Open access • Proceedings Article • DOI:10.2514/6.2005-5933

Dynamics Modeling and Simulation of Large Transport Airplanes in Upset Conditions — Source link

John V. Foster, Kevin Cunningham, Charles M. Fremaux, Gautam H. Shah ...+4 more authors

Institutions: Langley Research Center

Published on: 01 Jan 2005

Topics: Aviation safety

Dynamics Modeling and Simulation of Large Transport Airplanes in Upset Conditions

John V. Foster*, Kevin Cunningham†, Charles M. Fremaux‡, Gautam H. Shah§, Eric C. Stewart**,
NASA Langley Research Center, Hampton, VA, 23681-2199

Robert A. Rivers††
NASA Johnson Space Center, Houston, TX, 77058

and

James E. Wilborn‡‡, William Gato§§
The Boeing Company, Seattle, WA 98124

As part of NASA's Aviation Safety and Security Program, research has been in progress to develop aerodynamic modeling methods for simulations that accurately predict the flight dynamics characteristics of large transport airplanes in upset conditions. The motivation for this research stems from the recognition that simulation is a vital tool for addressing loss-of-control accidents, including applications to pilot training, accident reconstruction, and advanced control system analysis. The ultimate goal of this effort is to contribute to the reduction of the fatal accident rate due to loss-of-control. Research activities have involved accident analyses, wind tunnel testing, and piloted simulation. Results have shown that significant improvements in simulation fidelity for upset conditions, compared to current training simulations, can be achieved using state-of-the-art wind tunnel testing and aerodynamic modeling methods. This paper provides a summary of research completed to date and includes discussion on key technical results, lessons learned, and future research needs.

Nomenclature

α	= angle of attack, deg
β	= angle of sideslip, deg
δ_e	= elevator deflection, deg
b	= span
C_l	= aerodynamic rolling moment coefficient
C_m	= aerodynamic pitching moment coefficient
C_n	= aerodynamic yawing moment coefficient
$C_{n\beta,dynamic}$.	= departure susceptibility parameter
CG	= center of gravity
L	= length
AvSSP	= Aviation Safety and Security Program
CAST	= Commercial Aviation Safety Team
CFIT	= controlled flight into terrain
EUR	= Enhanced Upset Recovery aerodynamic model
HATP	= High Alpha Technology Program
IFD	= Integration Flight Deck simulator
LaRC	= Langley Research Center

* Senior Research Engineer, Flight Dynamics Branch, Mail Stop 308, AIAA Associate Fellow.
† Senior Research Engineer, Flight Dynamics Branch, Mail Stop 308, AIAA Senior Member.
‡ Senior Research Engineer, Flight Dynamics Branch, Mail Stop 308, AIAA Senior Member.
§ Senior Research Engineer, Flight Dynamics Branch, Mail Stop 308, AIAA Senior Member.
** Senior Research Engineer, Flight Dynamics Branch, Mail Stop 308.
†† Research Pilot, Aircraft Operations Division, Mail Stop CC4, AIAA Senior Member.
‡‡Lead Engineer, Accident Investigation and Safety Initiatives, P.O. Box 3707, Mail Stop 67-FH, AIAA Member.
§§ Associate Technical Fellow, Accident Investigation and Safety Initiatives, P.O. Box 3707, Mail Stop 67-FH.

LOC = loss of control
NASA = National Aeronautics and Space Administration
Rev J = Revision J baseline aerodynamic model

I. Introduction

In the late 1990's, the Commercial Aviation Safety Team (CAST), a government/industry partnership formed to address aviation accidents, identified loss-of-control (LOC) as a leading contributor to the fatal accident rate (Fig. 1). Based on extensive accident analysis, the CAST recommended "intervention strategies" to provide specific courses of action with the goal of significantly reducing the LOC accident rate. Several of these intervention strategies addressed the need for advances in simulation technology to enable realistic pilot training for conditions beyond the normal flight envelope (e.g. stall and post-stall), and for supporting the recent industry initiative for upset recovery training[1]. In addition, it was recognized that simulations that are accurate for conditions beyond the normal flight envelope would enhance accident/incident analysis and enable the design of advanced control systems.

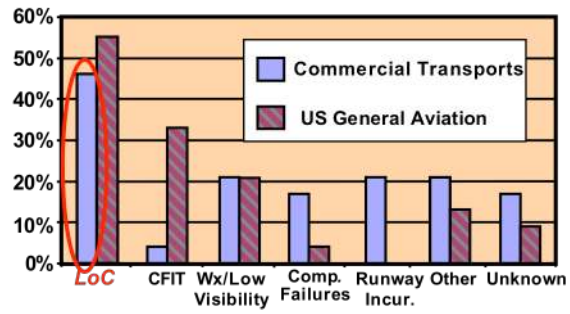

Figure 1. Fatal accident distribution for commercial transports and general aviation. *Source: NTSB database 1990-1996.*

As part of NASA's Aviation Safety and Security Program (AvSSP), research has been in progress to address the state-of-the-art of simulation fidelity of large transport airplanes in loss-of-control flight, including flight at large angles of attack and sideslip, high angular rates, and abnormal control conditions. In partnership with the Boeing Company, studies were conducted to analyze previous LOC accidents to more fully understand the conditions and precursors for these types of events and to define simulation requirements for these conditions[2,3]. A key finding in these studies was that the aerodynamic databases for large commercial transport airplanes are typically not designed to be accurate for upset conditions because 1) simulator certification requirements are very limited for conditions beyond the normal flight envelope and 2) aerodynamic measurements at upset conditions are normally not acquired from wind tunnel nor flight tests.

Figure 2 illustrates the limitations of current aerodynamic models for conditions outside of the normal flight envelope. Typically wind tunnel testing is conducted for the normal flight envelope at angles of attack up to and just beyond stall for sideslip angle equal to zero. Characteristics in sideslip are usually measured up to the angle of attack for stall warning activation and out to sideslip angles representative of crosswind landing. Limited data are acquired at angles of attack significantly beyond the stall primarily because the focus of the testing is configuration development for the purpose of predicting performance and certification characteristics. Minimal data are taken for the purpose of predicting post-stall departure. When a simulation database is derived from the wind tunnel data, it is common practice to implement a table-lookup database that is a rectangular function of angle of attack and sideslip, resulting in regions of extrapolated or estimated data. However, as illustrated in the figure, loss-of-control accidents have been known to achieve flight conditions far beyond the normal flight envelope and well beyond stall conditions where knowledge of aerodynamic characteristics is limited.

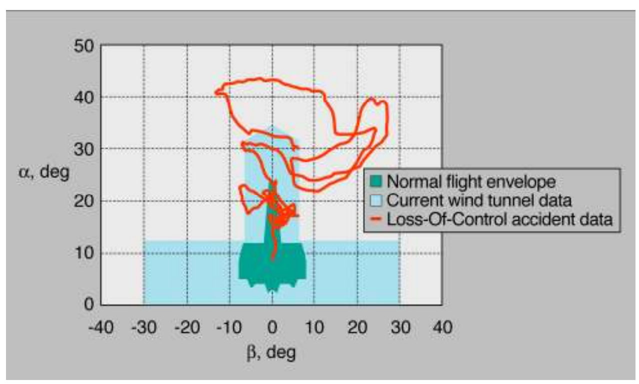

Figure 2. Illustration of aerodynamic envelopes for current transport simulations.

The studies reported in Refs. 2 and 3 concluded that LOC accidents are caused by many factors, resulting in many unique flight conditions and motions. This result highlighted the difficulties in training for upset events and designing a comprehensive database for LOC conditions. However, a review of Ref. 1 concluded that specific improvements in current simulations could benefit upset training maneuvers. It was also concluded that improvements to the aerodynamic database were warranted and necessary to achieve the goal of providing simulations that accurately emulate upset dynamics.

The issue of modeling and predicting flight behavior outside of the normal flight envelope is not unique to large transport airplanes. Aerodynamic modeling of high performance military configurations at high angles of attack and sideslip conditions has been the focus of extensive research over the past several decades due to the need to reduce stall/spin accidents during air-to-air combat. This research contributed to reliable ground test methods and aerodynamic modeling techniques for stall, departure, and spin conditions that are commonly used for aircraft development. Government/industry research, such as the NASA High Alpha Program (HATP)[4], made significant contributions to the understanding of stability and control, flow physics, and computational methods for these conditions. Another category of airplanes, light general aviation, was the subject of ground and flight research in the 1980's, due to the stall/spin accident rate, that resulted in advanced spin-resistant wing designs and simulation modeling methods[5]. Primarily based on this previous research, an experimental wind tunnel test program for large transport configurations was chosen as a viable approach to measure and study aerodynamic characteristics for upset conditions.

The purpose of this paper is to summarize focused research conducted under the NASA Aviation Safety and Security Program (AvSSP) specifically addressing LOC flight dynamic behavior of large transport airplanes. Discussion on accident analyses, aerodynamic ground testing, simulation modeling, and flight dynamics will be presented. In addition, comments on simulation validation and potential uses of improved simulations will be provided. Finally, discussion on issues related to LOC accidents, pilot training, and experimental methods will be included with the goal of highlighting future research needs and providing further emphasis on reducing fatalities due to LOC accidents.

II. Aerodynamic Ground Testing

Description of tests

An extensive wind tunnel test program, using subscale models, was initiated in 2001 to investigate and document aerodynamic characteristics of large transport airplanes at upset flight conditions. This investigation used 3.5% and 5.5% subscale models representative of a modern transport configuration to study aerodynamic stability (static and dynamic), control power, configuration effects, and scale effects. The focus vehicle, illustrated in Fig. 3, utilized a conventional elevator and an all-moving horizontal stabilizer, rudder, ailerons, and spoilers. In addition, representative leading- and trailing-edge flap configurations were tested. Various test methods were employed in the program. Static and forced oscillation testing was conducted using the 5.5% model in the LaRC 14- by 22-Ft Tunnel (Fig. 4). Rotary balance testing was conducted using the 3.5% scale model in the LaRC 20-Ft Vertical Spin Tunnel (Fig. 5). In addition, flow diagnostic studies were conducted in the LaRC 12-Ft Low Speed Tunnel with the 5.5% model. Test data were obtained at angles of attack up to 85° and sideslip angles up to ±45°. Preliminary results of this testing were reported in Ref. 6.

As discussed in the introduction, the wind tunnel test program leveraged off of experimental techniques previously developed for military fighter aircraft over the past several decades. While there has been extensive literature on sub-scale aerodynamic testing of fighter configurations at post-stall conditions, publications addressing aerodynamic characteristics of transport configurations at high wind incidence angles have been limited. Based on published data and industry experience, concerns regarding scale effects (e.g. Reynolds number), separated flows, and time-dependent effects were recognized as important issues for testing transport configurations.

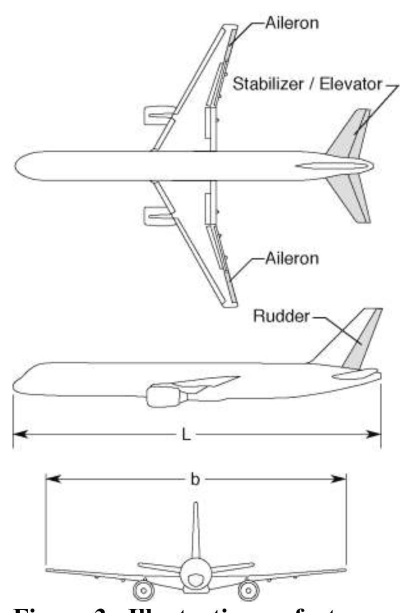

Figure 3. Illustration of transport configuration used for wind tunnel testing.

Figure 4. Photo of 5.5% sub-scale wind tunnel model in the LaRC 14- by 22-Ft Tunnel.

Figure 5. Photo of 3.5% sub-scale wind tunnel model in the LaRC 20-Ft Vertical Spin Tunnel.

B. Experimental Results

The following sections present selected wind tunnel test results for the purpose of illustrating key aerodynamic characteristics that should be considered for modeling flight behavior in upset conditions. Specifically these results show the effect of flight condition on aerodynamic stability and highlight the non-linear nature of aerodynamics in the stall and post-stall regimes. Due to proprietary data restrictions, numerical labels are removed on certain figures. In a later section on aerodynamic modeling for simulation, wind tunnel results are compared to a current training simulator database to explain the limitations of using current training simulator databases for upset conditions.

1. Static Pitch Stability

Aerodynamic pitching moment characteristics from the wind tunnel tests are shown in Fig. 6. This figure shows the variation in static pitch stability and elevator control effectiveness over the angle of attack range. The configuration is statically stable at low angles of attack as indicated by the negative local slope of pitching moment coefficient with angle of attack. However, in the stall region ($\alpha \approx 10^{\circ}$-$14^{\circ}$), the stability is reduced generally due to combined effects of outboard wing stall and downwash interactions with the horizontal tail. The pitch control remains effective throughout the angle of attack range but diminishes with increasing angle of attack, due initially to the immersion of the horizontal tail in the wing wake and ultimately due to flow separation on the horizontal tail itself at post- and deep-stall angles of attack. The maximum steady angle of attack with full nose-up elevator deflection is at $\alpha \approx 25^{\circ}$, which is significantly higher than the stall region near $\alpha \approx 12^{\circ}$ and this result indicates the potential for the airplane to enter upset conditions using normal pilot controls during un-accelerated flight.

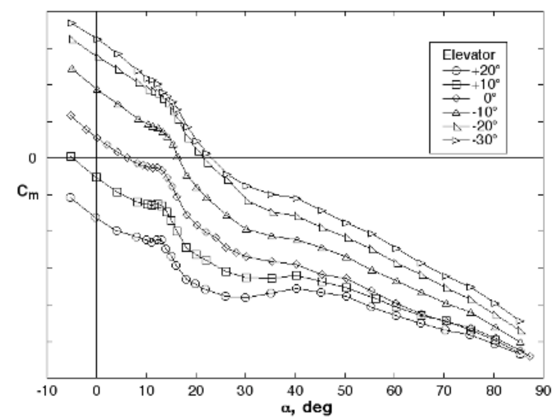

Figure 6. Aerodynamic pitching moment coefficient from wind tunnel tests. Stabilizer angle=0°. CG=mid.

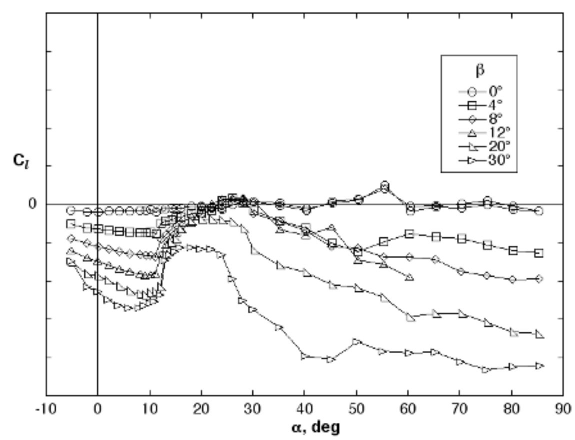

Figure 7. Variation of aerodynamic rolling moment coefficient with angle of attack and sideslip. All controls=0.

2. Static Lateral Stability

Static lateral-directional stability is indicated by the variation of aerodynamic rolling moment and yawing moment with sideslip angle. Wind tunnel data for static roll stability are shown in Fig. 7 for various angles of sideslip. These data indicate nearly linear variation of rolling moment with sideslip angle up to $\alpha \approx 12^\circ$ but significant non-linear variations at higher angles. The variation with angle of attack shows stable and unstable characteristics that can be very important for modeling LOC dynamics.

3. Aerodynamic Asymmetries

Aerodynamic asymmetries refer to non-zero values of side force or rolling/yawing moment coefficients at zero sideslip angle. It is a common expectation that the aerodynamic asymmetry is small at low angles of attack prior to stall where the flow is not separated. However in separated flow, asymmetries may be large and time varying. The potential for asymmetries can be seen in the rolling moment coefficient for two different flap deflections at $\beta=0^\circ$ (Fig. 8). These data show variations in asymmetries in the stall and post-stall regimes. Although the source of the asymmetries is not well understood, potential sources include asymmetric wing stall or asymmetric flow fields emanating from the forebody and propagating downstream. Flow visualization photos, presented in a later section, suggest the potential influence of vortical flow on asymmetries. Inclusion of asymmetries can be very important in capturing flying qualities characteristics during stalls and departures and is further discussed in the section on piloted simulation.

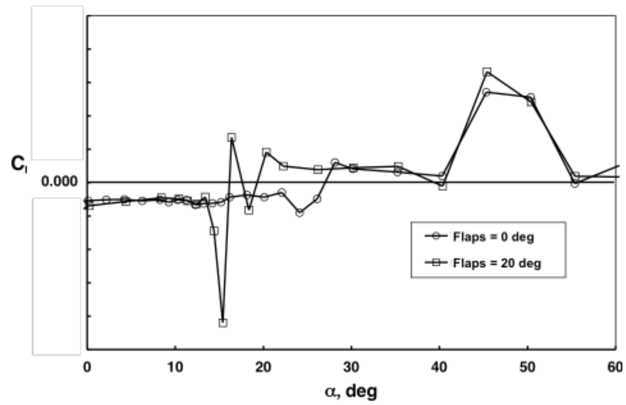

Figure 8. Effect of flap deflection on aerodynamic rolling moment asymmetries.

4. Directional Control Power

The effect of angle of attack on control power is illustrated in Fig. 9 by yawing moment coefficient for various rudder deflections. At low angles of attack, the effectiveness is non-linear, particularly at rudder deflections beyond 30˚. The control effectiveness is shown to decay with angle of attack in the stall regime and exhibits approximately a 66% reduction in effectiveness at $\alpha=30^\circ$.

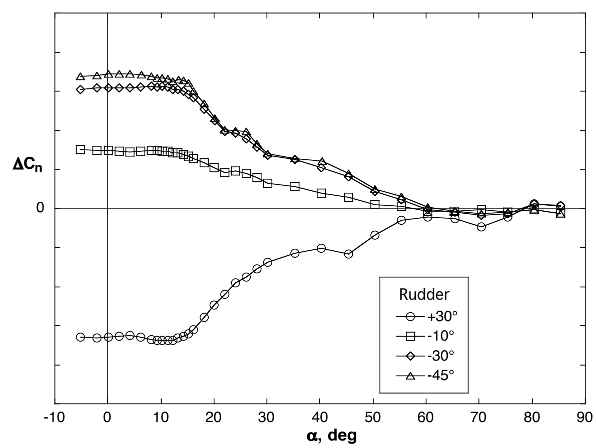

Figure 9. Rudder control effectiveness.

5. Rate Damping Effects

The effects angular rate (e.g. pitch rate, roll rate, and yaw rate) on aerodynamic forces and moments are commonly referred to as "damping effects" and are often modeled as linear derivatives at a given angle of attack. These effects are measured using specialized wind tunnel rigs that emulate various flight motions. The forced oscillation rig oscillates the model in the body axes at various frequencies and amplitudes to measure aerodynamic forces and moments over a range of angular rates. Figure 10 shows rolling moment coefficient from forced oscillation testing plotted versus peak roll rate in each oscillation cycle at two angles of attack. At $\alpha=4^\circ$, the rolling moment varies nearly linearly with rate, suggesting these data can be adequately represented as a linear derivative with rate. At $\alpha=40^\circ$, the variation in rolling moment is highly non-linear with rate, which could not be adequately represented by a linear derivative with rate.

Rotary balance data provide the effects of angular rate on aerodynamic forces and moments for steady angular rate, in contrast to the varying angular rates in forced oscillation testing. Whereas the forced oscillation data is measured during sinusoidal motions with various frequencies, the rotary balance data does not have frequency effects. The rotary balance data are commonly used to predict and model steady spin dynamics and therefore implementation involves combining rotary balance data with forced oscillation data in order to fully model departure and spin dynamics. To date the research reported in this paper has not addressed the blending of rotary balance data with forced oscillation data

The effect of sideslip angle on rate damping effects has been the subject of research for many years but remains a challenge to measure due to the difficulty of separating various state effects. For example, using the forced oscillation technique, a roll body-axis oscillation produces sideslip but that effect must be simultaneously separated from those due to the angular roll acceleration. For the purposes of this research, sideslip effects on damping characteristics were not included but warrant further study and wind tunnel data measurements.

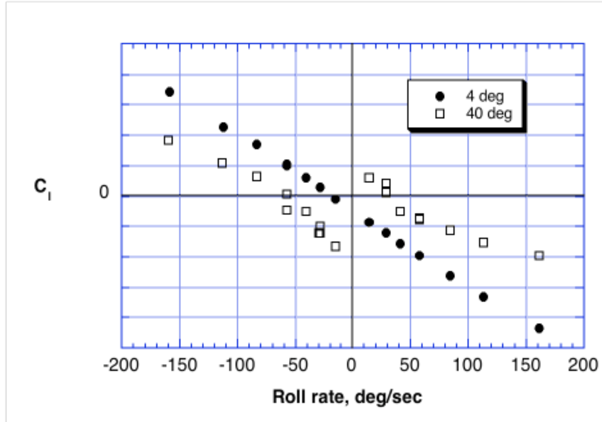

Figure 10. Variation of rolling moment coefficient with angular rate for α=4° and α=40°. Flaps=0.

6. Reynolds Number Effects

Reynolds number is an aerodynamic similitude parameter that is correlated with flow separation characteristics affecting lift and drag measurements. For example, wind tunnel data shown in Fig. 11, measured at low Reynolds number, underestimates full-scale lift coefficient especially in the stall region. However, at higher angles of attack, the low Reynolds number wind tunnel data are in good agreement with flight validated data, suggesting that Reynolds number effects are diminished at large wind incidence angles where the flow is largely separated. This result shows that scaling corrections to low Reynolds number wind tunnel data may not be required for aerodynamic modeling at post-stall angles of attack. An important consideration for upset modeling is that Reynolds number can also affect stability and control parameters, such as pitching moment and roll damping, which are important to consider for piloted simulations.

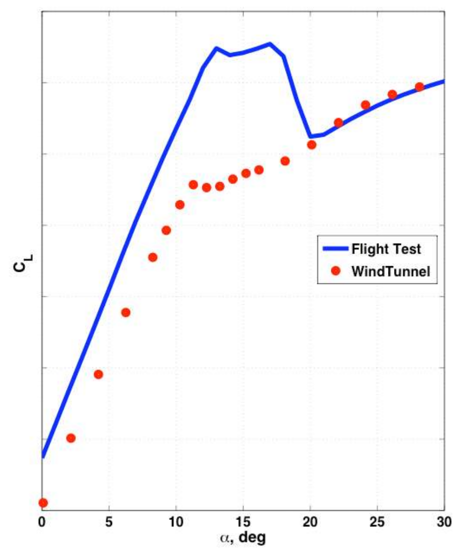

Figure 11. Comparison of low Reynolds number wind tunnel data to flight data.

7. Time-Dependent Effects

Time-dependent aerodynamic effects often occur in separated flow conditions (e.g. high angles of attack or sideslip). Based on previous literature[7], these effects typically manifest as time-varying, or unsteady, aerodynamic forces and moments at constant wind incidence angles and zero angular rates, or as dynamic flow lags (hysteresis) under varying angular rates.

Several time-dependent effects were observed during static and dynamic wind tunnel testing of the transport configuration. Figure 12 shows photos of limited flow visualization studies that were conducted to examine off-surface flow characteristics and to determine fundamental flow behavior. These tests used a laser light sheet with oil-based smoke to capture images at various fuselage stations for constant flow conditions. In this figure, a vortical flow system is apparent with vortex cores near the top of the fuselage and impinging on the vertical tail. Although not conclusive, these results highlighted the complex flow field at high angles of attack and a potential source of unsteady flow characteristics and aerodynamic asymmetries.

Figure 12. Photo of flow visualization results showing unsteady flow field at α=60˚.

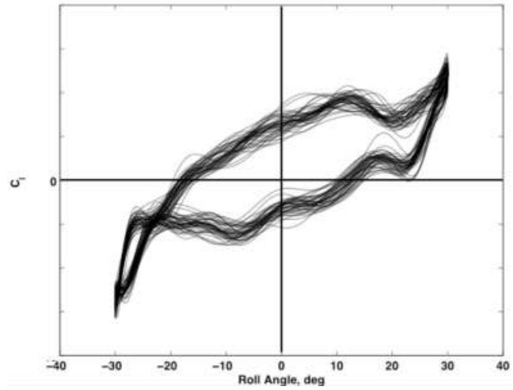

Figure 13. Rolling moment coefficient data from forced oscillation test at α=40˚.

Figure 13 shows rolling moment coefficient versus roll angle for forty cycles at a typical forced oscillation test condition. This figure shows the variations in aerodynamic rolling moment between cycles that are primarily attributed to unsteady effects that occur throughout each oscillation cycle. The forced oscillation data reduction approach usually computes the "average" value of the aerodynamic coefficients for numerous cycles, but the time-dependency is considered a real effect that remains a research topic[7].

III. Piloted Simulation Studies

A. Aerodynamic Modeling and Database Implementation

For the purposes of this research, an existing training simulation, referred to as "Rev J" in some of the figures, was used as a baseline to evaluate an enhanced aerodynamic database designed to model stall and post-stall flight characteristics. The enhanced model, known as the Enhanced Upset Recovery (EUR) model, is described in Refs. 8-10 and it incorporates the wind tunnel data previously discussed. Because the baseline simulation is representative of that previously validated via FAA certification for flight crew training, enhancements for the EUR model were made primarily to post-stall regimes where there are no certification requirements. This "retro-fit" approach also served to demonstrate methods for updating current simulations that exist for most operational transport airplanes.

The EUR database includes effects for takeoff and landing configurations as well as cruise configurations for angles of attack up to 85˚ and angles of sideslip up to ±45˚. It should be noted that propulsion characteristics and structural limitations were not modeled for conditions outside of the normal flight envelope. Due to the potential influence of thrust on LOC flight dynamics, models of engine performance at high wind incidence angles could potentially be important to fully address characteristics in this regime.

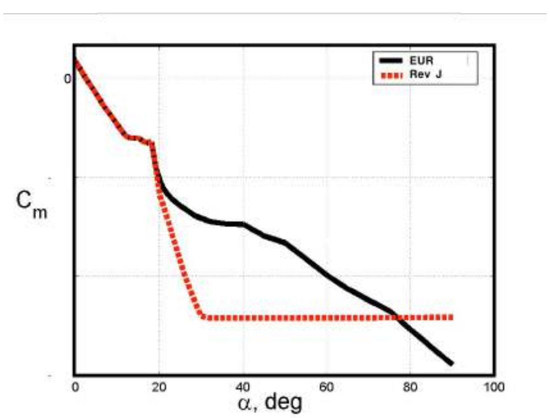

Figure 14. Comparison of EUR to baseline simulation aerodynamic model for pitching moment.

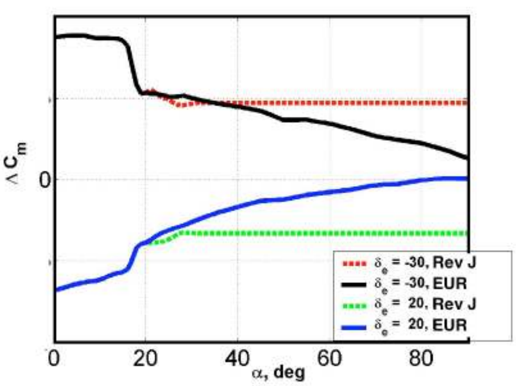

Figure 15. Comparison of EUR to baseline aerodynamic model for elevator control.

A comparison of the EUR model to current training simulator data for aerodynamic pitching moment (Fig. 14) illustrates the limitations of current simulators for stall and post-stall training. In this example the training simulator database extrapolates from α=20˚ to α=30˚ and then maintains a constant value beyond α=30˚. As shown, the extrapolated data significantly over-predicts pitch stability from α=20-30˚, and under-predicts stability beyond α=30˚. A similar result for elevator control power is shown in Fig. 15 where the control effectiveness is constant above α=20˚, which significantly over-predicts pitch control power. Figure 16 shows a comparison of roll damping, in linear derivative form, between measured wind tunnel data and the model in a current training simulator. The wind tunnel data show the large variations in roll damping, particularly at stall/post-stall angles of attack, which are not modeled in the current simulator. Similar comparisons are seen for the other aircraft axes that clearly illustrate the limitations of using currents simulations for stall or upset training. Furthermore, use of the simulator for conditions beyond the valid database could potentially provide "negative training" due to the unrepresentative characteristics that would result from an inaccurate aerodynamic model.

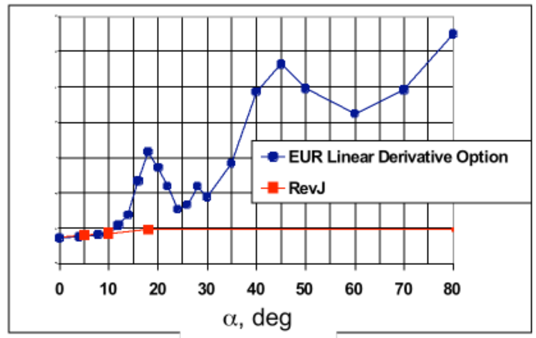

Figure 16. Comparison of EUR and baseline roll damping models. Flaps=0.

B. Description of Piloted Simulation Facility

The EUR database was installed in the Integration Flight Deck (IFD) simulator at LaRC (Fig. 17). This simulator is a fixed-based facility representative of a current transport flight deck. This facility incorporates high-resolution visual displays, fully functioning pilot controls with representative force feel and a stick shaker system, a flight management system, and representative flight displays. In addition, custom displays were installed to facilitate research by providing additional information during piloted simulation testing.

Figure 17. Photo of NASA LaRC IFD simulation cockpit.

C. Handling Qualities Results

Flying qualities design criteria for large transports in the normal flight envelope are well understood and have been the subject of research for many years[11]. As a result of these efforts, the design process for new configurations typically yields excellent piloted handling qualities within the normal flight envelope. In contrast, handling qualities design criteria for large transports outside of the normal flight envelope are limited and they focus primarily on stall identification for certification purposes. Additionally, identification of departure characteristics is very limited due to the inability to safely conduct maneuvers for this purpose. Reference 12 addresses the need for quantitative definitions of loss-of-control for transports by analyzing previous LOC events to develop critical handling qualities boundaries. These boundaries are defined by the previously discussed aerodynamic envelope, along with boundaries for structural integrity, unusual attitudes, and abnormal control response. In contrast to highly maneuverable airplane configurations, structural integrity and unusual attitudes pose significant limits for out-of-control maneuvers on large transports.

The following section discusses important handling qualities results from piloted simulation research [13,14] that should be considered for stall/post-stall simulations of large transports. Note that evaluation of the simulation based on available flight test data is ongoing, and these results should be considered preliminary. Furthermore, it should be emphasized that, while high angle-of-attack and angle-of-sideslip departures during flight test stall demonstrations do occur (Fig. 18), their frequency is rare and generally only happens in conjunction with the most extreme conditions of aft CG loading combined with large and abrupt aft column control inputs. The specific characteristics that result in flight test departures are still under investigation, and the simulator results that follow were obtained by intentionally attempting to reach extreme angles-of-attack and sideslip through aggravated, misapplied control inputs. One such simulator stall is presented in Fig. 18 and compares its wind incidence path to that from a flight test stall departure; this comparison will be used to discuss key results.

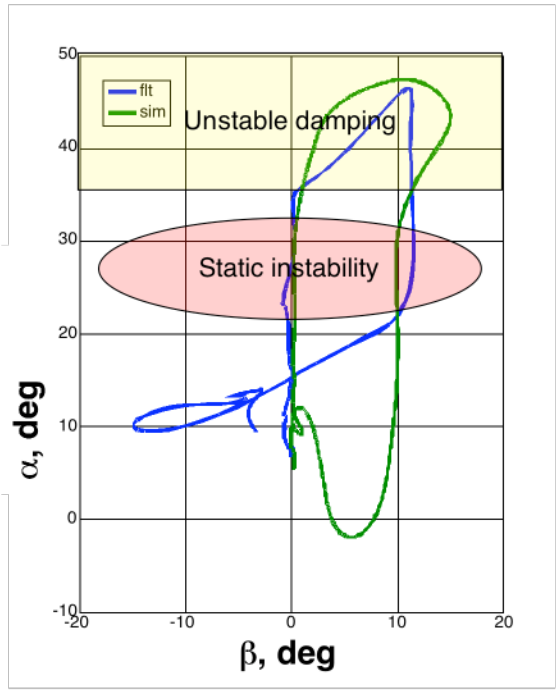

Figure 18. Effect of lateral/directional aerodynamic stability on stall/departure characteristics. Flaps =0. CG=aft.

1. Pitch Response Characteristics

Pitch response characteristics were evaluated to determine the maximum angle of attack that could be achieved in steady 1g flight using normal pilot pitch controls. From figure 6, the maximum achievable angle of attack is approximately $\alpha=25^\circ$ using full nose-up elevator with idle thrust and neutral stabilizer position. However, other effects such as nose-up moment from low wing-mounted engines, aft CG location, nose-up stabilizer trim, weak pitch damping, and aggressive control inputs can further increase the maximum achievable angle of attack to over 40˚, as shown in Fig. 18. This result highlights the potential to achieve flight conditions far beyond initial stall, which is preceded by a "stick shaker" warning system at $\alpha\approx11^\circ$.

2. Stall/Departure Characteristics

Piloted simulation research, reported in Ref. 13, studied the effects of aerodynamic model enhancements on stall behavior with the flaps retracted. Key results indicated that the improvements in modeling pitching moment, static lateral-directional stability, and damping effects provided significant improvements in predicting full scale flight behavior.

The approach-to-stall maneuver using the enhanced simulation model was characterized by positive pitch control with noticeable changes in pitch stability and tendencies for roll-off under certain conditions. Directional stability augmentation (i.e. the yaw damper) was observed to improve handling qualities during the stall by reducing nose wandering tendencies. Pilot comments noted the potential importance of other cues, such as aerodynamic buffet and motion on the pilot's perception of stall behavior and departure warning. While this simulation did not provide motion or noise cues, other than "stick shaker", this topic remains an important issue for further study.

For slow stall entries, departure was characterized by a nose-slice divergence at $\alpha\approx25\text{-}30^\circ$. Figure 18 shows the region labeled "static instability" where the configuration is predicted to exhibit unstable static stability characteristics based on the $C_{n\beta,dynamic}$ departure susceptibility parameter. At higher angles of attack, a roll divergence was observed which was due to unstable values of roll damping as described in figure 16. Another characteristic observed during departure testing was termed the "hung yaw", in which the simulation entered a quasi-steady condition at a non-zero sideslip angle ($\beta\approx15^\circ$) at $\alpha=20\text{-}30^\circ$ during stall/departure recovery. Under certain conditions, this phenomenon resulted in delayed stall recovery and degraded control.

A key result from the piloted simulation research was the lack of repeatability for stall and departure maneuvers. Using normal piloted control inputs, stall and departure characteristics were highly sensitive to rate of control input and wind incidence path. In contrast to typical small amplitude maneuvers, which are commonly used for proof-of-match methods in simulator certification, strong non-linear effects, such as kinematic coupling and aerodynamic characteristics, produced significant variations in handling qualities and flight path for stall and post-stall maneuvers.

3. Effect of Flaps on Stall Behavior

The piloted simulation research reported in Ref. 14 focused on the effect of leading-edge slat and trailing-edge flap deflections on stall/departure characteristics. The primary effect of trailing edge flaps on aerodynamic stability was the reduction in roll damping between $\alpha\approx25\text{-}35^\circ$, attributed to substantial changes in lift characteristics with flaps deflected. In contrast, improvement in static lateral stability between $\alpha \approx 20\text{-}35^\circ$ was attributed to leading edge flap effects on rolling moment. The effects of flaps on roll asymmetries, previously discussed in figure 8, were not included and remain a topic for future research.

Evaluation of stalls with the flaps down showed significant differences in characteristics compared to the flaps-up configuration. Generally, the peak angle of attack achieved with full aft column was 4-5 degrees lower with the flaps down. However, the region of unstable roll damping also occurs at a lower angle of attack, and thus similar departure characteristics are observed as when the flaps are up. Flight test stall data support the conclusion that departures can also occur with the flaps down and the leading edges extended; however, ongoing validation of the flaps-down model indicates that certain specific characteristics of the simulator departures, such as the angle-of-attack for onset and the degree of instability, may need to be modified to better reflect flight test characteristics.

IV. Aerodynamic Model Validation

The ultimate goal of this research is to provide validated methods for developing modern transport simulators that are accurate for upset conditions. Because of the risks associated with full-scale airplane flight tests in upset conditions, several alternative methods are being employed to validate the EUR model. First, time histories from the simulation have been compared to certification flight test maneuvers, such as stalls. For example, Fig. 19 shows stall time histories for the current and EUR simulations compared to flight test data. As shown, use of the EUR model provides a significant improvement in simulation fidelity compared to the current simulation model, and it captures important flight dynamics characteristics such as yaw rate excursions. Secondly, accident data have been compared to the EUR simulation, however limitations in flight data recorders pose a challenge for obtaining accurate data at post-stall conditions. Finally, a remotely-piloted sub-scale aircraft test program is underway to validate modeling methods and flight dynamics characteristics for upset conditions. This 5.5% flying testbed, shown in Fig. 20, is an instrumented, dynamically-scaled, turbine-powered aircraft that is designed to be flown into and safely recovered from extreme upset flight conditions. Planned maneuvers include stalls, departures, and high angular rate maneuvers designed to identify aerodynamic stability characteristics. All three of these approaches have advantages and limitations for achieving the necessary level of accuracy for model validation.

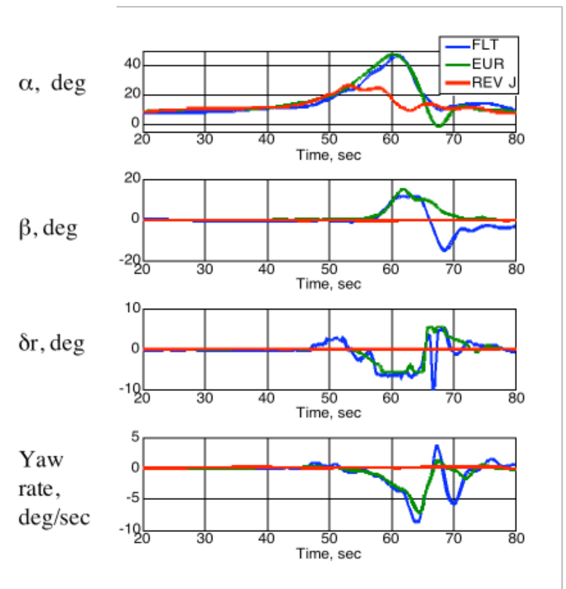

Figure 19. Comparison of baseline and enhanced simulations to flight test data.

Figure 20. Photo of Generic Transport Model sub-scale flying testbed.

The concept of simulation validation can involve several approaches. For example, time history matching is a common approach for certification and it is based on comparing state values between flight data and the simulation over a period of time. Typical metrics include error values, or the difference between the flight and simulator data. For short time intervals, this approach has been shown to be effective. However over long time periods, small differences in state values can accumulate over time resulting in “integrated errors”. For example, small differences in roll acceleration over short time periods can integrate to produce large errors in roll attitude. Another common approach, and perhaps more amenable to upset model validation, is “coefficient matching” whereby non-dimensional forces and moments, derived from flight test linear and angular accelerations, are compared over time to simulator forces and moments resulting from the model buildup using the flight test state variables (i.e. angle of attack, airspeed, angular rates, etc.) This approach involves a direct measure of accuracy of the aerodynamic database and can provide insight regarding modeling errors and point to necessary model corrections. While less graphic for airplane motions, it has been shown to an effective approach for long duration maneuvers, such as stalls and departures.

Finally, more qualitative methods are considered in which general flight behavior is compared between flight and simulation. As previously discussed, figure 19 shows a comparison of wind incidence angles between flight and the EUR simulation. While the states do not perfectly match, the general characteristics are in agreement. Furthermore, the limitations of replicating maneuvers in post-stall conditions must be considered. For example, experience in conducting stalls during flight or simulation testing shows the difficulty in repeating flight behavior, which can be due to time-dependent effects, kinematic coupling (path dependencies), and limitations of exactly repeating human pilot control inputs. The characteristic lack of repeatability of upset maneuvers, such as stalls and departures, should be considered when conducting simulation validation for these regimes.

V. Applications of Research Results

A. Pilot Training

The Upset Recovery Training Aid[1], originally released in 1998, was designed in response to the alarming number of loss-of-control accidents that suggested pilots needed training to cope with airplane upsets. The general goals of this training were "to increase the pilot's ability to recognize and avoid situations that can lead to airplane upsets and improve the pilot's ability to recover control of an airplane that has exceeded the normal flight regime". However, it was recognized that current training simulators are limited and "were not designed for the purpose of replicating upsets"; therefore it was recommended to limit training so that maneuvers remain within the normal envelope of the simulator database. An ongoing industry debate regarding the use of simulators for upset training has further highlighted the need for research on simulation technology for large commercial transport airplanes [15,16,17]. For example, one concern has been that use of low-fidelity simulators could provide "negative training" whereby the pilot learns inappropriate control responses to upset scenarios.

Results from NASA/Boeing research conducted to date have led to a recommendation to re-examine the potential uses of simulators that are specifically designed for upset training. This research has demonstrated that simulation fidelity can be significantly improved such that the useful envelope for upset training may be expanded. One maneuver that is currently impacted by limitations of the aerodynamic database is the accelerated stall demonstration. During this maneuver the pilot-in-training is instructed to pull aft column until the stick shaker activates, then unload to initiate recovery. A common error, and caution in the training guide, is allowing the angle of attack to exceed the range for simulator fidelity. Results of this research would suggest that this limitation could be re-evaluated and potentially allow more training for stall conditions where the stick shaker is activated.

As part of the debate regarding upset training, proposals to provide pilots upset training in aerobatic airplanes have been presented[15]. These training programs have included emulating upsets where the airplane is flown into steep bank angles to experience the physiological effects and motion cues. Therefore the issue of motion effects remains an issue to consider for simulator upset training, especially if the training expands to include stalls and/or departure from controlled flight. Recently, designs for motion simulators that are specifically designed for upset training have been proposed. For example, centrifuge-based motion simulators that can provide accelerations in all three axes have been proposed but substantial research remains to determine the suitability and fidelity requirements of this approach for upset training.

Validation and certification of training simulators specifically designed for upset training will become a necessary topic to consider as upset training expands. As previously mentioned, current simulator certification, although very comprehensive, does not address fidelity during upsets outside of the normal flight envelope. Many of the current certification maneuvers are typically short-duration maneuvers where aircraft states do not vary substantially from trimmed conditions. In contrast, stalls, departures, and post-stall gyrations tend to be long duration maneuvers where states may vary through the full range of the simulator database, making validation methods much more difficult. Therefore, certification requirements and validation methods remain as very important research topics.

B. Advanced Control System Research

The introduction of digital fly-by-wire control systems has revolutionized control system design capabilities[9]. First introduced in fighter airplanes and later in large transports, these systems have allowed tailoring of complex control systems to provide excellent handling qualities while optimizing system performance and allowing updates without major hardware changes. A necessary tool for digital control system design is a valid simulation to determine gains and control system architecture. A recent innovation in large transport control system design is known as "envelope protection" where critical airplane states are monitored to determine if the airplane is operating in the known safe flight envelope. Some systems include the monitoring of states that define out-of-control limits such as those previously discussed on defining LOC. Although the intent of these systems is to prevent airplanes from exceeding the normal flight envelope, for design purposes valid simulations are required to design and test these systems prior to hardware implementation. Other control systems currently under research include automatic recovery systems, whereby computer control is provided to effect recovery from extreme bank and pitch attitudes due to upsets.

C. Accident Investigation

Typically, aviation accident/incident investigation relies on aerodynamic models and simulations for detailed analysis of the airplane flight dynamics that occurred. In particular, LOC accident analysis presents a challenge to analyze and correlate flight data recorder information and determine the causes of the accident. Simulation is often used to reproduce accident scenarios, including analysis of pilot control inputs and the flight trajectory, and to quantify important flight parameters. The aerodynamic database and simulation results reported herein have demonstrated the potential to provide valuable information for accident/incident analysis for those regimes outside of the normal flight envelope.

VI. Conclusion

Simulation of large transport airplanes in upset conditions remains a topic of high interest to commercial aviation as part of the effort to reduce the fatal accident rate due to loss-of-control accidents. In support of this goal, research has been in progress, as part of the NASA Aviation Safety and Security Program, to develop technologies that enable improved simulation and prediction of flight behavior in regimes outside of the normal flight envelope. Based on extensive wind tunnel testing, significant improvements in current transport simulations have been demonstrated, particularly in predicting stall and post-stall behavior, and the limitations of current training simulators for upset training have been documented.

This research has allowed advancements in the state-of-the-art of transport airplane simulators for modeling upset flight behavior to a point nearing the fidelity for high-angle-of-attack fighter simulators. However, many issues remain which were identified in this research and warrant further study. Aerodynamic scale effects, time dependencies in separated flow, and non-linear angular rate effects currently limit model fidelity and remain the subject of ongoing research. The piloted simulation studies conducted to date focused on the impact of improved aerodynamic models on predicting stall/departure behavior. As a result of this research, important flight dynamics characteristics were observed but as improvements in aerodynamic modeling occur, additional study of stall handling qualities and abnormal control scenarios, such as mis-applied controls, will be needed. Finally, model validation for upset conditions remains a critical issue that will require significant efforts to address. Unlike highly maneuverable configurations (e.g. fighters), flight-testing of large transports at extreme wind incidence angles is not feasible due to the risks and structural limitations involved. Therefore, validation will continue to rely on limited flight data, accident data, and sub-scale model testing.

Based on the results of this research, several near-term applications of improved upset modeling are recommended. First, current limitations of simulator upset training should be addressed to determine if enhanced modeling technology can allow improvements or expansion of current training. Secondly, stability and control engineers should consider expanded aerodynamic databases during preliminary design of new configurations or for control system analysis. Lastly, the aerodynamic database acquired in this research can be used for accident investigations or motivate additional testing using the methods utilized in this research.

Acknowledgments

The authors would like to acknowledge the valuable contributions made to this research by Boeing test pilots Mr. John Cashman, Mr. Dave Carbaugh, Mr. Leon Robert and Mr. Chuck Kilberg and UNISYS programmer Ms. Missy Hill.

References

[1]Airplane Upset Recovery Training Aid, Revision 1, August 6, 2004.

[2]Wilborn, James E., "Configuration Study of Modern Transports in Adverse Flight Conditions", final report for NASA contract NAS1-20342, Task 24, Oct. 29, 1998.

[3]Wilborn, James E., "An Analysis of Commercial Transport Aircraft Loss-of-Control Accident Intervention Strategies", final report for NASA contract NAS1-20341, Task 10, June 29, 2001.

[4]Chambers, Joseph R., Burley, James R. III, and Meyer, Robert R. Jr., *"High-Angle-of-Attack Technology; Accomplishments, Lessons Learned, and Future Directions"*, NASA/CP-1998-207676, June 1998.

[5]Chambers, Joseph R., and Stough, H. Paul III, "Summary of NASA Stall/Spin Research for General Aviation Configurations", AIAA General Aviation Technology Conference, AIAA 86-2597, September 29-October 1, 1986.

[6]Shah, Gautam H., et al, "Wind-Tunnel Investigation of Commercial Transport Aircraft Aerodynamics at Extreme Flight Conditions", SAE 2002-01-2912, World Aviation Congress & Display, November 5-7, 2002.

[7]Brandon, Jay M., Foster, John V., Shah, Gautam H., Gato, William, and Wilborn, James, E.; Comparison of Rolling Moment Characteristics During Roll Oscillations for a Low and a High Aspect Ratio Configuration, AIAA-2004-5273, AIAA Atmospheric Flight Mechanics Conference, August, 2004.

[8]Dynamics Modeling of Large Transports for Upset Conditions; final report for NASA contract NAS1-00106, Task 1003, October 31, 2002.

[9]Aerodynamic Modeling of Large Transports for Upset Conditions: Stage 2 EURS Progress Report for NAS1-00106 Task 1010, October 31, 2003.

[10]Aerodynamic Modeling of Large Transports for Upset Conditions: 2004 EURS Progress Report for NAS1-00106, November 3, 2004.

[11]Hodgkinson, John, "History of Low-Order Equivalent Systems for Aircraft Flying Qualities", *AIAA Journal of Guidance, Control, and Dynamics*, Vol. 28, No. 4, July-August, 2005.

[12]Wilborn,, James E., and Foster, John V.; Defining Loss-of-Control: A Quantitative Approach; AIAA 2004-4811, AIAA Atmospheric Flight Mechanics Conference, August, 2004.

[13]Cunningham, Kevin, Foster, John V., Shah, Gautam H., Stewart, Eric C., Rivers, Robert A., Wilborn, James E., and Gato, William, "Simulation Study of a Commercial Transport Airplane During Stall and Post-Stall Flight", 2004 SAE World Aviation Congress, SAE 2004-01-3100, Nov. 2-4, 2004.

[14]Cunningham, Kevin, et al, "Simulation Study of Flap Effects on a Commercial Transport Airplane in Upset Conditions", AIAA-2005-5908, AIAA Atmospheric Flight Mechanics Conference, August, 2005.

[15]Croft, John; "Taming Loss-of-Control: Solutions are Elusive", Aviation Week and Space Technology, August 26, 2002.

[16] Stowe, Capt. Steve, Melody, Capt. Tom, "Upset Recovery in Large Transport Aircraft: Handling Qualities Issues", SAE S7 committee report, Aug, 2003.

[17] Scott, William B.; "Rethinking Upset Training", Aviation Week and Space Technology, January 12, 2004.