FINAL RESULTS OF THE SUPRA PROJECT: IMPROVED SIMULATION OF UPSET RECOVERY

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Abstract

The objective of the European research project SUPRA (Simulation of Upset Recovery in Aviation) is to develop technologies that eventually contribute to a reduction of risk of Loss of control – in flight (LOC-I) accidents, today's major cause of fatal accidents in commercial aviation. To this end the project developed novel concepts to improve ground-based simulation of upset events. Current flight simulators are considered inadequate for the simulation of many upset conditions as the flight dynamics and aerodynamic models apply only to the normal flight regimes and aircraft behavior may change significantly outside this envelope. Furthermore, standard hexapod-based motion systems are unable to reproduce the high accelerations, angular rates, and sustained G-forces inherent to upset conditions. SUPRA investigates new engineering methods to extend the aerodynamic model to higher angles of attack as well as innovative motion cueing solutions, including the use of centrifuge-based simulators. These new technologies have been evaluated by test pilots for a selection of relevant upset scenarios. It was found that the SUPRA all-envelope simulation model is representative of the airplane class being simulated within and outside the normal flight envelope as well as that improved motion cueing is possible on hexapod and centrifuge devices.

1 Introduction

For several years now, Loss of control - in flight (LOC-I) continues to be the leading cause of fatal accidents in commercial aviation ([1], see Figure 1).

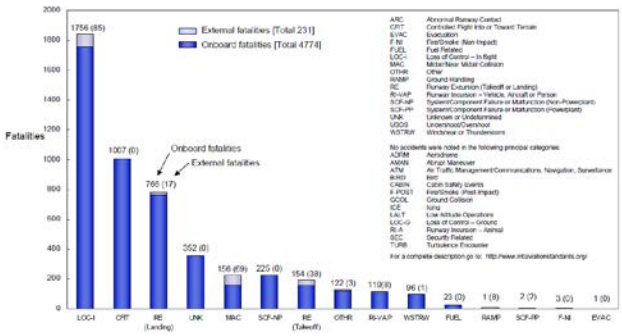

Figure 1: LOC-I leading the fatality statistics in commercial aviation 2001-2010 [1]

Many LOC-I accidents have been attributed to a lack of the crew's awareness and experience in extreme flight conditions. In the course of loss of control events, the aircraft often enters unusual attitudes or stalls. To prevent or timely exit a loss of control situation it is essential that the pilots rapidly recognize the condition, initiate recovery action and follow appropriate recovery procedures. Inadequate recovery may exacerbate the situation and lead to loss of the aircraft.

In-flight upsets are infrequent events in today's operations and many commercial pilots have never experienced such a situation, neither on part 25 certified (large transport category) aircraft nor during training on smaller airplanes or in military aircraft. This fortunate fact can have unfavorable implications for the proficiency of aircrews in dealing with such events and calls for specific upset recovery training. Aviation authorities recognize the need to educate pilots on upset recovery techniques. In-flight training with large aircraft is expensive and unsafe. Therefore, it is generally agreed that the availability of ground-based flight simulators capable of accurately representing extreme flight conditions would be an important component of upset awareness and recovery training programs. Since commercial pilots already receive a large part of their training in flight simulators, this would also be a cost-effective solution.

However, current flight simulators are considered inadequate for the simulation of many upset conditions as the aerodynamic models merely apply to the normal flight envelope. However, upset events can take the aircraft outside the normal envelope where aircraft behavior may change dramatically, and pilots may have to adopt unconventional control strategies [2]. Furthermore, standard hexapod-based motion systems are unable to reproduce the high accelerations, angular rates, and sustained G-forces occurring during upsets and recovery from upsets. The European Seventh Framework Program project SUPRA – Simulation of Upset Recovery in Aviation – aims to push both the aerodynamic and the motion envelope of ground-based flight simulators and investigate the feasibility of conducting advanced upset recovery simulation. The research not only involves hexapod-type flight simulators but also experimental centrifuge-based simulators.

2 SUPRA Upset Scenarios

Consistent with general understanding an upset is defined as an airplane in flight unintentionally exceeding the parameters normally experienced in line operations or training [3]:

- Unusual attitudes (pitch attitude greater than 25 degrees nose up, or greater than 10 degrees nose down; bank angles > 45 degrees);
- Stall;
- Spin;
- Exceeding Mach or G-load limits.

Upset situations are highly dynamic. As shown in Figure 1 conditions can change quickly and the flight can pass from one type of upset to another, depending on environmental events or flight crew actions.

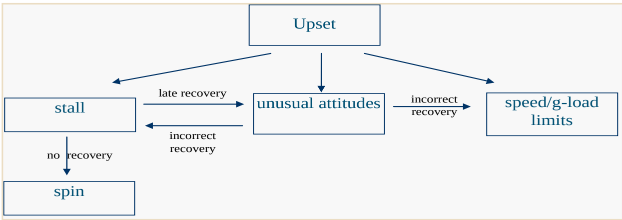

Figure 2: Different types of upsets

Detection, understanding and initiation of proper recovery actions are challenging tasks for commercial flight crews; such is analysis and simulation of those scenarios. Breaking the scenarios down into categories of upsets makes them amenable to engineering analysis and enables structured, scenario-based training with the goal to provide flight crews with a readily available category-specific set of recovery actions whenever one of the upset types is detected and rapid crew action is required.

Based on analysis of the publicly available LOC-I accident and incident data, e.g. in [4], and discussions with the SUPRA expert advisory group, the SUPRA consortium identified a number of scenarios that was used for the final validation. These scenarios have been grouped into three types: Unusual Attitudes, Approach-to-Stall and Stall. Recovery from developed spins was considered beyond the scope of commercial pilot training. The existing industry Upset Recovery Training Aid (URTA) defines a number of Unusual Attitude scenarios that will be used as the basis for the SUPRA Upset Scenarios [3]. Since the URTA is widely accepted by the industry and regulatory authorities it is regarded as an ideal starting point. The expert advisory group suggested to validate the transfer of the URTA scenarios to SUPRA scenarios that extend beyond the currently validated envelope using the extended aerodynamic models and enhanced simulator motion developed as part of the project.

3 Aerodynamic Model

The mathematical aerodynamic and flight dynamic models together designated the "aircraft model", is the heart of modern flight simulators. They are derived using a variety of engineering methods including wind tunnel and in-flight measurements as well as computational fluid dynamics and system identification methods. For Level D certified Full Flight Simulators (FFS) the model output accurately matches aircraft responses measured in-flight. However, this Proof-of-Match is only performed for conditions within the normal flight envelope. Much of the aerodynamic data outside that envelope, although some of it is available through wind-tunnel and flight testing, is currently not integrated into simulator data packages. In other words, simulated aircraft behavior is currently only valid and reliable within the boundaries of the normal envelope. Analysis of LOC-I accident data however shows that transport aircraft often exceed the boundaries of the normal envelope in the course of an upset event (Figure 3).

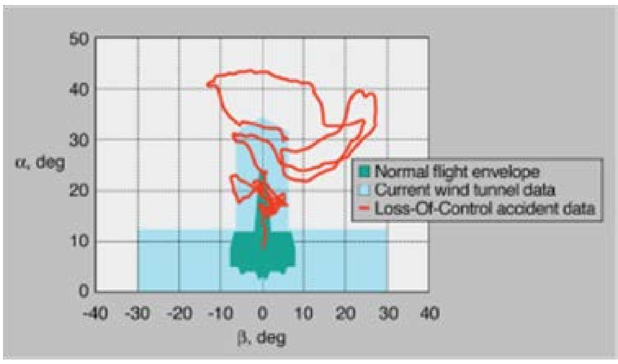

Figure 3: LOC accident and data envelopes

The extension of the flight envelope required for the simulation of advanced upset conditions is depicted in Figure 4 in terms of angle of attack (α), rotation rate (ω), and Mach number (M) typical for take-off/landing and cruise flight conditions. Wind tunnel and flight test data on Mach number are available in the yellow region for a limited range of angles of attack. Although this includes stall conditions, this is not sufficient for simulation of aircraft departures, post-stall gyration and incipient spin modes. Beyond-stall conditions at high angles of attack special wind tunnel tests are conducted only at low speed using static and rotary balance experimental rigs (blue region). At moderate and cruise Mach numbers, stall conditions can occur in the flight envelope region where aerodynamic loads are below structural limits (see the question mark in Figure 4) and where wind tunnel data is not available. The aerodynamic modeling within SUPRA is targeting this area.

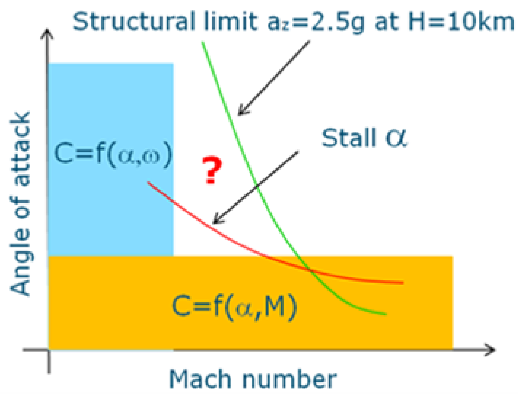

Figure 4: Available aerodynamic data in extended α and M flight envelopes (blue and yellow area).

As control and stability characteristics can change significantly when leaving the mostly linear aerodynamic envelope, it is important to develop simulation models that are capable of reproducing this behavior in order not to misinform the simulator pilot. A number of important aerodynamic effects should be taken into account at stall and post-stall flight conditions, for example:

- The lift force reaches its maximum value at a certain angle of attack. Further increase of angle of attack causes flow separation and loss of lift (stall).
- Dynamic aerodynamic hysteresis in the stall region, resulting from time delays in development of flow separation, may lead to dynamic instability in pitch, roll, and yaw.

- For a number of airplane configurations, for example T-tail, significant pitch-up moments are generated due to the wing tail interaction leading to the onset of a deep stall.
- Asymmetrical development of flow separation leads to onset of destabilizing aerodynamic rolling/yawing moments and steady autorotation.
- Unsteady aerodynamic coupling between the wing and tail can generate aerodynamic negative damping effects leading to onset of bucking, wing-rock, etc.

3.1 SUPRA Engineering Methods

Within SUPRA, experts from De Montfort University use special system identification methods to capture the unsteady aerodynamic phenomena, representing the major effects by ordinary differential equations [5][6]. This so-called “phenomenological model” for high angles of attack is superimposed on the standard mathematical model, preserving the traditional aerodynamic dependencies in the normal flight regime and corresponding low angles of attack.
Previously, phenomenological models for unsteady aerodynamic dependencies at stalled flow conditions were identified using experimental wind tunnel data obtained in forced oscillation tests. Under SUPRA it is being investigated whether it is possible to produce the non-linear aerodynamic responses required for the extended aircraft model using Computational Fluid Dynamics (CFD) in a cost-effective way. The Dutch National Aerospace Laboratory (NLR) has developed advanced CFD methods and previously validated these methods extensively against wind tunnel data for a wide range of extreme flight conditions of military aircraft; covered phenomena include shock waves, flow separation, and vortices. CFD predictions provided a very good estimate of the conditions encountered in real flight [5] [7][8][9]. In SUPRA, CFD predictions are made at harmonic variations of angle of attack, sideslip and roll rates for different amplitudes and frequencies.

The SUPRA engineering approach is illustrated in Figure 5 for the non-linear variation of the lift coefficient with angle of attack. Other than in static conditions, there is a significant dynamic hysteresis effect when the angle of attack varies periodically in the stalled region (green loop). This typical aerodynamic response can be captured using a phenomenological model based on a simple differential equation. There is a close match between the phenomenological model and CFD predictions (red loop) [10].

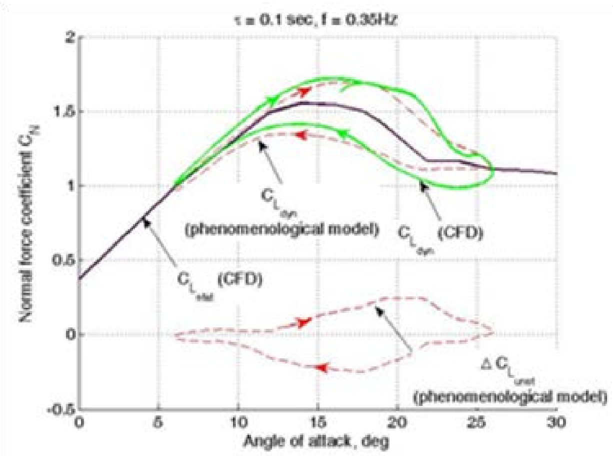

Figure 5: Comparison of CFD (green) and phenomenological (red) predictions of the lift coefficient as function of angle of attack in dynamic conditions.

3.2 Reconfigurable Model

An important feature of the SUPRA phenomenological aircraft model is that it is not matched to a particular aircraft type. Rather it will represent class-specific aircraft behavior. By adjusting the appropriate parameters, the model can be reconfigured to represent different aircraft classes. In Figure 6 this is illustrated for the difference in pitching moment characteristics of a T-tail with tail-mounted engines, on the one hand, and a low tail with wing-mounted engines on the other hand.

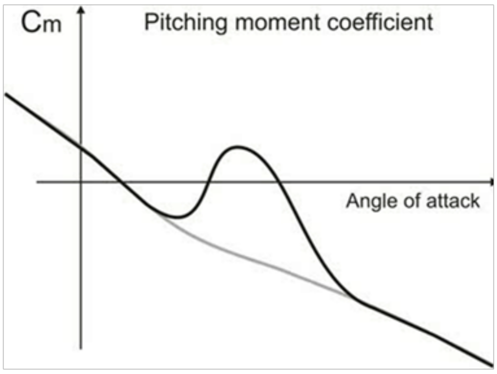

Figure 6: Impression of pitching moment for low-tail (gray) and T-tail configuration (black).

4 Motion Cueing

In order to provide the pilot with motion feedback, FFS are traditionally equipped with a hexapod motion platform, also known as "Stewart platform" (Figure 7). The six linear actuators move synergistically to translate or rotate the simulator cabin. The motion is controlled by motion cueing software, which transforms the output of the mathematical aircraft model into input signals for the simulator motion platform.

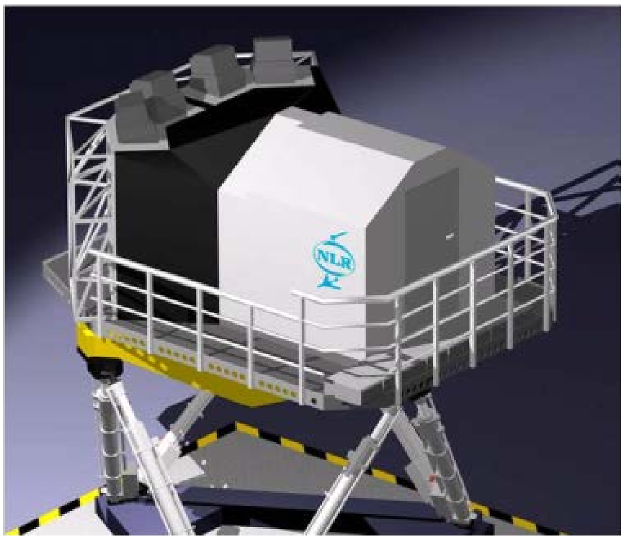

Figure 7: The Generic Research Aircraft Cockpit Environment (GRACE) at NLR, featuring a modifiable cockpit on a hexapod motion platform.

As shown in Figure 8, linear (Fa/c) and rotational (ωa/c) aircraft motion signals are normally high-pass (HP) filtered, so as to merely reproduce brief motion onsets that stay within the limited simulator motion space. An additional low-pass filter (LP in Figure 8) is often used to simulate sustained linear aircraft accelerations, such as the longitudinal acceleration during takeoff, by tilting the simulator cabin, a procedure know as "tilt coordination". Classical motion cueing is acceptable for a wide range of commercial pilot training scenarios, but it has clear limitations for upset simulation which may require reproduction of large angular rates, large attitude excursions, un-coordinated flight and sustained accelerations [11].

Within SUPRA, NLR and TsAGI investigated the possibility of optimizing classical motion cueing filters for the specific needs of upset recovery simulation. Namely two different approaches were taken: 1) optimizing the filters to use the maximum of the available simulator workspace during upset scenarios; 2) optimize the motion filters to provide vital cues during upset simulation based on motion perception knowledge. The experiments were carried out at end of 2011/start of 2012

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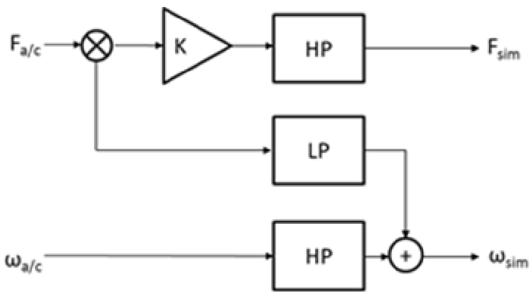

Figure 8: Classical motion cueing algorithm with high-pass onset cueing and tilt-coordination

4.1 Centrifuge-based Solutions

Hexapod motion platforms are inherently limited to a 1g regime. This limitation is overcome by centrifuge-based flight simulators, such as the new-generation research facility DESDEMONA ("DESorientation DEMONstrator Amst") at TNO (Figure 9). The facility integrates a single-seat cockpit with a six degrees-of-freedom (DoF) motion platform. For the purpose of SUPRA the originally fighter-type simulator cabin was outfitted with the captain side of a commercial aircraft flight deck. The simulator cabin is fully gimbaled, i.e. can rotate infinitely about all axes; can move vertically along a heave axis (±1m) and horizontally along a linear arm (±4m). The linear arm can rotate about its central vertical axis to generate sustained centripetal forces in the cabin. With the maximum arm of 4m and a maximum rotational speed of 155°/s DESDEMONA can simulate sustained G-loads of up to 3G. Unique about DESDEMONA's six DoF motion capabilities is that it can combine onset cueing along the x, y and z-axis (like a hexapod simulator) with sustained acceleration cueing. In addition, unusual attitudes and large attitude changes (in excess of 60° bank or pitch) can be simulated one-to-one. Innovative motion cueing solutions were developed within SUPRA to fully employ these motion capabilities.

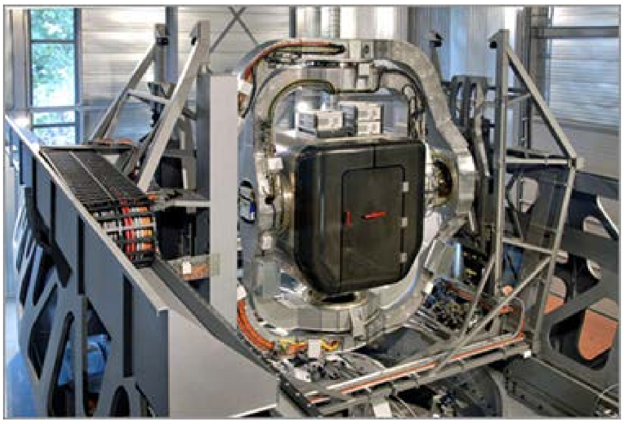

Figure 9: DESDEMONA facility at TNO, the Netherlands

The first motion cueing developments on DESDEMONA were focused on new G-cueing strategies which produce less false cues than conventional centrifuge solutions. In conventional centrifuge-based G-cueing the simulator cabin moves tangentially in the direction of the rotation and the cabin rolls outward when the G-force increases in order to keep the resultant force coordinated with the pilot's z-axis (in coordinated flight). Hence, when G-load increases the simulator centrifuge axis spins up and the cabin rotates outward (roll for the pilot); when G-load decreases, the centrifuge axis slows down and the cabin rolls inward (opposite roll for the pilot). This conventional solution, used in all centrifuge-based flight simulators, suffers from a large false cue that gives the pilot a false sensation of rotation (tumbling). This is especially pronounced when decreasing the G-load after a loaded maneuver (e.g. pulling up from a nose-low attitude). With the extra rotational degrees of freedom of the DESDEMONA cabin the false tumbling cue can be largely avoided by applying G-cueing strategies that use less, or no roll motion of the simulator cabin. Instead another axis, such as the pitch and/or yaw, was used to align the cabin with the resulting G-load vector.

5 Piloted Evaluation

The evaluation phase of the project had two goals: a) establish that the generic, class-specific aircraft model developed is representative of the aircraft class behavior within and outside the normal flight envelope; b) demonstrate that improvements to motion cueing are feasible on standard, hexapod-type devices as well as on advanced, centrifuge-based platforms. The entire evaluation task is depicted in Figure 10.

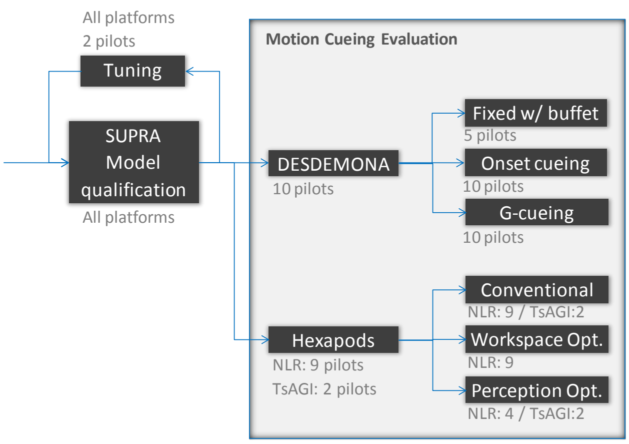

Figure 10: Flow of the SUPRA evaluation program

The SUPRA evaluation exercise was very similar to a (micro)-certification program. It was required that participating pilots have experience in flying commercial type aircraft in upset conditions as well as being familiar with evaluation of aircraft handling characteristics. Hence, only test pilots could be used for this task.

In order to establish the aircraft model's usability for upset simulation it had to be qualified for simulation inside and outside the normal flight envelope. The model was developed to be representative of a commercial airliner in conventional configuration, under-wing mounted engines and a fuselage mounted horizontal tail with a maximum take-off weight of approx. 100 tons. Armed with this basic information a team of up to 10 test pilots flew qualification simulator tests for normal maneuvering as well as approach to stall and full stall maneuvers and rated the airplane behavior acceptable/non-acceptable for a set of pre-defined characteristics. Additionally two general ratings for model behavior inside and outside the normal flight envelope were collected (Figure 11).

Rating	A – Simulation model	
1	Representative of the class of airplane.	Acceptable
2	Largely representative of aircraft class and does not misinform the pilot, i.e. is acceptable for training purposes.	
3	Not always representative of aircraft class and shows limited acceptability for training purposes.*	Not acceptable
4	Mostly not representative of aircraft class and hence not acceptable for training purposes.	

Figure 11: General aircraft model behavior rating scale (A-rating)

After fine-tuning, the SUPRA aircraft model was found to be representative of the airplane class on all simulator platforms. Figure 12 shows a box plot of the general acceptability ratings collected on the two hexapod simulators PSPK102 (TsAGI) and GRACE (NLR).

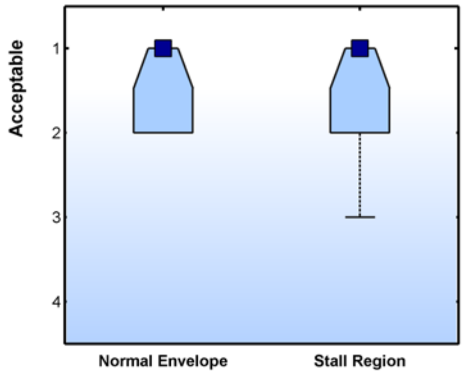

Figure 12: Airplane model ratings collected on the two hexapod simulators within SUPRA

After establishing usability of the aircraft model the project moved on to evaluating the motion cueing concepts developed by SUPRA. The motion drive solutions are shown in Figure 10. A similar approach to the aircraft model evaluation was used. For four different stall scenarios, 2 symmetric and 2 asymmetric, pilot ratings on cue strength and inaccuracies (false cues, phase shifts, etc.) were collected for key motion cues (selected by pilots: roll rate, pitch rate, lateral force or vertical acceleration).

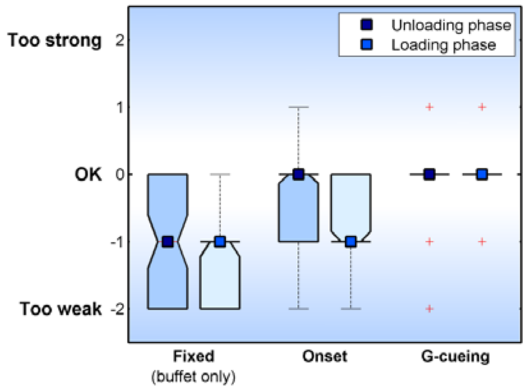

Figure 13: Key motion cue strength ratings from DESDEMONA tests

As can be seen in Figure 13 motion cueing “Buffet Only” were consistently rated as too weak; “Onset Cueing” yields a slight improvement in strength ratings but a large spread can be observed, especially during the unloading phase of the upset; “G-cueing” seems to reproduce key motion cues at appropriate magnitude. On hexapod platforms motion cue strength was consistently rated as slightly weak, with a spread up to slightly strong for “Workspace Optimized” cueing.

As step two of the motion evaluation the pilots rated general acceptability of key motion reproduction (B-rating) as well as general acceptability in terms of false cues (C-rating). Both ratings were given on a scale of 1 through 4, 1: equivalent to the airplane/no false cues, 2: slight deficiencies, not misinforming the pilots/some false cues but not disturbing. 1 and 2 were considered acceptable; 3 and 4 represent non-acceptable motion cue ratings.

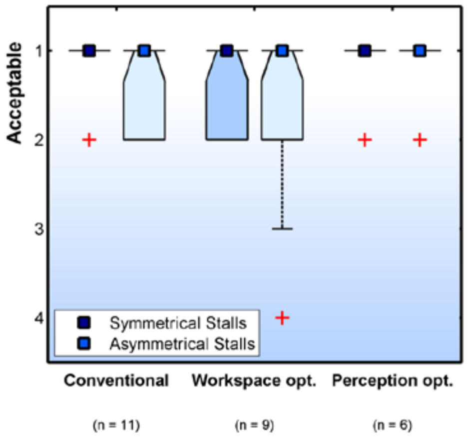

Figure 14: General rating for false cues, hexapod platforms

Figure 14 shows false cue ratings received on the hexapod platforms. Especially the "Perception Optimized" filter seems to offer significant improvements over conventional hexapod cueing. Key motion cue ratings on hexapods were generally acceptable with some spread into the non-acceptable range for "conventional" and "perception optimized" cueing.

On the g-capable platform Desdemona key motion cue ratings received for "buffet only" and "onset cueing" were acceptable with slight deficiencies while "G-cueing" received a median rating of 1 which is "equivalent to the real airplane" (Figure 15).

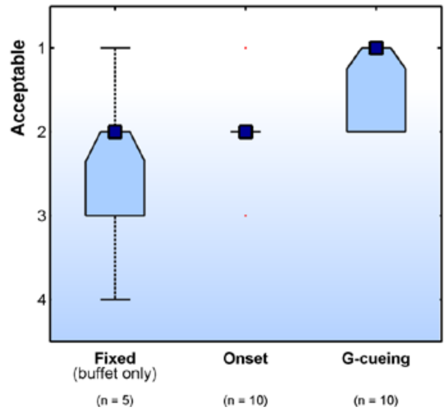

Figure 15: General motion cue ratings for the DESDEMONA platform

This however comes at a price, as can be seen in Figure 16. "G-cueing" received a large number of "non-acceptable" false cue ratings due to the false cues generated by centrifugation of the subject. It can be seen though that the median false cue rating improves from 3 ("non-acceptable") to 1 ("no perceivable false cues") for asymmetric stall scenarios. For such scenarios the highly dynamic cueing environment seems to mask some of the false cues caused by spin-up and spin-down of the centrifuge and Coriolis effects.

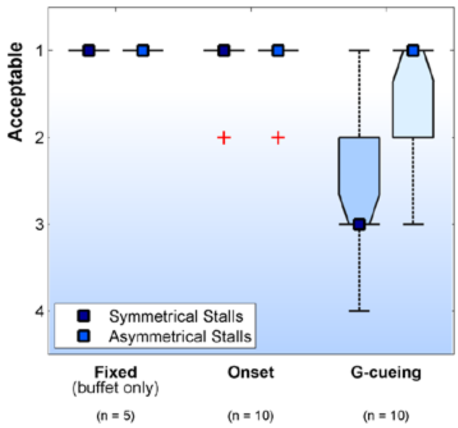

Figure 16: General false cue ratings obtained for the DESDEMONA platform

As a result "G-cueing" was selected as preferred cueing option for symmetric stall scenarios by approx. 50% of the pilots (5 pilots chose "onset cueing", 4 "G-cueing" as their preferred cueing options). For symmetric stalls 90% of the pilots chose "G-cueing" as their preferred option (8 out of 9 pilots). No pilot chose "buffet only" as can be seen in Figure 17.

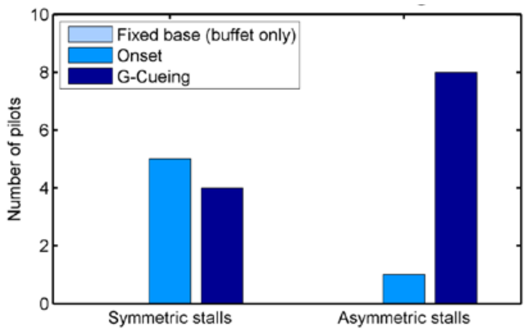

Figure 17: Preferred motion cueing solutions on DESDEMONA platform

On the hexapod platforms the “Workspace Optimized” and “Perception Optimized” SUPRA filters were clearly preferred over conventional cueing, as can be seen in Figure 18.

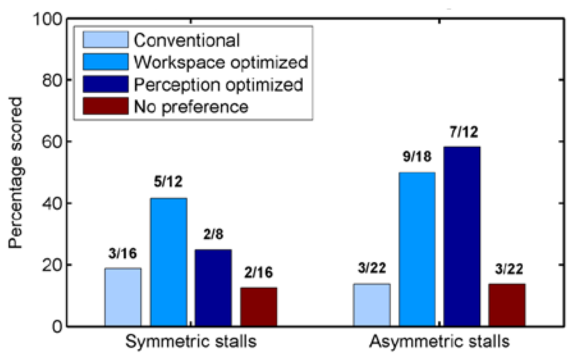

Figure 18: Preferred motion cueing ratings for hexapod platforms

6 Conclusions

The SUPRA Project did not aim at developing a training program to fight the risk of loss of control in flight. The project attempted to develop concepts to improve the fidelity and hence usability of ground-based simulation close to the edges of the normal flight envelope and beyond. Potential applications of the project findings might include flight crew training but also development and test of potential new flight deck indication concepts.

The SUPRA project has proven that the phenomenological modeling approach is a powerful tool to produce an all-envelope class-specific model, which can be reconfigured to reproduce certain type- or class-specific behaviors. Expert test pilots have rated model behavior for normal maneuvering as well as stall behavior fully representative of the airplane class. As the result of SUPRA a simulation model representative of a conventional jet transport with under wing mounted engines, a fuselage mounted horizontal stabilizer and an operating weight of approx. 100 tons is available.

Further it has been shown that motion cueing solutions currently employed on training simulators can be optimized for the reproduction of motion cues essential in upset regimes. Optimization leads to better acceptance by expert test pilots. A scenario dependant workspace optimization as well as a perception knowledge based optimization taking into account perceptual thresholds as well as the effects of vertical acceleration on the perception of other motion cues have proven to be superior to conventional hexapod cueing.

Reproduction of G-cues in centrifuge-based simulators has shown to be valuable and, if used with appropriate scenarios, greatly improves simulation fidelity. Applied properly G-cueing clearly is the preferred solution in upset regimes. Side studies performed as part of the piloted evaluation program have indicated that G-exposure of pilots inexperienced in upset regimes changes the control strategy of those pilots. In addition provision of G-cues seems to have a large impact on workload during loading maneuvers.

In order to apply SUPRA findings in the training realm the scope of the side study needs to be enlarged; a training program should be developed and effectiveness should be demonstrated. This would require formulation of appropriate performance metrics.

Another important field where SUPRA work should be continued is further development of CFD modeling techniques for aerodynamic model development beyond the normal envelope.

References

[1] Boeing Commercial Airplanes, Statistical Summary of Commercial Jet Airplane Accidents, Worldwide Operations 1959 – 2010.

[2] Burks B., Upset Recovery Training: A Call for a Higher Standard of Training, RAeS Flight Simulation Conference: Towards the Edge of the Envelope, Royal Aeronautical Society, London (UK), June 3-4, 2009.

[3] Flight Safety Foundation, "Industry Airplane Upset Recovery Training Aid, Rev. 2, "November 2008.

[4] Lambregts A., Nesemeier G., Newman R., and Wilborn J., Airplane Upsets: Old Problem, New Issues, AIAA Modeling and Simulation Technologies Conference, American Institute of Aeronautics and Astronautics, Honolulu (HI), August 18-21, 2008, AIAA-2008-6867.

[5] Goman M.G., Khrabrov A.N., State-Space Representation of Aerodynamic Characteristics of an Aircraft at High Angles of Attack. Journal of Aircraft 31, (5), 1994, pp.1109-1115

[6] Abramov, N.B., Goman, M.G., and Khrabrov, A.N. Aircraft Dynamics at High Incidence Flight with Account of Unsteady Aerodynamic Effects, AIAA Atmospheric Flight Mechanics Conference and Exhibit, American Institute of Aeronautics and Astronautics, Providence (RI), August 16-19, 2004, AIAA-2004-5274.

[7] Prananta B.B., Veul R.P.G., Houwink R., Hounjet M.H.L. , and van Muijden J., A generic flexible aircraft loads database system for fatigue analysis, International Forum on Aeroelasticity and Structural Dynamics, Stockholm, June 18-20, 2007.

[8] Soemarwoto B.I., Boelens O.J., Allan M. Arthur M.T., Butefisch K., Ceresola N., and Fritz W. Towards the simulation of unsteady manoeuvre dominated by vortical flow, 33rd Fluid Dynamics Conference, American Institute of Aeronautics and Astronautics, AIAA-2003-3528.

[9] Boelens O.J, Spekreijse S.P., Sytsma H.A., and de Cock K.M.J., Comparison of measured and simulated flow features for the full-scale F-16XL aircraft, 45th AIAA Aerospace Sciences Meeting and Exhibit, American Institute of Aeronautics and Astronautics, Reno (NV), January 8-11, 2007, AIAA-2007-489.

[10] Goman M., Abramov N., Khrabrov A., Soemarwoto B., Aerodynamic Model Development for Simulation of Upset Recovery of Transport Airplane, Applied Aerodynamics: Capabilities and Future Requirements, Royal Aeronautical Society, London (UK), July 27-28, 2010.

[11] Fucke L., Biryukov V., Grigoriev M., Groen E., Wentink M., Field J., and Soemarwoto B. Developing Scenarios for Research into Upset Recovery Simulation, AIAA Modeling and Simulation Technologies Conference, American Institute of Aeronautics and Astronautics AIAA, August 2-5, 2010, Toronto (CA), AIAA-2010-7794.

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