Aerodynamics modelling for training on the edge of the flight envelope

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ABSTRACT

Aircraft upset and Loss of Control (LOC) is a leading cause of accidents in commercial and general aviation aircraft operations. A number of measures have been taken in the commercial segment to improve training and awareness of this problem and several organisations offer in-flight training to enhance awareness. In relative terms, in both commercial and general aviation sectors, the use of Full Flight Simulators (FFS) and Flight Training Devices (FTD) for this purpose is minimal. A key reason for this is the limited capability and coverage of flight models used in these devices. This paper provides examples of the limitations in civilian simulators in contrast to military efforts that have been using full envelope modelling for decades to enhance pilot training. The paper also presents techniques used in full-envelope modelling, their validity, and a regulatory vehicle that is in-line with current international guidelines for application to civilian trainer development.

NOMENCLATURE

b	reference span
c	mean aerodynamic chord
p	angular rate about body X-axis (roll)
q	angular rate about body Y-axis (pitch)
r	angular rate about body Z-axis (yaw)
Cl	rolling moment coefficient (body axes)
Clp	rolling moment damping derivative (body axes)

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Cm	pitching moment coefficient (body axes)
Cn	yawing moment coefficient (body axes)
$C_{n\beta}$	$\partial Cn/\partial\beta$ – directional static stability (body axes)
CA	axial force coefficient (body axes)
CD	drag coefficient (stability axes)
CL	lift coefficient (body axes)
CN	normal force coefficient (body axes)
Dh	symmetric horizontal tail deflection
Ddh	differential horizontal tail deflection
V,Vo	true velocity
α	angle of attack
α_{stall}	stall angle-of-attack
β	angle of sideslip
$\beta_{SHSSmax}$	maximum angle-of-attack achieved during steady heading side slip tests
$\dot{\Omega}$	omega wind-axis roll rate (rotation about velocity vector)
$\Omega_{ctrlmax}$	vector (**p,q,r**) representing maximum anglular rates achieved with control system Inputs

1.0 INTRODUCTION

A number of efforts in recent years have sought to identify and mitigate leading causes of air-traffic accidents and losses, with systems, hardware and training being the typical identified tools used to reduce the occurrence of the incident. For example, aviation safety organisations have long identified Controlled Flight In to Terrain (CFIT) as a leading cause of aviation related losses. As a result, a number of efforts to develop test and integrate ground proximity and synthetic visions systems have effectively demonstrated their viability as cost effective options in the effort to reduce CFIT occurrences. In this light, Boeing's *Statistical Summary of Commercial Jet Airplane Accidents – Worldwide Operations 1959 – 2006*[1] recognised in flight Loss of Control (LOC) as the most severe accident causal factor in commercial aviation – with the most crash related fatalities – over the past 10 years. In addition, statistics tracking both fatal and nonfatal incidents in general aviation, compiled by the National Transportation Safety Bureau (NTSB)[2], show similar results. With the advent of the Very Light Jet (VLJ) and their increasing operations, this trend will likely continue. In fact, manufacturers of VLJ's see upset training as a requirement and are offering programs to pilots[3].

The focus of a number of current programs offering training to combat upset and loss of control accidents is in-flight training using aerobatic and or military aircraft. Such programs offer course work and practical exposure to unusual attitudes, stalls, and spins. Although these programs provide valuable experience to pilots in a general sense, this type of training lacks exposure to aircraft-specific characteristics that may provide a critical basis that is needed when attempting to negotiate difficult upset conditions.

There are also efforts to make use of ground-based simulators for such training: specialised devices such as centrifuges as well as FAA and JAR qualified simulators. The commercial aircraft industry, in a collaborative effort, published a training aid for upset recovery[4] that offers training recommendations for use in conventional ground-based simulators. The basic premise of this training aid is that a training syllabus may be performed without 'extensive simulator modification.' It also advises that instructors must be trained to avoid nonstandardised or ineffective training, and that excursions outside the validated flight regime can lead to such ineffective or negative training.

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The training aid document acknowledges that a simulation may be 'extended to represent regions outside the typical operating envelope by using reliable predictive methods.' It further points to the fact that flight data are rarely available for these regions. Readily accepted analytical and empirical approaches have provided reasonable predictions of the aerodynamic response beyond the typical flight envelop for decades. Most of the research and work in this area has been conducted as part of military aircraft development efforts for engineering use and migrated for use in operational training simulations. The objective of this paper is to present the state of the art in the modelling of unusual flight conditions and how these proven techniques are well suited for use to expand the usable flight envelope of civil ground-based simulators.

2.0 UPSET CONDITIONS AND THE FLIGHT ENVELOPE

Upset conditions are typically described as an unintentional pitch attitude of greater than 25° nose up, a pitch angle of 10° nose down, bank angle of greater than 45°, or 'inappropriate' airspeeds within the above parameters. Such conditions may be caused by environmental conditions, system anomalies, and or pilot inputs. Although the attitude of the vehicle does not necessarily mean that the aircraft has ventured beyond the typical flight envelope covered in a flight simulator, the maneuvering or anomaly that causes the upset or the recovery from the condition may result in an excursion outside the typical flight envelope. Figure 1 presents the typical coverage of a commercial aerodynamics database in the angle-of-attack – angle-of-sideslip space.

Also presented in the figure are regions of typical interpolated analytical/empirical data coverage, extrapolated data coverage, and where data are held constant[5]. For reference, a representative FAA/JAA approved validation region, labeled 'ACCEPTANCE', is superimposed, showing that the normal flight envelope, to stall, is well covered during the validation and acceptance process.

Further overlaying regions of data that have been gathered and/or reconstructed from accident investigations from the 1990s clearly shows the lack of coverage of modelling these extreme events.

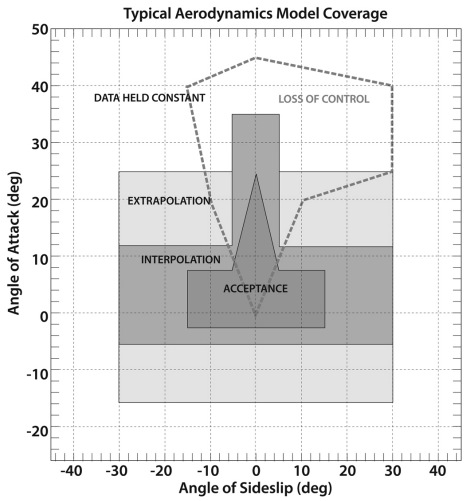


Figure 1. Typical commercial trainer aerodynamics model coverage.

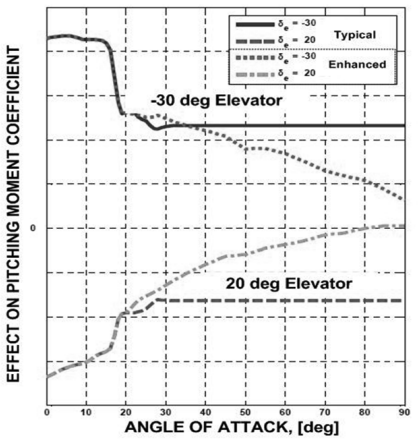


Figure 2. Typical pitch control coverage.

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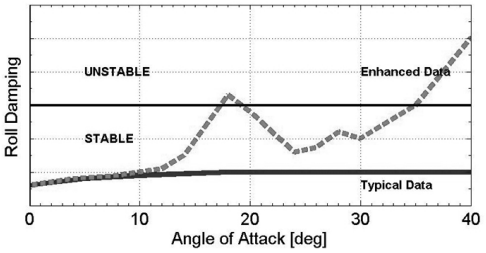


Figure 3. Example of roll damping.

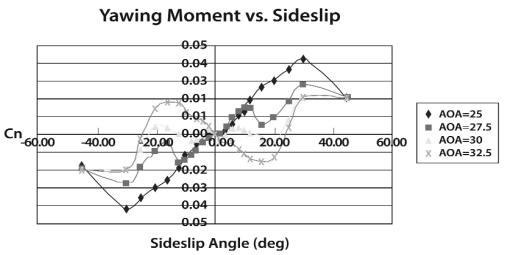


Figure 4. Yawing moment coefficient *vs* sideslip.

When one looks deeper into the coverage of aerodynamics models typically used for commercial flight simulators, an assessment of control power envelope coverage reveals that coverage is quite limited. An example of this can be seen in pitch-control data presented in Ref. 5 and reproduced here in Fig. 2.

Representation of the dynamics, or aerodynamic 'damping effects' in typical simulations used for training, is typically by conventional derivatives that vary with Mach number and angle of attack, but have minimal variation beyond stall, as can be seen in representative roll damping in Fig. 3 again from Ref. 5.

The dynamic range of a transport aircraft in-flight incident can be quite extreme. Non-dimensional angular rates during these events are typically on the order of magnitude of a military fighter[6]. Therefore, limitations in the dynamic coverage of the aerodynamics model may lead to unrepresentative aircraft response to adverse conditions or post-stall recovery. For example, extrapolated damping as seen in Fig. 3 in the stall region would provide an unrealistic dynamic response, where the flight vehicle may have an unstable trend in dynamics stability making recovery from an upset condition much more difficult.

It is because of these limitations that recommended procedures for upset training in ground-based simulators is quite restrictive. An ideal situation provides a simulation that contains realistic data beyond the typical flight envelope and thus allows 'Fly In- Fly-Out' (FIFO) upset and recovery training. Methods for achieving this goal have been used in the development of flight models for the military for several decades and have seen continuous improvement.

3.0 STALL/POST-STALL MODEL DEVELOPMENT

In efforts to increase the understanding of military aircraft loss, improve airframe and flight control design, and finally to improve training, the military launched several parallel efforts to improve stall and post-stall modelling. Assessment of existing EA-6B, F-18, and F-16 engineering and training simulations[7,8,9] in use in the early 1980s revealed several issues impacting the use of simulations to model the stall/post-stall regime. The most important, a legacy of limited computer capacity, cost, or the application of linearised flight extracted data (or all of the above) had left an implementation of the flight model in the traditional derivative expansion form. This architecture was incapable of providing the representation of the stall aerodynamic behavior, behavior that even these early simulations attempted to accommodate. As a result, a common practice with these models was the integration of model 'effects' or adjustments, non-physical accommodations made to the flight model in an attempt to inject more complex behavior on a relatively simple model form. As was clearly demonstrated in these early model assessments, these sorts of flight model manipulations, even if justified with improved model response, typically do not capture

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true physical aerodynamic characteristics, and once outside of the adjustment validated envelope, model fidelity is generally compromised further. The need to identify and physically model aerodynamic functional dependencies in this flight regime was clearly seen.

As a result, efforts were made to develop a new modelling approach, utilising new testing, data reduction and data mechanisation methods to characterise the true aerodynamic behaviors. The following discussion describes some of the major attributes of this modelling approach.

3.1 Static aerodynamics characterisation

While the introduction of wind-tunnel-test data in simulations has been accomplished since the earliest applications, the practice of simplifying the data set to its basic derivative form has left important aerodynamic functionality unrepresented in simulation datasets. Exhaustive wind-tunnel testing in the stall and post-stall regime has shown the aerodynamic characteristics to be much more complex and interrelated as stall is approached and exceeded. These functional dependencies are crucial to proper modelling of the aircraft's behavior in this regime.

Figure 4 illustrates the importance of capturing the effect of sideslip angles beyond the typical angle-of-attack and sideslip ranges. While the yawing moment exhibits a slope that could be effectively represented as a derivative below 12° of sideslip, the directional, $Cn\beta$, stability is dramatically reduced at higher sideslips. These trends require expanded sideslip functionality and a non-linear multi-dimensional table characterisation. Normal flight typically does not require such large angular excursions; however, sideslip angles of 20° and above can be experienced during the stall and post-stall motions. Further, due to asymmetric stall behavior that is frequently observed on modern military and civil aircraft, the symmetric effect of sideslip may not always be assumed in the stall region.

The appropriate modelling of control-surface effectiveness is also of primary importance in exposing pilots to the efficacy of the controls during upset conditions. This is nevertheless a component that is frequently highly simplified. Figure 5 presents examples of the control interactions

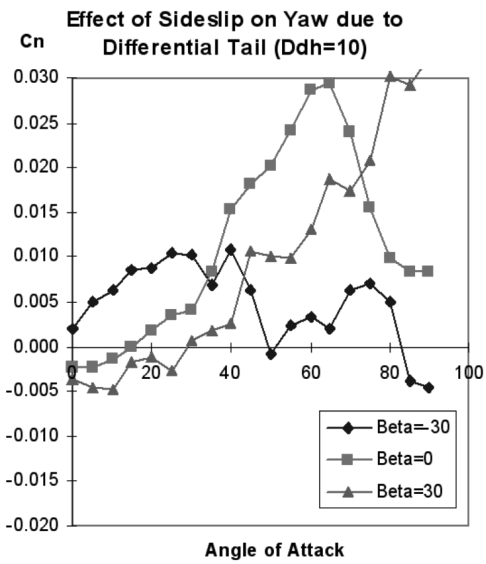


Figure 5. Non-linear control interaction effect functionality with angle of sideslip.

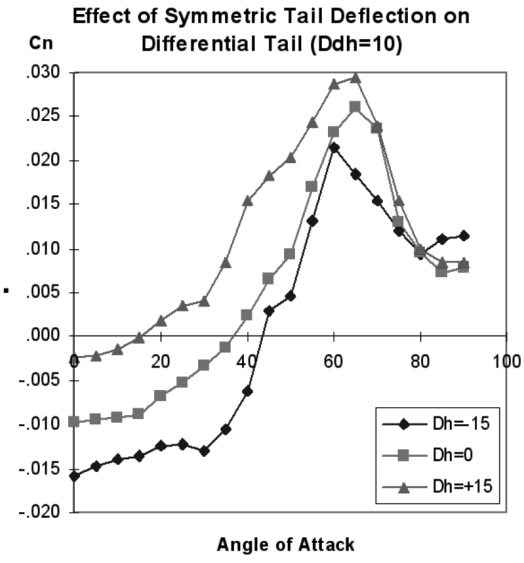


Figure 6. Non-linear control interaction effects.

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that are typically excluded and illustrates the profound effect that sideslip, particularly at large angles, has on yawing moment. Analysis of yaw versus sideslip provides information on the level of directional static stability of the aircraft. In this case, with differential horizontal tail deflection, the directional stability is greatly affected. The effectiveness of deflecting the rudder is similarly affected by sideslip, particularly in the stall region.

Figure 6 illustrates the effect of symmetric control deflection on the incremental yaw effectiveness of the same differential horizontal tail deflection. As seen in the plot, the effectiveness of the controller varies from proverse to adverse (even well below stall) depending on the symmetric control deflection that is imposed. These data were collected as part of a simulation envelope expansion effort. The fact that the original simulation used a linear mechanisation for the yaw due to differential horizontal tail led to a number of modifications and factors being applied in attempts to improve the simulation response, particularly in the stall regime. While this controller is obviously from a military application, it is worth noting that similar interactions have been observed on conventional civil configurations with the elevator/stabiliser deflection interaction on rudder effectiveness.

The key result of the assessment of the static characteristics was the need to acquire functional complexity beyond what has traditionally been incorporated in these simulations. This functional expansion should be based on tangible configuration dependent interactions between the aircraft states and the airframe and control surfaces. Identifying these functionalities is typically well beyond the scope of even the most comprehensive flight test, given the complex, non-linear responses seen in the stall/post-stall region. In this regard, the successful application of post-stall flight modelling in military and civil applications has utilised a series of low speed, low-cost wind-tunnel test applications[10,11] to exercise the large test matrices that are required to quantify these effects.

3.2 Dynamic aerodynamics characterisation

Beyond the issues that arose from the assessment of the static modelling for stall/post-stall flight, assessment of the modelling of dynamic or unsteady characteristics revealed considerably more complexity. Even in flight model situations where increased functionality was introduced into the

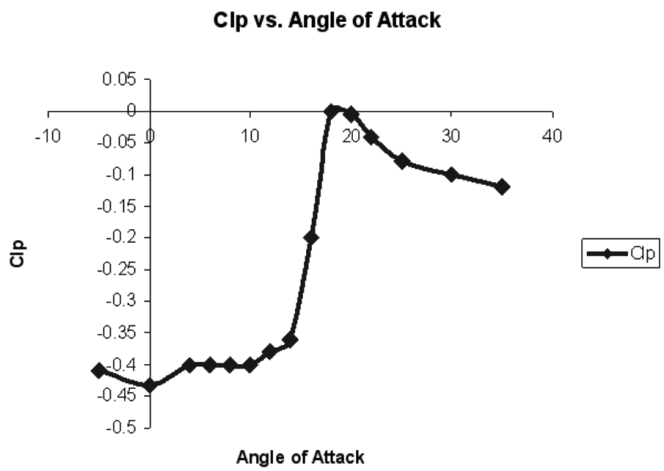


Figure 7. Roll damping derivative versus angle of attack.

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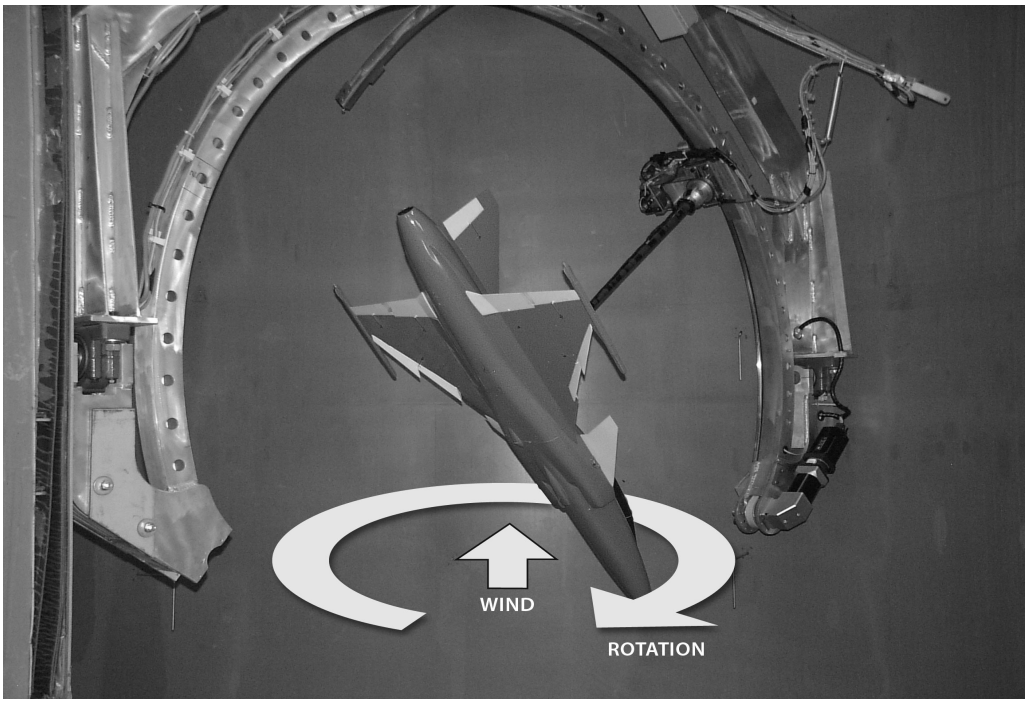


Figure 8. Velocity-vector rotation testing.

basic static components, the body-axis dynamic aerodynamic effects, also known as 'damping effects' or 'damping derivatives,' remained in derivative form, modeled as non-linear functions of angle of attack, but linear functions of angular rate as presented in Fig. 7.

Concurrent with this renewed assessment of the body-axis dynamics characterisation, considerable progress had been made in the acquisition and data implementation of velocity vector dynamic characteristics[12]. This test method, initially developed to help analyse and model a configuration's spin characteristics, uses a steady rotation rate about the velocity vector at a set angle-of-attack and sideslip Fig. 8.

By rotating at specific rates, the test method allows the definition of the vehicle's linear and non-linear damping characteristics about the velocity vector as a function of rate. Such data revealed, at low angles of attack, the dynamics can be expressed as a linear function of the non-dimensional rate $\Omega b/2V$, Fig. 9, but as the aircraft enters the stall condition, the data exhibits a significant non-linear variation with rate, the effect varying from propelling to damped depending on the condition. In the stall region, a velocity-vector roll can also be decomposed as a combination of body-axis roll and yaw rates, so the inference would be that these individual terms would likely exhibit nonlinear variation with their respective rates as well.

This conclusion was initially difficult to identify since the methods for identifying damping, from wind-tunnel and flight test, used assumptions and acquisition techniques that forced the derivative form. In order to acquire non-linear body-axis damping data, test methods were devised that allowed the measurement of the damping term at a particular rate as the model oscillated through the reference attitude in the wind tunnel. This method, referred to as the specific point method[13] allowed the acquisition of dynamic data at unique non-dimensional rates at specific reference angles of attack and sideslip, and is expressed in the same fashion as the velocity vector damping

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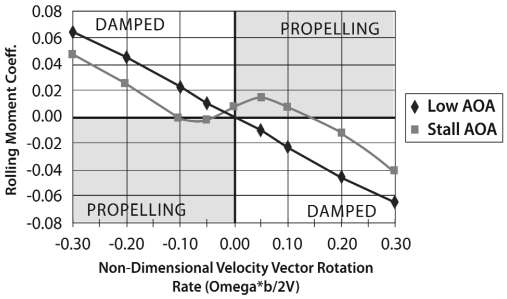


Figure 9. Rolling moment effects from rotation about the velocity vector.

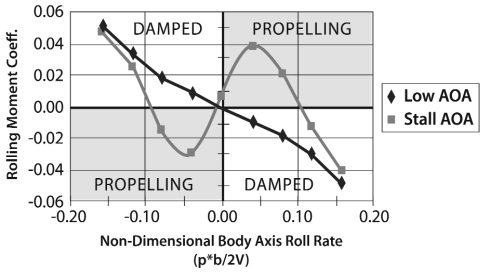


Figure 10. Effect of body-axis roll rate on rolling moment coefficient.

data mentioned above. Assessment of these data immediately illustrated the same sort of characteristics seen in the velocity vector data, with generally linear variation with rate below stall, but as stall is approached and exceeded, the damping characteristics can also vary in a non-linear fashion with non-dimensional angular rate. For example, Fig. 10 shows the variation of roll increment as a function of rate for selected angles of attack. The significance of attempting to model this region's damping with a linearised term is displayed in Fig. 11, where the extrapolation of the linear term can lead to grossly incorrect roll-damping increments.

A secondary issue arose as these data were analysed. The superposition of the new body-axis rate terms to produce an equivalent velocity vector roll damping did exhibit identical damping as the rotary balance velocity vector rate damping data below stall. However, in the stall regime, the superposition of body-axis rate terms did not represent velocity vector damping acquired from rotary balance test technique.

The net result from this analysis was the conclusion that to build the most physically representative dynamic modelling of a particular airframe in the stall/ post-stall region, the combination of the two types of dynamic data were needed, and these had to be specifically combined based on real time evaluation of the simulated rate excursions. This research led to a number of postulated dynamic data mechanisation schemes[14,15] and the most appropriate have been successfully demonstrated and applied in a number of current military and civil applications.

Further investigation into the significance of the dynamic characteristics illuminated other issues as well. Unlike the previous methods of dynamic data acquisition and reduction techniques, the specific point approach allows the identification of functional effects such as the effect of sideslip, control deflection and the sign of the rate, interactions that had not previously been identified. The evaluation of these effects in the dynamic test data revealed that these states can have significant impact on the dynamic responses in the stall and beyond. Figure 12 shows an example of a variation of incremental pitching moment as a function of non-dimensional pitch rate at stall angle-of-attack for a business jet. The pitch increments are shown for the clean aircraft, the aircraft with landing flaps deployed, and finally, the flaps and full aft stick elevator configuration. At the angle-of-attack shown, the basic aircraft exhibits a stable pitch-damping characteristic. The deployment of the flaps significantly reduces the positive rate stability to effectively neutral stability (with negative rate damping remaining unchanged). The addition of full aft stick to this combination results in a configuration that is quite unstable for low positive pitch rates. These significant effects had not previously been identified or modeled.

This figure also illustrates the impact these identified effects have on the modelling of the stall behavior. Evaluation of many military and civil stall simulations has identified a number of

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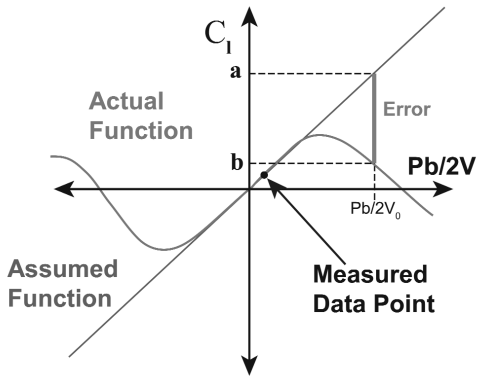


Figure 11. Consequence of linearisation.

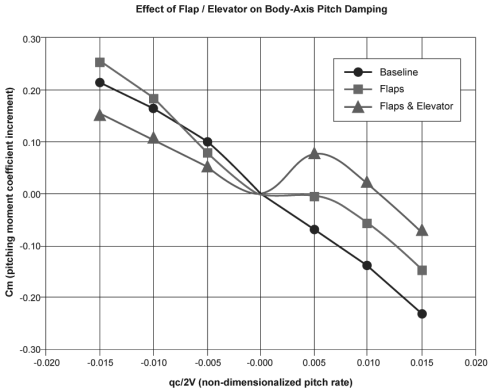


Figure 12. Example of control effects on pitch damping.

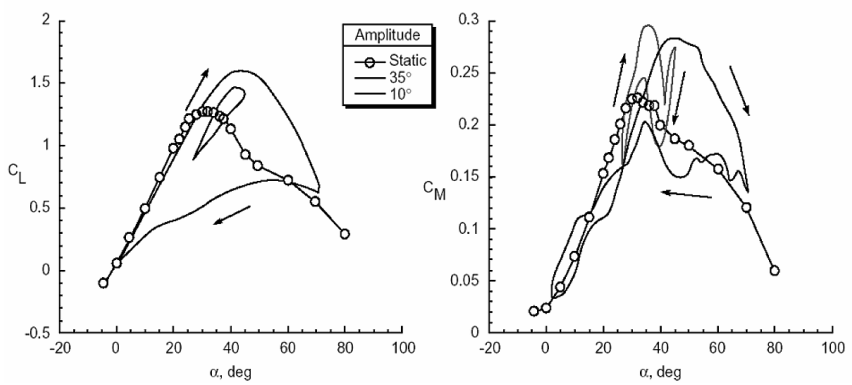


Figure 13. Example of dynamic effects near stall or 'hysteresis'[16].

complicated model 'effects' incorporated to provide a level of what is frequently referred to as 'stall hysteresis' or dynamic stall. This behavior is characterised by unsteady aerodynamics that cause dissimilar aircraft response as the aircraft pitches up through stall versus the response that occurs as the aircraft pitches down through the same angle-of-attack Fig. 13. This behavior has important training consequences and because the conventional model build-up does not provide any attitude or rate unique characterisation, simulations have used mechanical effects such as 'latching' increments based on angle-of-attack history, or other similar devices to attempt to introduce these effects. Referring to the test data presented in Fig. 13[16], one can easily see how this stall hysteresis characteristic is accommodated by actual aerodynamic variation of the pitch damping as a function of positive and negative rate.

4.0 EXAMPLES OF MILITARY APPLICATIONS

To illustrate the validity of the methods described two example of military applications of high-angle-of-attack modelling have been selected, a variant of the F-16 and the F/A-18CD. Both aircraft are highly maneuverable and provide excellent example of the capability of modern flight models.

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Figure 14. F-16 MATV.

4.1 F-16 MATV (Multi-Axis Thrust Vectoring)

Application of the modelling techniques described above in the military has demonstrated the success of these new approaches. One of the early applications of these methods was the development of a new high-angle-of-attack flight model of the F-16 MATV (Fig. 14) configuration undertaken for the Air Force Research Laboratory[17,18]. This effort was the result of the existing F-16 simulation's inability to accurately model the stall and post-stall characteristics. This was particularly manifest in the poor roll co-ordination control in the immediate stall region. As a result, the aircraft was outfitted with a 'dial-a-gain' board that allowed the pilot to actively adjust the FCS in flight to attempt to improve post-stall controllability. Post-flight comparisons between flight data and existing F-16 simulation predictions were made. Figure 15 provides an example of such comparisons for a velocity-vector roll attempt at approximately 35° angle-of-attack. The comparison exhibits the simulations deficiency, and explains how an FCS developed using this simulation would likely be inadequate for controlling such a maneuver.

A new flight model was independently developed, incorporating the non-linear modelling and mechanisation techniques described above, including revised body-axis dynamic data utilised in conjunction with rotary balance based velocity axis dynamic data. Using the same flight conditions and inputs, the resulting predicted flight response is compared with the flight data (Figure (16)). The significant improvement in the correlation between flight and simulation was demonstrated for this maneuver as well as many other high-angle-of-attack conditions.

4.2 F/A-18C/D

Efforts to improve the Navy's high-angle-of-attack modelling of the F-18C/D (Fig. 17) configuration began in the 1980s as a result of observed deficiencies in the existing simulation's ability to model this aircraft's high-angle-of-attack characteristics, both in and out of control. The desire to enable

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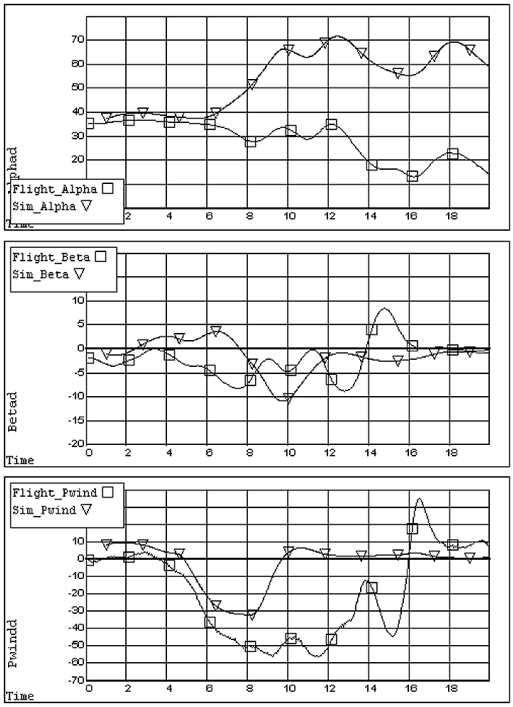


Figure 15. Comparison of unimproved F-16 MATV simulation with flight data.

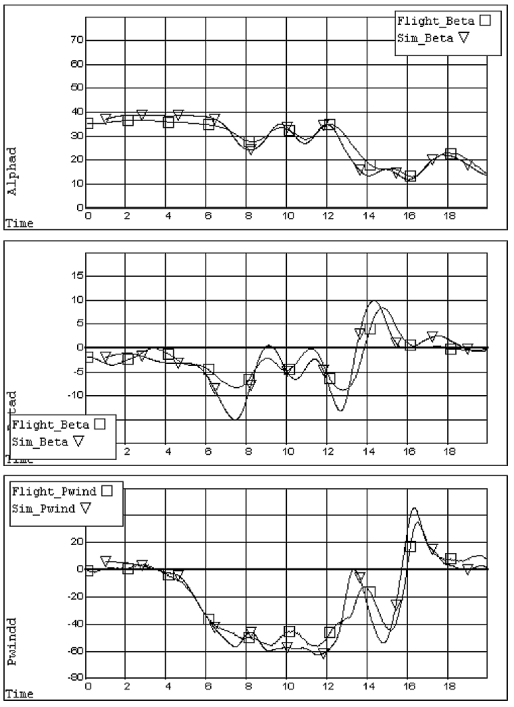


Figure 16. Comparison of improved F-16 MATV simulation with flight data.

flight test evaluation of and training exposure to these behaviors further drove these efforts. As a result, an extensive redesign of the original model to include an entirely new low-speed, high-angle-of-attack static and dynamic dataset was undertaken[8,20]. This model formed the basis for the development and distribution of an F-18 Common Aerodynamics Database to F-18 users.

Beyond the application of the simulation to support F-18 flight test and training, the availability of the simulation provided significant support in addressing an important flight deficiency. The F-18 is one of the few aircraft that exhibits an out of control mode that is referred to as the 'Falling Leaf'. This name refers to the dramatic large amplitude oscillations that are characteristic of this flight condition. Besides being very disorientating to the pilot, this motion can be unrecoverable depending on flight conditions, the flight control mode, and pilot inputs. As a result, numerous aircraft losses were attributed to its occurrence. The F-18 could enter falling-leaf condition during aggressive maneuvering at low angles of attack, as the time history shown in Fig. 18 exhibits; it shows a low angle-of-attack, large-sideslip excursion entry, as well as the subsequent complex and highly oscillatory motions.

The original F-18 simulation was incapable of providing a representation of the entry and the subsequent motions, consequently, evaluation of the entry aerodynamics and FCS update testing in ground-based simulators was compromised. The revised model, with the expanded static and dynamic characteristics, was able to very accurately represent the entry and subsequent motions, as shown in Fig. 18. The availability of this modelling capability enabled not only a detailed understanding of the aerodynamics behind the departure and subsequent motion, but also provided a platform for FCS update evaluation prior to flight testing[21-22].

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Figure 17. F/A-18C/D (D-model shown).

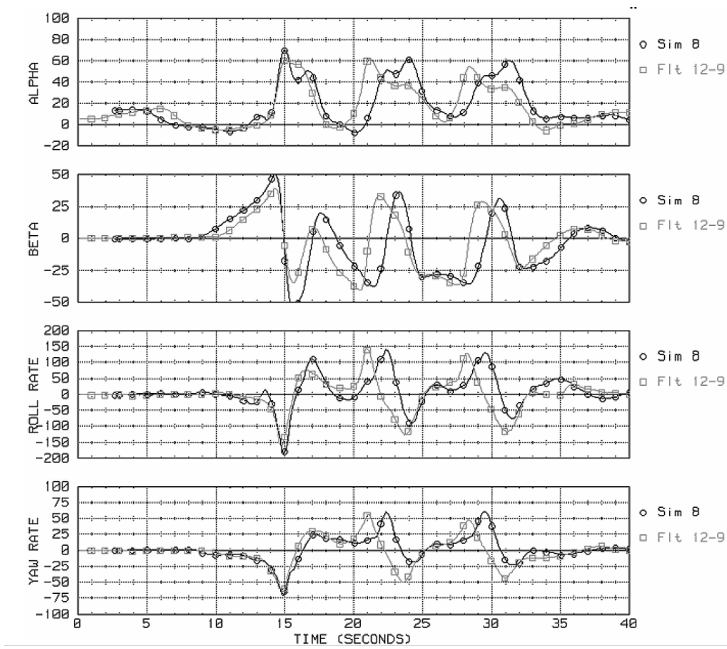


Figure 18. Example of F/A-18C/D simulation comparison with flight data.

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Figure 19. Photos of NASA DH-6 Twin Otter sub-scale wind-tunnel model and full-scale Icing research vehicle.

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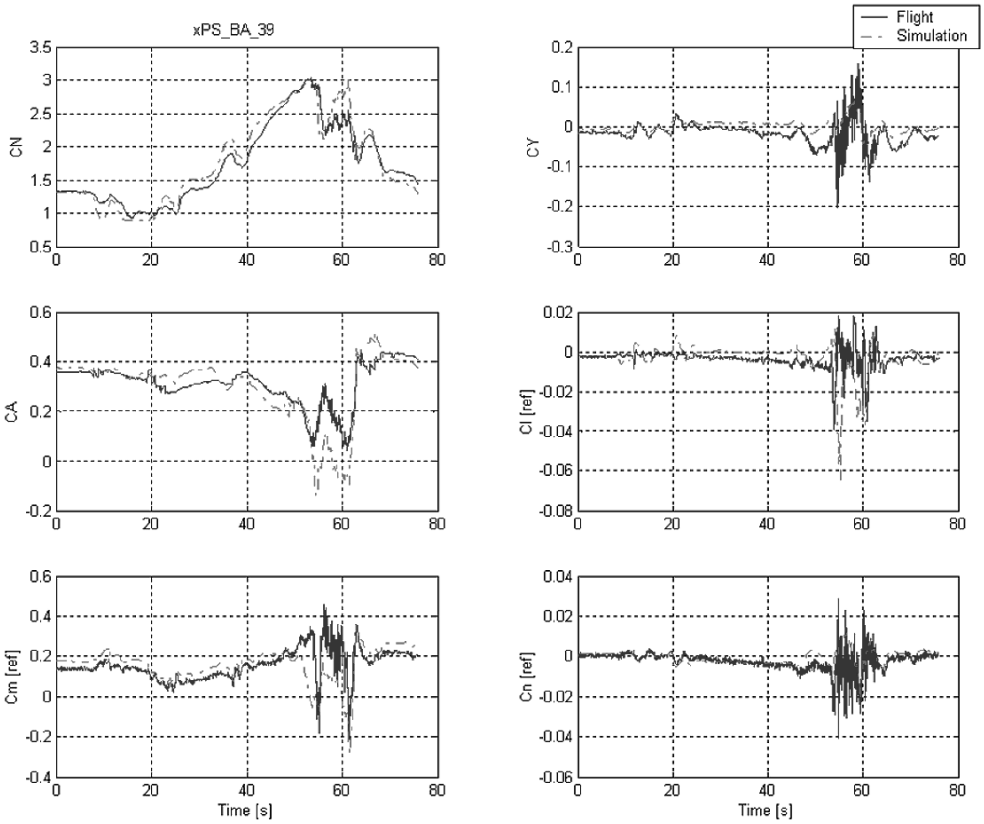


Figure 20. Example of comparison of aerodynamics coefficient prediction during stall comparison with flight extracted data.



Figure 21. Photos of NASA 5·5% and 3·5% scale wind-tunnel models in the Langley 14- by 22- foot and 20-foot vertical wind tunnels.

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5.0 APPLICATION TO CIVIL SIMULATIONS

As indicated in the previous sections much work has been performed to develop wind-tunnel testing, data collection, and data reduction methods to best predict aircraft aerodynamic response in extreme conditions. In addition to the vast amount of work that has been performed in the area for military applications, the approach described above has also been applied to a number of civil configurations. In fact, techniques have been used since the 1970s to investigate spin behavior of general aviation aircraft[23]. Because of confidentiality agreements no specific work may be discussed in this paper, but within the past decade, a number of civil aircraft manufacturers have employed advanced data collection and reduction techniques along with simulation to predict behavior of new configurations in the stall and post-stall regimes to facilitate and reduce flight test time during certification.

Work has also been performed using civilian configurations in the non-commercial world. NASA has sponsored efforts for simulation development for research and training purposes. Two examples are provided below.

5.1 De Havilland DH-6 twin otter

In the early 2000s, in support of NASA's in-flight icing program in conjunction with NASA's Aviation Safety Program a training simulation was developed by Bihrle Applied Research Inc. to model the effects of in-flight icing on the flight dynamics of the DH-6 aircraft Fig. 19[24-25].

The primary objective of the work was to establish a process that could be used to modify and enhance existing flight aerodynamics models with data to appropriately model the effects of in-flight icing in normal and extreme flight conditions. The baseline and icing effects model was developed from wind-tunnel data collected at the Wichita State 7ft by 10ft low-speed tunnel in Kansas, and at Bihrle Applied Research Inc. Large Amplitude Multi Purpose (LAMP) facility in Germany. The test data covered a large angle-of-attack and side slip range including inverted angles of attack, with and without deflected flaps and control surfaces. As part of the comprehensive data collection effort, body-axis forced oscillation and rotary balance data were collected and implemented into the model. The tests were then repeated with prescribed ice-shaped fixtures adhered to the wing, vertical, and horizontal tails.

Data from wind-tunnel tests were reduced and incorporated into an aerodynamics model that was validated against flight test data (Fig. 20) and implemented into a unique Icing Contamination Effects Flight Training Device (ICEFTD). The main purpose of this device is to demonstrate and train pilots on the effects of in-flight icing[26]. The ICEFTD has been a key element in a number of hands-on short courses conducted by the University of Tennessee Space Institute (UTSI)[27].

5.2 Large twin engine transport

As part of NASA's Aviation Safety and Security Program, a collaborative effort performed by NASA and The Boeing Company leveraged state-of-the-art practices in the modelling of flight dynamics to better model the stall and post-stall flight regime of a large twin-engine commercial transport[5]. During the effort comprehensive wind-tunnel tests using 3·5% and 5·5% scale models, Fig. 21, were conducted employing the extended static, body-axis forced oscillation and rotary-balance test techniques described above. The data from these tests were reduced by NASA, using techniques presented in Ref. 15, and used by Boeing to create an 'enhanced' flight model of the subject aircraft.

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The resulting simulation was used in a piloted simulation study in which the response of the enhanced model was compared to a baseline model with typical envelope coverage used for crew training. The study focused on maneuvers with flaps up in the stall and post-stall flight regimes. The conclusion of the study showed that the enhanced model was able to achieve 'higher angles of attack,' and that lateral-directional characteristics were 'more dynamic' than the baseline crew training model[28]. The enhanced model 'provides a better prediction of lateral/directional dynamics in post-stall flight where complex interactions of stability, control effectiveness, rate damping, and kinematic coupling occur.' Qualitative assessments from Boeing and NASA pilots indicated that the enhanced model was an 'improvement' over the baseline[28].

6.0 GROUND-BASED SIMULATOR ENVELOPE EXPANSION

Both FAR Part 60 Change 1[29] and JAR-STD 1A[30] contain the requirements for qualifying a simulator for pilot training. In the stated requirements, specifically for the aerodynamic and flight models, a number of requirements indicated proper functionality and behavior of the flight model. For example, Part 60 requires that overall aerodynamics modelling must have appropriate functionality for corresponding levels of qualification, such as 'Nonlinearities due to sideslip,' 'Mach effects at high altitude,' etc. The requirements also contain a detailed list of objective tests, commonly included in a document named the Qualification Test Guide (QTG), which must be performed where results must fall within specific tolerances of acknowledged truth data – data typically provided by the manufacturer. Revisiting Fig. 1, the region of the simulator flight envelope that undergoes rigorous validation and acceptance, the QTG region, during FAA or JAR qualification efforts is quite small relative to the 'entire' flight envelope. One can raise the argument that the QTG envelope does not completely cover the entire normal flight envelope and that it is readily accepted that interpolated data collected from approved methods that has NOT been validated is used every day for pilot training. It is generally accepted that these responses must be of the correct trend and magnitude, and thus deemed appropriate by piloted subjective tests.

Since the use of data that generates 'correct trend and magnitude' response without objective testing is an accepted practice within the 'normal' flight envelope, it is reasonable to suggest that such data collected outside the 'normal' flight envelope would be appropriate as well.

As presented in the previous sections, the state-of-the-art in the modelling of flight dynamics has evolved much like other technologies used in the deployment of flight simulators such as image generators and motion systems. The methods are well suited for providing data, that at the very least, can be used to generate aerodynamics models that will yield responses that are of the correct trend and magnitude for use in training of scenarios in which the flight vehicle experiences flight motions that are beyond the normal flight envelope and beyond stall.

6.1 The process for envelope enhancement

The addition of data in the post-stall regime to aerodynamics data packages can be a controversial subject. On the one hand it is desirable to field comprehensive models for training pilots to improve safety by allowing them to train for events that are not practical to execute in the

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aircraft. On the other hand, the addition of data at extreme conditions to the database by aircraft manufactures may not be possible. Current requirements do not require modelling past stall or at extreme flight conditions. Perhaps it is time to recommend a change in thinking.

In order to extend capabilities beyond the currently accepted usage of ground-based simulators, a qualified 'endorsement' strategy is proposed that is in-line with task-driven trainer requirements being proposed in the latest version of ICAO 9625[31]. Such endorsements would serve as a mechanism for allowing simulator manufacturers to exceed capabilities that the aircraft manufactures are not willing or capable of providing. In addition, it provides a potential revenue stream for aircraft manufacturers and other vendors with data package options that support the endorsements. Each endorsement would have a set of requirements, much like requirements for qualification. For the topic at hand, an 'upset training and extreme flight endorsement,' would carry requirements that ensures the FAA or JAR qualification level, B,C,D etc. are satisfied, and that augmentation to the qualified aerodynamics model are performed using readily accepted methods, such as those presented in this paper. An official endorsement program would provide standardisation and motivation for enhancing and improving the flight envelope coverage for flight simulators.

The process of enhancing existing aerodynamics models by an aircraft or simulator manufacturer would require a number of steps that are outlined below.

1. Define the Enhancement Envelope

   (a) Several guidelines can be used for determining the true extent of the required aerodynamics model enhancement.

      (i) Angle-of-Attack: $-2\alpha_{stall}$ to $5\alpha_{stall}$

         (1) Reference 32 presents a quantitative approach to the determination of loss of control. In this work an adverse aerodynamics envelope is defined by a normalised angle-of-attack and sideslip. The normalised angle-of-attack is equal to 1 at stall and zero at 0°. When overlaying accident data on this adverse aerodynamics envelope, several accidents exceed normalised angles of attack of 4·5.

      (ii) Angle of sideslip: $-2\beta_{SHSSmax}$ to $\beta_{SHSSmax}$

         (1) The extents for angle of sideslip are a function of maximum sideslip achieved in any condition during a steady heading sideslip maneuver from flight test.

      (iii) Control power and flaps

         (1) Primary controls and flap coverage that may be available to the pilot in extreme conditions should be covered in the enhanced model for the angle-of-attack and sideslip coverage specified above.

         (2) Control surface effects must capture nonlinearities and inter action effects.

      (iv) Pitch, roll, and yaw rate: $-2\Omega_{ctrlmax}$ to $2\Omega_{ctrlmax}$

         (1) The maximum nondimensional angular rate, $\Omega_{ctrlmax}$, is the maximum rate that can be generated by the flight controls in any of the three aircraft axes, pitch, roll, and yaw. These rates are typically nondimensionalised using a characteristic length in the corresponding axis, span for example in the lateral axis, and divided by twice the true airspeed, thus $pb/2v$.

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(2) Modelling of dynamic effects must account for nonlinearities throughout the flight envelope.

2. Assessment of the existing envelope coverage

(a) The assessment of the existing envelope coverage focuses on the determination of what are believable data and what are not and the relation of this coverage to the envelope specified in step 1.

(i) This may be a difficult task, but obvious answers may be revealed by simple inspection of data like those seen in Fig. 2. It is obvious that elevator effectiveness does not physically remain constant after stall. Other data's functionality and validity may not be as obvious.

3. Data Acquisition

(a) Develop a plan for data not covered by the baseline data. Several options exist as data sources.

(i) Wind-tunnel testing (low-speed, dynamic)

(1) As presented in a number of examples in this paper the data that are collected from low-speed wind-tunnel testing are well-suited for populating extreme envelope aerodynamics models. Much work has been performed in the development of using dynamic data from such facilities in modern aerodynamics models.

(ii) Computational aerodynamics and computational fluid dynamics

(1) Currently options exist that can be used to model aerodynamics beyond stall, and at extreme flight conditions. Several solutions provide good correlation with wind-tunnel data.

(b) Data collection, reduction and implementation

(i) Data would be collected from the chosen source and need to be organised into a database that would be merged with the baseline aerodynamics model. In this step expert judgment must be made as to any corrections that must be made to the data that will enhance the baseline data in order to seamlessly blend data coverage.

4. Testing and Verification

(a) As with all modifications to a simulation used for training, the QTG must be run to ensure the baseline fidelity was not corrupted by the enhancement. Further testing must be conducted to verify proper implementation and blend of the enhanced data envelope.

(b) Subjective test flights by subject experts

7.0 CONCLUSION

Much work has been performed in the modelling and simulation of flight dynamics in 'extreme' conditions. Through this work, a process has been established that yields models with very good predictive capability and subsequent correlation with flight test data. Although most of the work in this area has focused on highly maneuverable military aircraft, the concepts for data collection and reduction are well suited for use in the civil arena, as was proven during two efforts sponsored by NASA in the past decade.

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The current typical coverage of aerodynamics models used in training simulators is inadequate to provide realistic 'fly-in fly-out' upset and extreme condition training. With the application of techniques and processes presented here along with the concept of FAA and or JAR endorsements, the industry is provided with a path toward increased use of ground-based simulators for upset training by the expansion of the typical simulator flight envelopes.

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