2005

Flight Simulation as an Investigative Tool for Understanding Human Factors in Aviation Accidents

Bart Elias

FLIGHT SIMULATION AS AN INVESTIGATIVE TOOL FOR UNDERSTANDING HUMAN FACTORS IN AVIATION ACCIDENTS

Bart Elias
The Library of Congress, Congressional Research Service
Washington, DC

As aviation accidents become more complex, the need to better understand human factors aspects increasingly requires more sophisticated investigative tools and techniques. The capabilities of modern research, engineering, and flight training simulators provide human performance investigators with unique opportunities to reconstruct aviation accidents and test hypotheses regarding possible causal and contributing human factors. Two recent examples - the investigation of a flight test accident in October 2000, and the investigation of the crash of American Airlines flight 587 in November 2001 - highlight the potential role of flight simulation as an investigative tool. Building on these experiences, agencies responsible for accident investigations may consider adopting more formal guidelines for using flight simulation as a tool for understanding human factors in aviation accidents.

Background

Increasingly, human performance investigators are turning to simulation to reconstruct complex accidents and test specific hypotheses regarding possible human factors aspects. The improved fidelity and enhanced capabilities of modern research, engineering, and training simulators provide unique opportunities to reconstruct aviation accidents and test hypotheses regarding possible causal and contributing human factors. Using flight simulation, members of an investigation team can experience an accident reconstruction in an immersive environment that provides great flexibility to examine the accident sequence as a whole or focus on specific details.

Experiencing an accident reconstruction is, of course, highly dependent on one's background, training, and perspective. For example, a pilot is likely to focus on very different features than an aircraft performance specialist or a simulator engineer. Similarly, an airline or pilot union representative is likely to have a very different perspective than an airline manufacturer's representative that they bring to bear when assessing investigative activities conducted in a simulator. Therefore, an emerging role for human performance investigators is to lead multidisciplinary teams through these simulator reconstructions and synthesize the unique perspectives of team members into a cohesive understanding of the reconstructed accident sequence. Another emerging role for human performance investigators is to develop and test specific hypotheses regarding possible causal or contributing human factors using flight simulation.

Case Studies

Both of these roles were exemplified in two recent National Transportation Safety Board (NTSB) investigations that highlight the potential role of flight simulation as an investigative tool for understanding human factors in aviation accidents. During the investigation of a recent flight test accident in Wichita, Kansas, the investigation team used both an engineering simulator and a motion-based training simulator to reconstruct the accident and test hypotheses regarding pilot performance. Also, during the investigation of the American Airlines Flight 587 accident, the NTSB's human performance group participated in an accident reconstruction using a unique research simulator, the NASA Ames Vertical Motion Simulator (VMS), and examined upset recovery training procedures in the airline's training simulator.

Bombardier Challenger Flight Test Accident

Accident Summary. On October 10, 2000, a Canadair Challenger, operated by Bombardier Incorporated, crashed during initial climb from the Wichita Mid-Continent Airport (ICT), Kansas. The airplane was departing for a test flight to evaluate stick force characteristics of a new pitch-feel system (PFS) installed for European certification requirements. The aircraft's center of gravity (CG) had been set at the certified aft limit for the purposes of the flight test. The pilot and flight test engineer were fatally injured in the crash. The copilot was seriously injured and later died from his injuries. The NTSB determined that the probable cause of the accident was the pilot's excessive takeoff rotation combined with a rearward shift in the airplane's CG due to fuel migration that placed the airplane in a stall at too low of an altitude for recovery (NTSB, 2004, April 14).

Simulator Studies. A central issue in the investigation was the possible contribution and potential interactions between the pilot's takeoff technique, the flight test's aft-CG configuration, and the PFS installed for testing. To examine these issues in detail, the investigative team conducted studies using an engineering simulator and a level-D training simulator.

Two studies were conducted in the Bombardier Aerospace reconfigurable engineering flight simulator (REFS). In both studies, two type-rated pilots flew takeoff runs in the REFS which was configured with engineering models of the Challenger aircraft. At the completion of each takeoff run, the pilots provided a Cooper-Harper rating assessing the airplane handling characteristics with respect to pitch force, rotation rate, and ability to capture and hold the target pitch attitude (see Cooper and Harper, 1969). The pilots also provided comments on airplane handling characteristics.

The first study was conducted to assess the effects of airplane CG location on rotation rate and the ability to capture the target pitch attitude (nominally, 14 degrees). After completing several "familiarization flight" takeoffs performed with the CG set at 37.9 percent mean aerodynamic chord (% MAC), the pilots completed several takeoffs with the airplane's CG set at six different locations between 35% and 42% MAC. While the NTSB calculated the static CG for the accident flight to be 37.9% MAC and the airplane's certified aft-CG limit is 38% MAC, four CG positions aft of this limit were included in the test because the NTSB determined that a rearward fuel migration shifted the CG on the accident flight to about 40.5% MAC.

The CG locations were randomly presented, and the pilots were not told what CG location to expect for a given takeoff. Each pilot completed two takeoffs at each CG location using normal rotation techniques to achieve a rotation rate of about 3 deg./s. Each of the six CG locations was presented once before being repeated in another randomly ordered set of six takeoffs. Once the pilots had completed these 12 takeoffs using normal rotation techniques, they completed another two takeoffs at each CG location. However, for these takeoffs, the pilots were instructed to use a more "aggressive" rotation technique to try to achieve a rotation rate of about 6 deg./s.

Figure 1 presents the mean Cooper-Harper ratings for each combination of CG location and rotation technique. The pilots generally gave significantly higher Cooper-Harper ratings, indicating more handling difficulties, when they were instructed to use increased rotation rates. CG location, on the other hand, had no statistically significant effect on the Cooper-Harper ratings. However, the pilots, in general, commented that forward CG positions caused the simulator control column to feel heavy, while aft CG positions caused them to rotate at a somewhat higher rate and overshoot target pitch attitude slightly. The pilots generally noted that these effects were more noticeable when they used increased rotation rates. When increased rotation rates were used, the pilots noted that the stick shaker frequently activated, but usually for only short periods of time. The pilots also indicated that the simulator was controllable at all CG locations using both normal and increased rotation rates.

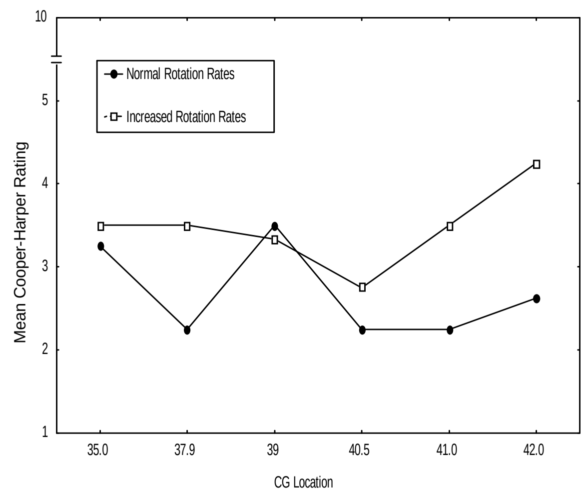

Figure 1. *Mean Cooper-Harper Ratings as a function of CG location and rotation technique.*

A second study was conducted in the REFS to assess any perceptible differences between the handling characteristics of the PFS installed for the flight test in the accident airplane and the PFS installed on certified Challenger airplanes at the time of the accident. Each pilot performed takeoffs with either the modified or production PFS units and provided Cooper-Harper ratings and comments. The CG was set at 40.5% MAC for each takeoff. The pilots reported no handling differences between the modified PFS and the production PFS and there were no significant differences in Cooper-Harper ratings.

Studies were also conducted in a motion-based training simulator. A reconstruction of the accident was played in the training simulator to allow investigators to experience the accident sequence. Also, a scaled-down version of the rotation rate study performed in the REFS was conducted in the training simulator. However, the most notable study conducted in the training simulator was designed to examine the perceptibility of rotation rates. At issue was whether the accident pilot's rotation technique was noticeably more aggressive than recommended procedures dictate during flights prior to the accident. The motion-based simulator was back driven with recorded flight test data from four Challenger takeoffs flown by the accident pilot and one comparison takeoff flown by another Bombardier flight test pilot. The peak pitch rates of the sample takeoffs flown by the accident pilot were 4, 6, 6.5 and 7 deg./s while the peak pitch rate of the comparison takeoff was 3 deg./s. Three pilots took turns experiencing the takeoffs from both the left and right seats of the simulator. The right seat occupant performed routine pilot not flying (PNF) duties during each takeoff while the left seat occupant manually followed the back-driven controls throughout each takeoff. On each run, the pilots observed two takeoffs, the comparison takeoff and one of the four sample takeoffs flown by the accident pilot. The comparison takeoff was presented either before or after the sample takeoff and the participants were not told what takeoffs they would be observing on any given run. After each run, the pilots compared the perceived peak rotation rate of the two takeoffs.

The data were analyzed by comparing the estimated (perceived) difference in peak rotation rates between the sample takeoff flown by the accident pilot and the comparison takeoff to the actual difference. The mean differences between estimated and actual peak rotation rates for each of accident pilot's takeoffs observed are shown in *Figure 2*. If the pilots had accurately estimated the rotation rates, then these values would be zero. Positive values reflect an overestimation of pitch rate while negative values indicate an underestimation. In general, there was a slight tendency among the pilots to overestimate the peak rotation rate for the flight with the lowest peak rotation rate and underestimate the peak rotation rate for flights with faster rotation rates. This trend was somewhat more pronounced for pilots occupying the right seat and performing PNF duties, but these differences in ratings between left and right seat observers were not statistically significant.

As evidenced from these studies, flight simulation was used extensively to address specific human performance questions regarding the handling characteristics of the airplane and pilot rotation technique. Human factors studies were conducted using flight simulators to test hypotheses and support conclusions regarding specific human factors aspects of this accident. Flight simulation was also used extensively to study pilot actions and flight control systems characteristics in the crash of American Airlines Flight 587.

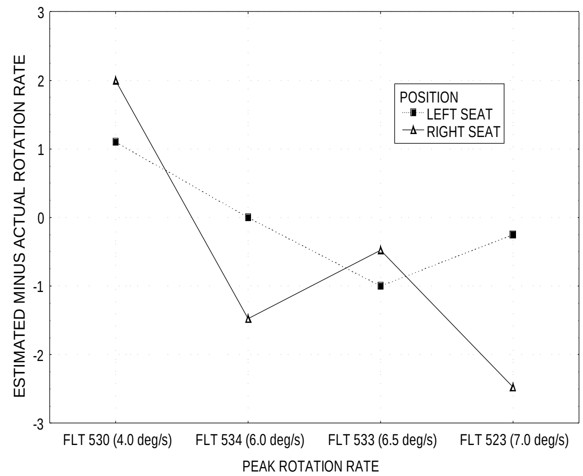

Figure 2. *Estimated minus actual peak rotation rates derived from the rotation rate comparison data*.

American Airlines Flight 587

Accident Summary. On the morning of November 12, 2001, American Airlines flight 587, an Airbus A300-600, was destroyed when it crashed into a residential area shortly after takeoff from the John F. Kennedy International Airport (JFK). All 260 on board and 5 people on the ground were killed in one of the deadliest crashes in U.S. history. The NTSB determined that the airplane crashed following an in-flight separation of the vertical stabilizer caused by excessive and unnecessary rudder pedal inputs. The NTSB also found that the rudder system design and the techniques used to train the pilot in upset recovery were contributing factors (NTSB, 2004). Human factors were a central focus of this investigation, and flight simulation proved to be an important tool in studying these factors.

Simulator Studies. To reconstruct the accident sequence and examine the acceleration forces and motions experienced by the pilots preceding the accident, the NTSB conducted tests and observations at the NASA Vertical Motion Simulator (VMS), a unique facility located at Moffett Field, CA (NTSB, 2002, October 3). The VMS, depicted in *Figure 3*, offers unparalleled capabilities for replicating large amplitude motion cues. The VMS cab is mounted on a six-degree-of-freedom motion platform that provides the following motion capabilities, making it the world's largest motion based simulator:

Table 1. *VMS Nominal Motion Limits*

Motion	Range	Velocity	Acceleration
Vertical	±30 ft	16 ft/sec	24 ft/sec/sec
Lateral	±20 ft	8 ft/sec	16 ft/sec/sec
Longitudinal	±4 ft	4 ft/sec	10 ft/sec/sec
Roll	±18 deg	40 deg/sec	115 deg/s^2
Pitch	±18 deg	40 deg/sec	115 deg/s^2
Yaw	±24 deg	46 deg/sec	115 deg/s^2

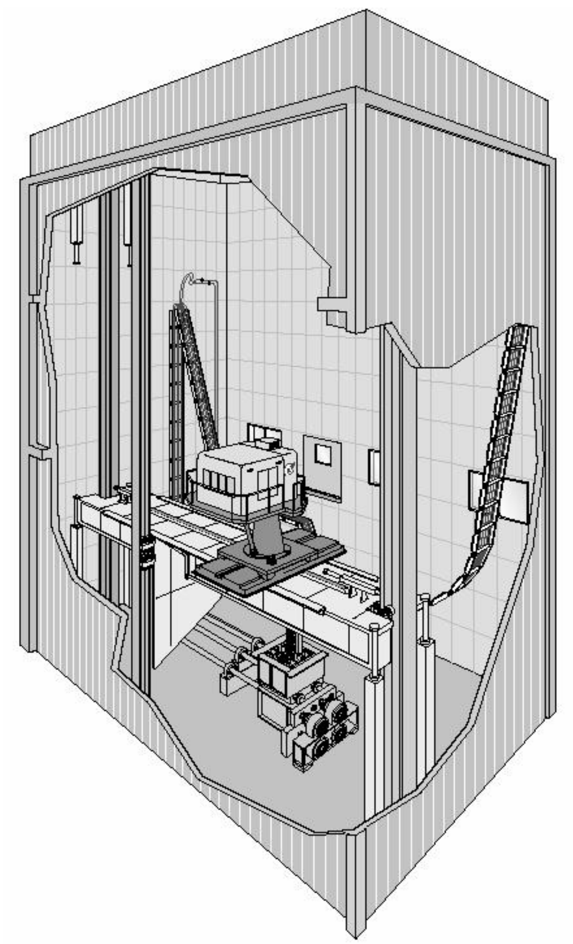

Figure 3. *A cutaway view of the NASA VMS facility (NASA Ames Research Center, 2000, October).*

The accident was reconstructed in the VMS using data derived from the accident aircraft's digital flight data recorder (DFDR) and calculations made by NTSB aircraft performance specialists. Audio segments of the accident aircraft's cockpit voice recorder (CVR) were synchronized for playback during the simulations. The VMS simulator cab was configured with two side-by-side pilot stations, each equipped with three side-by-side CRT monitors. At each station, the outboard monitor presented graphical strip charts of the input (derived from DFDR data) and actual (simulator cab recorded) accelerations for pitch, roll, and yaw axes, and flight control positions. The inboard monitor displayed a compass rose navigation display and the center monitor presented a primary flight display (PFD) similar to those in Airbus A300-600 airplanes.

The cab motion, flight displays, primary flight controls –including the rudder pedals, control wheel, control column–and throttles were back-driven from interpolated DFDR data during simulator runs. Although the cab was equipped with gear, spoiler, and flaps levers, these controls were not back-driven during simulator sessions. Some observers elected to manipulate these controls in response to CVR events to further involve themselves in the accident reconstruction. An out-the-window visual scene of prominent visual features and coastline in the vicinity of JFK airport was presented during simulator sessions. The simulator sessions were videotaped and a cockpit push-to-record button allowed participants to record verbal comments for later reference.

After the nine member human performance group spent two days experiencing the accident reconstruction in the VMS, the group met to formalize their consensus observations. The group focused on the accelerations and motions produced by encounters with wake turbulence and the subsequent flight control inputs made by the first officer on the accident flight. Many of the group members described the first encounter with wake turbulence as typical of a crossing wake encounter. Some participants felt a slight yaw before the flight controls moved. The slight yaw was described as a characteristic motion of an A300 flying through turbulence. This was followed by a vertical acceleration, described by the participants as a "bump", that seemed to result from the wake encounter rather than flight control movements. No flight control inputs followed this event. The group members generally agreed that "very slight" cab motions were felt as a result of a second wake turbulence encounter a few moments later that immediately preceded the initial movements of the control wheel and rudder pedal to the right. The cab motions were described as "barely perceptible" left lateral accelerations. Most participants did not experience any cab motion until less than one second before the first wheel motion. The first movements of the control wheel and rudder pedal to the right were considered to be "large and abrupt." The participants did not observe a visual or acceleration cue that would cause a pilot to apply the magnitude of wheel and pedal inputs observed. Transport pilots in the group noted that the large magnitude and rapid speed of these inputs were analogous to potential flight control inputs made during an avoidance maneuver. After these first movements of the wheel and pedal to the right, large lateral accelerations were felt, and additional large, abrupt flight control movements in the yaw, pitch, and roll axes were observed.

While the Airbus A300-600 is equipped with a variable stop rudder system that limits rudder pedal travel at higher airspeeds, the VMS was also used to evaluate how the same reconstruction would feel when equipped with a variable ratio rudder travel limiter system that maintains full rudder pedal travel at all airspeeds. During VMS runs in which a variable ratio limiter system was simulated, some participants felt that the movements of the pedals were so fast that it was hard to keep their feet on the pedals as they moved.

The group concluded that the VMS, while constrained by certain inherent limitations, provided insight and was a beneficial tool for experiencing time synchronized motions, flight control motions, and displays as opposed to just looking at tabular or charted data. The VMS proved to be an important tool for observing the perceptual cues experienced by the pilots during the accident sequence and assessing the appropriateness of the pilot's inputs and the possible contribution of the rudder system design. These all proved to be central issues in the investigation.

Another central issue in the investigation was the potential role of simulator training in large aircraft upset recovery taught to the pilots. To assess this training, the human performance group conducted a study in the American Airlines A310/300 training simulator to examine the excessive bank angle recovery exercise that the accident pilots completed (NTSB, 2004). Six pilots from the group performed the exercise six times, employing different recovery techniques each time. In the first case, the simulator instructor set up the exercise to replicate the simulator training that pilots received before this accident occurred. The pilots were told they were departing behind a 747 and the instructor initiated an upset when the airplane was banked at an altitude between 2,000 and 2,500 feet and traveling about 240 knots. During the upset, the simulator underwent an uncommanded roll that was randomly set to be either to the left or the right, followed immediately by a large uncommanded roll in the opposite direction. The simulator momentarily inhibited the airplane's response to pilot wheel and rudder pedal inputs during the event to allow the airplane to reach a substantial bank angle before recovery began. Pilots were instructed to recover the airplane according to the method described in the American Airlines advanced aircraft maneuvering program (AAMP), using simultaneous, coordinated rudder in conjunction with control wheel inputs. Each pilot repeated the procedure five additional times, except the roll maneuver was initiated during level flight after the pilot indicated his readiness. The pilots were instructed to use each of the following five recovery methods: partial wheel and no rudder, full wheel and no rudder, full wheel and partial rudder, full wheel and full rudder, and the pilot's preference.

In the AAMP recovery method trials, all of the pilots responded with a full control wheel input (between 77° and 80°) supported by a rudder pedal input (ranging from 6.7° to 14.5° with an average of 10.8°). Five of the six pilots used the rudder pedal simultaneously with the control wheel. Three of the pilots recovered before the airplane reached a 90° bank angle, and the other three pilots recovered the airplane with a maximum bank angle between 108° and 114°. Four of the pilots stated that they were surprised by the onset of the event. The four other prescribed recovery methods showed little difference in average maximum bank angle reached before recovery (between 104° and 107°), and none of pilots recovered before the airplane reached a bank angle of 100°. Three of the six pilots reported that partial wheel and no rudder was the worst recovery method, and all six pilots questioned whether this method provided sufficient control authority for recovery. Two of the pilots felt that a recovery with full wheel and full rudder was the worst method because it created a potential to overcontrol. Data from the full wheel and full rudder recovery suggested a discrepancy between the simulator and the airplane concerning compliance in the rudder control system. Specifically, at 240 knots, the maximum pedal travel on the A300-600 should be limited to 7.9°. When the pilots made full rudder inputs, the maximum pedal travel varied from 10.3° to 18.9°. Some of the pilots reported that they were not able to perceive pushing past the pedal stop when making full pedal inputs in this condition. When the pilots were allowed to recover using their own technique, most of the pilots responded with nearly full wheel and partial rudder pedal inputs. Slightly less input was made on both controls compared to trials where pilots were told to use the AAMP recovery technique, and the pedal response was typically delayed by at least 1 second from the initial control wheel input. The pilots demonstrated a preferred recovery strategy of full wheel and limited rudder in response to the simulator exercise. Also, five of the six pilots indicated, at least once during the six trials, that there was a lack of flight control response during the initial upset.

As with the Bombardier Challenger test flight accident, flight simulation proved to be an invaluable tool during the investigation of the crash of American Airlines Flight 587. In this high-profile accident, unique facilities were used and specific simulator studies were tailored to address specific human performance issues that were ultimately determined to be causal and contributing factors in the crash.

Considerations for Using Flight Simulation as an Investigative Tool

Building on these experiences, agencies responsible for accident investigations, like the NTSB, may consider drafting guidelines for evaluating and conducting flight simulator activities during the course of aviation accident investigations.

While simulation is a valuable tool that will likely have increasing importance in future accident investigations, there are some important considerations to bear in mind that could be formalized through specific guidelines. First, investigators should realize that conducting a simulation is costly and resource intensive. Therefore, the benefits to be derived from simulation should be weighed against these costs and, when appropriate, less costly alternatives considered. Also, in designing a simulation, human performance investigators should understand the limitations of simulation in general and the comparative capabilities, advantages, and disadvantages of different simulators. For example, training simulators may be beneficial in examining how accident flight crews were trained, or examining procedural issues in an accident, but are not well suited for examining highly dynamic motions and accelerations. If the acceleration forces experienced during an accident event are of particular interest, then a unique research facility like the VMS may be needed. Also, if flight control issues arise, training simulators may be inappropriate because they typically lack the fidelity and detail to accurately portray the aircraft's aerodynamic models to the extent that can be achieved in an engineering simulator. In sum, all simulators have limitations and these limitations should be carefully considered when deciding if flight simulation is appropriate and evaluating which particular simulator is best suited to meet the needs of an investigation. Specific simulator limitations should also be identified and considered when designing and executing a simulation plan so that member of the investigative team can understand how these limitations may affect their experiences and the conclusions that can be drawn from the simulation study.

Human performance investigators should also bear in mind some considerations that may limit their ability to answer fundamental questions regarding accident causation in the simulator. First, finding naïve participants may be extremely difficult if not impossible following a high-profile accident. For example, in the American Airlines Flight 587 accident, media coverage and NTSB recommendations focused attention on pilot use of the rudder pedal making it impractical to carry out a simulator study evaluating how certain populations of pilots might use rudder in response to aircraft upsets. Another thing to bear in mind is that some broader issues that arise may be beyond the scope of a focused accident investigation. For example, the American Airlines Flight 587 accident raised many interesting questions regarding the interaction of pilot rudder inputs and rudder system design that would require a large-scale research study to fully address. Formal guidelines for using flight simulation could help investigators better define the purpose, scope, and limitations of simulator activities conducted as part of an aviation accident investigation.

Disclaimer

This paper is based on the author's activities as a Senior Human Performance Investigator for the NTSB. The views expressed in this report are the author's and do not necessarily reflect those of the NTSB or the Congressional Research Service.

References

NTSB (2004, April 14). *Aircraft Accident Brief, CHI01MA006.* NTSB/AAB-04/01.

NTSB (2002, May 15). *Human Performance Study Report*. NTSB Docket Number CHI01MA0006.

NTSB (2002, October 3). *Human Performance Study Report, Vertical Motion Simulator Activities Phase 1: Backdrive of Accident Flight.* NTSB Docket Number DCA02MA001,

NTSB (2004). *Aircraft Accident Report: In-Flight Separation of Vertical Stabilizer, American Airlines Flight 587, Airbus Industrie A300-605R, N14053, Belle Harbor, New York, November 12, 2001*. NTSB/AAR-04/04.

NASA Ames Research Center (2000, October). *VMS Overview: Vertical Motion Simulator Research Facility*. Moffett Field, CA.

Cooper, G. E. & Harper, R. P., Jr. (1969). *The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities*. NASA TN D-5153, 1969.