned laterally for maximum lift effect and using the initial altitude profile was insufficient to account for the lift loss. Accordingly, the wake was moved down in this time range to produce the match. The thump sound at time = 135.2 was also used to place the wake.

The baseline wake position at the tail was simply the wake position at the wing adjusted for the time lag between the wing and the tail. A increment was added to this baseline tail wake position to match wake pitching moment. Wake pitching moment is a function of ΔX_{wake}, ΔY_{wake}, ΔH_{wake} and Δb_{wake}. For USAir427, ΔY_{wake} and Δb_{wake} remained zero. Flight test case 8765 (T33 time = 15:26:18 flight 19-7-2 on September 27th) showed wake incidence at the wing to be between -20 degrees and -25 degrees while the wake incidence was approximately +5 degrees at the horizontal tail. This flight would seem to justify some variation in the position of the wake at the tail beyond time delay from the wing.

Blind Kinematics Test

As further validation of the Boeing kinematics process, the Safety Board defined three flight control input time histories. These time histories were run through the Safety Board's 737-300 simulation. Time histories of the parameters which were recorded on USAir427's FDR were extracted from the simulation output. These parameters, output at 20 samples per sec, were reduced to the FDR sample rates using the Safety Board program Itp_depvs. The resulting datasets of simulated FDR results were provided to Boeing during the week of January 13th 1997 without providing the input controls or any intermediate parameters. The kinematics process was applied to each case. The kinematics predicted control input is compared to the actual control inputs for each case in attachment 6. As can be seen in attachment 6, the kinematics results favorably compare with the actual input control time histories.

Effect of Curve Fit

Kinematics shows that the rudder was neutral until between time 135.5 sec and 136 sec and then transitions to the rudder blow-down limit by 139 sec. Heading is the most important FDR parameter in producing this result. The heading data for USAir427 was sampled once per second. This is a low sample rate when dealing with a 3.5 second rudder transition. Accordingly, curve fit becomes very important for the details of the rudder transition (Note that the sample rate is not too low for nearly constant rudder deflections, such as the neutral rudder and the full rudder deflections that occurred before and after the 3.5 second rudder transition).

In January, 1997, an effort was undertaken to explore the possibility of other valid curve fits through the one sample per second heading data which might provide alternative solutions to the rudder time history presented by Boeing at the October 31st meeting in Pittsburgh. Test curve fits of airplane heading were made using program ADAPT. For this study, the curve was constrained only in that it must pass through all FDR heading points and that it must not produce a rudder deflection which exceeds the maximum rudder deflection limits. These curve fits were then run through three iterations of the USA427FLT_SIM.MTX kinematics macro to obtain the rudder deflection. A heading curve fit which resulted in a straighter rudder transition (Run 102) is compared to the October 31st results in attachment 7.

During the week of March 10th 1997, the performance group convened at Boeing's Renton facility to further explore the curve fit issue. Attending were Bob McCullough from USAir; Steve O'Neal from the FAA; Harry Dellicker, Jim Wilborn and Jim Kerrigan from Boeing; and Dennis Crider from the NTSB. The results of this curve fit activity are presented in attachment 8.

The first phase of the work consisted of an attempt to get more ramp-like[1] rudder curves without changing the wake. There were two approaches within this phase. The first used the January run 102 as a base line. The final heading and rudder from this approach are labeled "Run 19, smoothed Jan run 102." The second approach used a cubic spline as a baseline. Both a cubic spline on heading alone, and an eight samples per second cubic spline fit to all the parameters were tried with similar rudder results. Therefore it was decided to use the cubic spline on all parameters as a baseline. The rudder and heading for this baseline are labeled "Pure cubic 8 sps" in attachment 8. The heading from this pure cubic baseline was modified in an effort to reduce rudder oscillations at blow-down. The

[1] The term "ramp-like" refers to a curve that rises at a relatively steady rate.

heading and rudder from this effort are labeled "Run 82" in attachment 8.

The second phase of the work took the best curve from phase one (Run 82) into an environment where the wake encounter could be modified. A small movement of the wake at the tail, reducing it's offset from the c.g. wake position, significantly reduced the doublet between 136 sec and 137 sec without a significant adverse effect on the pitching moment match. The resulting rudder and heading are labeled "Modified Cubic Curve with new Wake" in attachment 8. This rudder curve was judged to be a ramp by the group, within the accuracy of wake modeling and the kinematics (secondary effects from the Fast Fourier Transform filter).

A plot containing several possible rudder solutions is also presented in attachment 8. This plot shows that all the rudder solutions depart the yaw damper trace between 135.5 sec and 135.7 seconds. The curves reach the rudder blow-down limit between 138.2 sec and 139.1 sec. Several curve fits through the one sample per second heading data are possible; giving a range of possible rudder transition time histories.

Simulator Response

To provide closure for the kinematics process, the derived flight control deflections were used to drive the Safety Board's 737-300 simulation and the results compared to the original FDR data. The simulation used the derived wake aerodynamic coefficient deltas time histories.

The simulation was run using both the Oct 31st kinematics results and the kinematics results produced by the curve fit study. All simulations were started from a trim at the aircraft state at 130 sec. Running the simulation holding the stabilizer at this trim position did not produce a good match with FDR data. The Boeing kinematics method does not output stabilizer position, so a stabilizer time history was obtained from the Safety Board kinematics software (see attachment 5). This stabilizer time history, however, had significant high frequency noise. A Stabilizer time history was faired through the noise and positioned within the noise band by iterating to match the pitch angle time history.

The results of this work are presented in attachment 9. With the exception of the pure cubic curve fit, all simulation proceeded using a kinematics output set as input. In the case of the pure cubic, the wheel trace derived from the kinematics did not agree with the wheel traces from the other cases. Accordingly, the derived wheel from Run 19 was substituted for the wheel in the pure cubic kinematics output set. It should be noted that the Safety Board's 737-300 simulation implements rudder blow-down. This limited the rudder to the rudder blow-down angle when the kinematics derived rudder exceeded the blow-down angle.

For all the alternative curve fit solutions, there is a dip in rudder position at about 137 seconds. To check the effect of this dip, the run 82 kinematics solution was modified to have a ramp rudder input over this period. A plot of the results is included in attachment 9. As can be seen, removing the rudder dip did not degrade the simulator/FDR match.

Dennis Crider
Aerospace Engineer

Attachments

1. Safety Board Kinematics Code Validation Summary.
2. Comparison of Boeing Conditioned FDR data with FDR data at the Safety Board.
3. Comparison of Boeing kinematics results with kinematics results using Boeing Conditioned FDR data as input to the FDRPlus and CoSurf Safety Board kinematics programs.
4. Comparison of Boeing kinematics results with kinematics results using Boeing aerodynamic coefficients and other parameters as input into the CoSurf program.
5. Kinematics results with Safety Board FDR data and software.
6. Results of "Blind" kinematics test.
7. Results of January 1997 curve fit study.
8. Results of March 1997 curve fit study.
9. Simulation response to Kinematics results.