



## Executive summary

# SUPRA - Enhanced Upset Recovery Simulation

An overview of the SUPRA experiments



### Report no.

NLR-TP-2012-320

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### Report classification

UNCLASSIFIED

### Date

November 2012

### Knowledge area(s)

Training, Missiesimulatie en  
Operator Performance  
Cockpit  
Vliegveiligheid (safety & security)

### Descriptor(s)

Simulation  
Aerodynamics  
Upset Recovery  
Motion

### Problem area

Loss of control in flight (LOC-I) is the leading cause of fatal accidents in commercial aviation today. During a LOC-I event, the aircraft often enters an unusual attitude or upset condition which would otherwise not be encountered in normal operations. Existing simulation facilities are limited in their ability to reproduce the environment of a stall or upset.

The Simulation of Upset Recovery in Aviation (SUPRA) project, a European Framework Programme 7 project, researched extending the aerodynamic models for simulators and investigated the modification of hexapod and centrifuge-based simulators that are used for upset recovery training.

### Description of work

The experiments that took place in the final phase of the SUPRA project investigated the application of the modifications to the aerodynamic model and motion

cueing algorithms to support stall and upset training. The experiments were carried out using a combination of experimental test pilots, senior instructor pilots and line pilots.

### Results and conclusions

The results of the experiment included the subjective analysis of the pilots as well as a comparison of their performance under different experimental conditions to evaluate the SUPRA modifications.

The conclusions demonstrated that the modifications to the aerodynamic model were noticeable and had a positive effect on the perceived realism of the simulation. The g-cueing was rated as a valuable cue for some elements of the stall environment. It was also demonstrated that existing simulators form an important element of the training environment for upset prevention and recovery training.

### **Applicability**

The results and discussion presented in this paper apply to the realm of Upset Prevention and Recovery Training of airline pilots. They are applicable to the use of conventional flight simulators, as well as centrifuge g-trainers.

The SUPRA project is funded under the European Union Framework Programme Seven (FP7), Grant Agreement no. 233543.



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An overview of the SUPRA experiments

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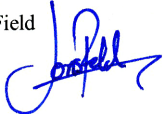


<sup>7</sup> GFRI

This report is based on a presentation held at the AIAA Modelling and Simulation Technologies Conference, Minneapolis, MN, August 13-16, 2012.

The contents of this report may be cited on condition that full credit is given to NLR and the author(s).

Customer	European Commission
Contract number	FP7-233543
Owner	European Commission
Division NLR	Air Transport
Distribution	Unlimited
Classification of title	Unclassified
	November 2012

Approved by:

Author J.N. Field 	Reviewer Z.C. Roza 	Managing department H. Bohmen 
Date: 29 October 2012	Date: 5-11-2012	Date: 10-11-2012

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## Abbreviations

AoA	Angle of Attack
CC	Clean configuration
CFD	Computational Fluid Dynamics
$C_L$	Lift coefficient
DESDEMONA	DESorientatie DEMONstrator Amst
DoF	Degree of Freedom
EC	European Commission
FFS	Full flight simulator
FL	Flight Level
GRACE	Generic Research Aircraft Cockpit Environment
ICATEE	International Committee for Aviation Training in Extended Envelopes
LOC-I	Loss of control –In-Flight
SUPRA	Simulation of Upset Recovery in Aviation
UPRT	Upset Prevention and Recovery Training
URTA	Upset Recovery Training Aid <sup>3</sup>
$\Phi$	Aircraft bank angle

# SUPRA – Enhanced Upset Recovery Simulation

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**The SUPRA research project – Simulation of Upset Recovery in Aviation – has been funded by the European Union 7th Framework Program to enhance the flight simulation envelope for upset recovery simulation. Within the project an extended aerodynamic model, capturing the key aerodynamics during and beyond stall for a large category transport aircraft and new motion cueing solutions for both hexapod and centrifuge-based platforms were developed. This paper describes the recent piloted evaluation experiments. In the first experiment a group of ten experimental test pilots, with actual experience in stall conditions, subjectively judged the validity of the aerodynamic model and the motion cueing solutions in the simulators in different upset conditions. Pilots rated the stall behavior of the SUPRA model as representative and useful for training. They preferred improved over conventional hexapod motion cueing. Centrifuge-based cueing was considered highly valuable to recognize the positive G-loads during the late recovery phase. The second experiment showed that line pilots without previous exposure**

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to upset conditions perform more conservative recoveries under actual G-loads in the centrifuge compared to hexapod. After some practice the number of stick shaker events and excursions into critical angle-of-attack was reduced. We conclude that the SUPRA aerodynamic model successfully demonstrates upset conditions, including stall, and that conventional hexapod motion cueing can be improved for the purpose of upset simulation. If available, centrifuge-based simulation of the G-load is a recommended addition to the upset recovery training.

## Nomenclature

<i>AoA</i>	=	Angle of Attack
<i>CC</i>	=	Clean configuration
<i>CFD</i>	=	Computational Fluid Dynamics
<i>C<sub>L</sub></i>	=	Lift coefficient
<i>DESDEMONA</i>	=	DESorientatie DEMONstrator Amst
<i>DoF</i>	=	Degree of Freedom
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<i>LOC-I</i>	=	Loss of control –In-Flight
<i>SUPRA</i>	=	Simulation of Upset Recovery in Aviation
<i>UPRT</i>	=	Upset Prevention and Recovery Training
<i>URTA</i>	=	Upset Recovery Training Aid <sup>3</sup>
$\phi$	=	Aircraft bank angle

## I. Introduction

For several years now, Loss of control - in flight (LOC-I) continues to be the leading cause of fatal accidents in commercial aviation<sup>1</sup>. 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 respond appropriately to 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<sup>2</sup>. 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<sup>3</sup>. 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. 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<sup>4</sup>. Furthermore, standard hexapod-based motion systems are unable to reproduce the high accelerations, angular rates, and sustained G-forces that can occur during upsets and recovery from upsets. In the European Seventh Framework Program project SUPRA – Simulation of Upset Recovery in Aviation – a consortium of ten European organizations<sup>13</sup> have worked together to develop enhanced aerodynamic models and motion cueing solutions to investigate the feasibility of conducting advanced upset recovery simulation in ground-based flight simulators. The research not only involved conventional hexapod-type flight simulators but included experimental centrifuge-based simulators. Building on the research carried out previously<sup>5,6</sup>, motion cueing developments were supported by motion perception experiments<sup>7,8</sup>.

<sup>13</sup> The SUPRA consortium consists of TNO, NLR, AMST Systemtechnik, Desdemona B.V., Boeing Research & Technology Europe, De Montfort University, Max-Planck Institute, TsAGI, Gromov Flight Research Institute and Dinamika

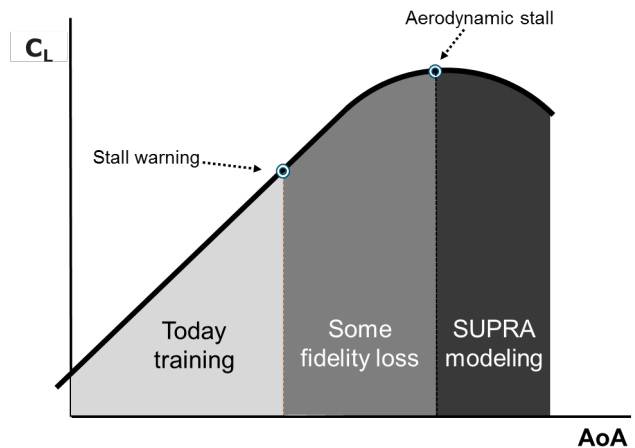
The project officially comes to a close on August 31, 2012. This paper provides an overview of the results of the final piloted evaluation experiments which were performed in the first part of 2012. Other more detailed papers will be published elsewhere. The experiments involved the evaluation of the extended aerodynamic model and modified motion cueing on the SUPRA simulators. The evaluation investigated the potential value of minor modifications to current motion cueing for upset recovery simulation, and the possibilities of using all-attitude cueing and G-cueing for upset recovery maneuvers. The evaluation was divided into two parts: in the first part expert test pilots with experience of stalls and unusual attitudes in transport category aircraft provided qualitative comments of the perceived aircraft dynamic response and the fidelity of the motion cues (for strength and false cues). In the second part, the recovery performance of commercial line pilots without previous exposure to real-life upset conditions was measured in a more objective way.

## II. SUPRA Aerodynamic modeling

The aerodynamic model in SUPRA has been developed to extend the aerodynamic envelope into the stall, and beyond the stall and unusual attitude region to provide aerodynamic cues that are representative of transport category aircraft. The model was designed to enable the key training cues for upset prevention and recovery training (UPRT) in full-flight simulators.

The mathematical aerodynamic and flight dynamic models, together designated the “aircraft model”, are 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 fully integrated into simulator data packages. It can therefore be argued that simulated aircraft behavior is currently only valid and reliable within the boundaries of the normal envelope. Analysis of LOC-I accident data shows that transport aircraft can exceed the boundaries of the normal envelope in the course of an upset event and the subsequent recovery.

Hence, simulation of advanced upset conditions requires extension of the aircraft model beyond the normal flight envelope for training purposes<sup>9</sup>. This is illustrated in Figure 1. Current simulator data packages realistically represent the normal flight at low and safe values of AoA. With some fidelity loss (e.g. in lateral axes) they may go up to the critical AoA, aerodynamic stall, for approach-to-stall training exercises. However, beyond this critical AoA the data become unreliable. The SUPRA aerodynamic modeling was to fill in this area to simulate aircraft departure, post-stall gyration and incipient spin modes in a representative way<sup>10</sup>. The aerodynamic model technologies will be presented in a separate paper at this conference<sup>11</sup>.



**Figure 1. SUPRA model for high AoA.** Whereas current simulator models may go up to maximum  $C_L$ , the SUPRA modeling was targeted to represent aircraft behavior beyond critical AoA.

## III. SUPRA motion cueing

The SUPRA motion cueing research was performed on the hexapod platforms at NLR and TsAGI, on the one hand, and on the DESDEMONA centrifuge-based research facility. The two hexapod motion platforms can be considered representative for a current Full Flight Simulator (FFS). The hexapod platforms are the standard solution for motion cueing within the flight simulator industry. However, the motion space of hexapod platform is determined by the actuator length, and due to the parallel kinematic design movement in one axis reduces motion space in another axis. Hexapod systems also lack the capability of generating low-frequency g loads. Therefore, the SUPRA project intended to investigate the possibilities of alternative (non-synergistic) motion platforms such as the DESDEMONA simulator.



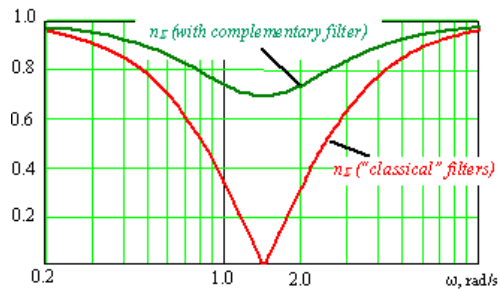
**A. Hexapod-based motion cueing**

The aircraft upset/stall is a rare, but very dangerous event. The majority of pilots have never experienced such an event and have no idea about the nature of the motion cues arising in upset and upset recovering. Inadequate motion cueing or motion distortions introduced by drive algorithms can distort pilot’s opinion and affect pilot training. Therefore, the main directions of hexapod driving algorithms optimization should be focused on two aspects: accurate and more effective reproduction of the motion cues; and minimizing false cues. At present, most hexapod-type simulators use “classical” motion drive algorithms based on washout filters. The algorithms allow for adequate reproduction of the motion cues that arise during standard flight modes of transport aircraft. One of the SUPRA research objectives was therefore to study how these “classical” motion drive algorithms could be optimized in combination with the existing hardware. This would therefore mean that any improvement would be directly available to today’s full flight simulators, requiring minimal changes to the existing simulator hard- and software. The SUPRA partners– NLR and TsAGI – collectively investigated the possible motion cueing improvements on hexapod platforms for Upset Prevention and Recovery Training (UPRT).

One of the start-points of this research was to explore the potential for maximizing the use of the motion space of hexapod platform to improve the motion cues for UPRT. In many cases the usage of the motion space on conventional hexapod-based simulators is conservative. This doesn’t present a problem for the acceleration onset cueing that is used within the normal flight envelope, however does raise questions for the dynamic maneuvers of an upset or stall recovery. At the same time there are questions within the industry of the validity of the motion cueing on a hexapod platform given the limitations – this has led to calls that motion should not be used for UPRT. To help answer this question, SUPRA investigated three hexapod-based motion-cueing solutions: no motion, conventional motion drive algorithms and motion drive algorithms optimized for UPRT (See Section IV).

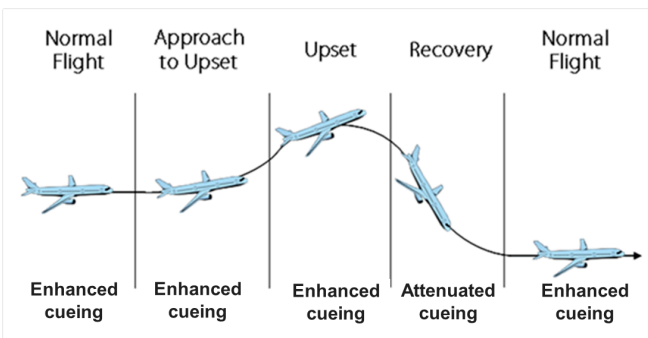
Two complementary philosophies were investigated in optimizing the motion drive algorithms for UPRT: tuning the motion drive algorithms to better match the acceleration onsets in the aircraft model; and tuning to the known perception thresholds of the pilots. The first approach has been carried out on the NLR Generic Research Aircraft Cockpit Environment (GRACE) simulator<sup>14</sup>. By better matching the initial aircraft motion cues – through motion workspace optimization – the objective was to give pilots a better experience. Furthermore, the effects of the limited motion space of conventional hexapod-based simulators were investigated to determine whether it caused problems or distractions in the extreme maneuvers expected during upsets and stalls. Given the increased dynamics in the lateral axes from the modified aerodynamic model, the motion cueing adjustments included improvements of the lateral cues.

For the second approach the TsAGI PSPK-102 simulator was used to establish motion perception criteria to adjust the motion drive algorithms such that the motion cues perceived by the pilot in the simulator better match to those in the real aircraft<sup>13</sup>. For example in this study it was found that due to increased G-loads of a recovery maneuver the perception of motion is reduced. This G-load effect is taken into account by the optimized motion drive algorithms in the recovery phase by attenuating the motion cues affected by this G-load. This research was combined with the improved analysis of the maneuvers as they are perceived by the pilots. An illustration of this is the modifications to improve the lateral accelerations in the filter. The “classical” low pass filter was replaced with a filter around middle frequencies that is more suited to the frequencies of the lateral accelerations that are perceived in upset recovery maneuvers.



**Figure 2. Minimization of phase distortion in lateral acceleration reproduction**

Figure 2 illustrates that the introduction of the complementary filter noticeably decreases the “drop” in lateral acceleration frequency response, and thus decreases the phase distortion.



**Figure 3. Motion filter phases for Hexapod simulators.**

The results of both approaches were combined into one single optimized motion drive algorithm for UPRT. The underlying principle of this algorithm is the runtime adaptation of the “classical” motion drive algorithm coefficients using a coefficient scheduling strategy based on the UPRT phase (Figure 3). Moreover, buffet motion cueing is also incorporated in this motion

drive algorithm. The SUPRA hexapod motion cueing improvements will be presented in more detail in two separate papers at this conference<sup>13,14</sup>.



Figure 4. DESDEMONA simulator at TNO.

**B. DESDEMONA motion cueing**

The DESDEMONA motion system integrates a fully gimballed cabin capable of rotating infinitely about all axes with a vertical heave axis, a horizontal linear track and a central vertical yaw axis in the linear arm itself, allowing the generation sustained centripetal forces (Figure 4). The DESDEMONA can simulate sustained G-loads of up to 3G. A unique aspect of DESDEMONA’s motion capabilities is that it can combine onset cueing along the x, y and z-axis (similar to 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.

Three different motion drive algorithms were compared on the DESDEMONA simulator: Fixed base, Onset cueing, and Centrifuge cueing. In all conditions (also Fixed base) buffet motion was present, generated through the heave system. The Onset cueing mode was intended to be comparable to a conventional hexapod simulator, though it has enhanced cueing for loading and unloading. In the Centrifuge mode the features of the hexapod cueing are combined with the centrifuge cueing. The simulation starts in the hexapod mode and fades into the centrifugation mode during stall recovery. That is, the centrifuge rotation is slowly initiated at the onset of buffet, so that the required G-load can be generated when the aircraft is loaded. The centrifugation in SUPRA differed from conventional (high g) centrifuges, where the pilot is facing the direction of motion in a free-swinging gondola that aligns with the resultant g load, comprised of centripetal acceleration and gravity. The problem with this approach is that upon deceleration the pilot experiences strong tumbling sensations in his pitch plane that are highly uncomfortable. For SUPRA the DESDEMONA cabin was oriented such that the pilot was facing inward to the centrifuge axis (Figure 5), and during centrifugation it was kept in a fixed orientation. In this way disorienting tumbling sensations were prevented. Now the deceleration of the centrifuge only resulted in some yaw and side force cues that were expected to be more congruent to the actual aircraft behavior during the maneuver. In addition, the pitched forward orientation of the cabin resulted in a sense of unloading (“hanging in the seat belts”) at initial recovery from a stall. When the pilot started pulling positive g load at the last phase of recovery, the centrifuge spun up to generate a centripetal acceleration causing the resultant load vector to tilt backwards and pushing the pilot into the seat again.

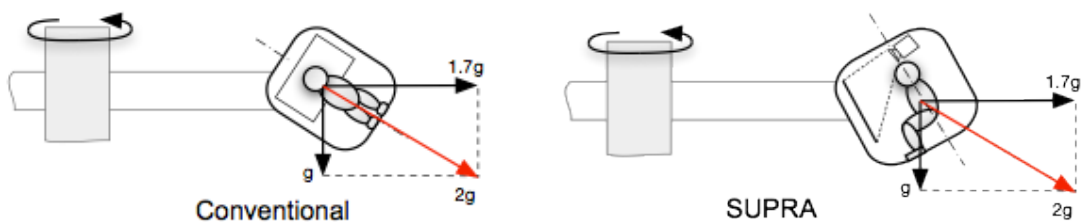


Figure 5. Cabin orientation in conventional (left) and SUPRA g cueing (right).

**IV. Evaluation experiments**

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. In the first part of the evaluation ten expert pilots participated subjectively qualified the SUPRA simulators on both aspects. In the second part of the evaluation the recovery performance of non-expert pilots was investigated in a more objective way.

**A. Phase I: experimental test pilots**

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 approximately 100 tons. Armed with this basic information a team of ten test pilots performed qualification simulator tests for normal maneuvering as well as approach to stall and full stall maneuvers. After the aerodynamic model evaluation, pilots were asked to evaluate the different motion cueing solutions in terms of required motion cues, on the one hand, and false cues, on the other hand.

*1. Aerodynamic model evaluation*

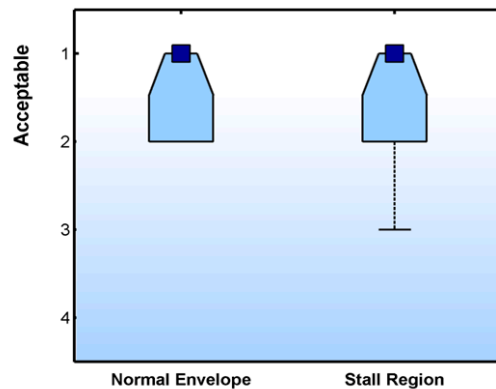
Before the evaluation maneuvers, pilots were familiarized with the cockpit and the SUPRA aerodynamic model with the simulator operating in the fixed-base mode. Subsequently, the key aerodynamic behavior during normal flight was evaluated, including three unusual attitudes including three unusual attitudes recoveries (nose-high, wings level recovery; nose-high, bank recovery; nose-low high-bank recovery. For the evaluation of stall behavior the simulator was operating in conventional cueing (NLR and TsAGI hexapod platforms) or onset cueing (DESDEMONA). The evaluation involved both approach to stall and developed stall scenarios. Stall scenarios either were: symmetric without roll instability; symmetric with mild roll instability; asymmetric with mild wing drop; or asymmetric with a large and aggressive wing drop. All evaluation scenarios were maneuver-based and were performed at FL 130. Pilots were instructed to enter the stall themselves in a predefined way. This included level flight or 30° bank turns with a 3kt/s deceleration or a 30° pitch up attitude with throttle idle. Pilots were instructed to initiate recovery when the angle of attack reached a magnitude of 15° (this was not shown to the pilot, but was available to the simulator operator).

**Table 1. Rating scale for aerodynamic behavior.**

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.	

Pilots rated the airplane behavior acceptable/non-acceptable for a set of pre-defined characteristics. In addition to these detailed characteristics, pilots also gave two ratings for the overall aerodynamic performance of the model inside and outside the normal flight envelope. This rating scale is depicted in Table 1. Ratings 1 or 2 indicated that the aircraft behavior was considered acceptable for training purposes. Ratings 3 or 4 meant that the simulator behavior was not acceptable for training purposes.

In general, the aerodynamic model was rated as representative, especially for stall behavior (Figure 6). For stall behavior, 7 out of the 10 pilots rated the acceptability with a score of 1, and the remaining 3 gave a score of 2 (representative with minimal or minor pilot adaptation, respectively). For the normal flight behavior this was reversed (7 pilots scored 2, 3 scored 1). This means that the test pilots found the SUPRA aerodynamic model acceptable for UPRT.



**Figure 6. General ratings for stall behavior.**

*2. Motion cueing assessment*

The motion cueing assessment was carried out in the same way on all three simulators. Many of the pilots that were involved in both the assessment of the GRACE and DESDEMONA simulators. For the motion evaluation the experimental test pilots performed the following four stall scenarios:

- 1) Symmetrical stall, no roll instability. Procedure: Level flight, decelerate at 3 kts/s up to stall, recover at full buffet (AoA > 15°, called out by operator);
- 2) Symmetrical stall, some roll instability. Procedure: Level flight, decelerate at 3 kts/s up to stall, recover at full buffet;
- 3) Asymmetrical stall, mild roll-off to the right. Procedure: Level turn left 30, decelerate at 3 kts/s, recover at full buffet;
- 4) Asymmetrical stall, intense roll-off to the right. Procedure: pitch 30, throttle idle, recover at full buffet.



In the DESDEMONA trials, each stall case was flown in the three different motion configurations in a fixed order (Fixed/buffet only – Onset Cueing – Centrifuge). In the NLR GRACE simulator trials also three different configurations were flown (Fixed/buffet only – Classic – Workspace/Perception Optimized). After each condition the pilot assessed:

- 1) The magnitude of the key motion cues
- 2) The presence of any inaccuracies or false motion cues
- 3) The overall acceptability of key and false motion cues

The pilots were asked to assess the motion cues with relation to the aircraft motion that was indicated in the simulator (on the PFD and from the outside view). They rated the strength of the motion cues in the key motion axes: Roll, Pitch, Sideforce and Gz. The pilots were also asked to report any inaccuracies or false cues, and identify whether these would represent a disturbance for a training environment.

The first two ratings are depicted in Figure 7. Key motion cues were defined as motion that should have been present during the simulation and could include pitch, roll, side force and/or vertical acceleration. Inaccuracies or false cues were defined as motion cues that were felt during the simulation, but that would not have been present in actual flight. For example, the feeling of the cabin moving back to its neutral position, or reaching the actuator limit. It also included any inaccuracies in timing or dynamic behavior of the felt motion (i.e., g cue coming to late, or building up to slow). The reference for the magnitude and inaccuracy ratings was the aircraft motion as indicated by the flight instruments. So for example, if the instruments indicated the presence of side force but the pilot did not perceive this motion cue, the magnitude of this cue was too weak (score -2 or -1). Pilots were asked to discriminate between the unloading phase, defined as the approach to stall and the start of recovery up to the G-break (unloading of the aircraft), and the loading phase, defined as the remainder of the recovery. Similar to the general rating on aerodynamic modeling, the overall rating on the acceptability of the motion comprised of a scale from 1 through 4, where 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. The same questionnaire and assessment was used on all simulators.

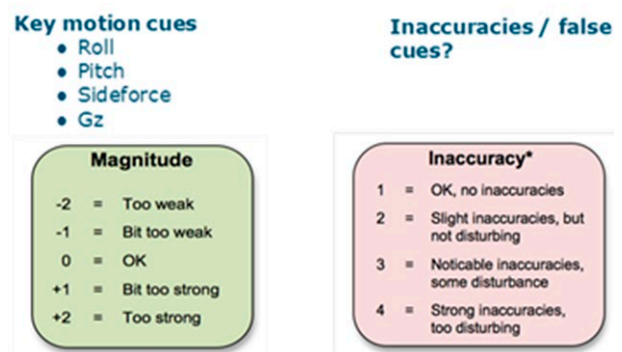


Figure 7. Motion ratings.

### 3. Hexapod results

The subjective assessment of the experimental test pilots indicated that the modifications to the motion cueing algorithms were an improvement to current motion cueing on hexapod simulators. The findings from the hexapod experiments are summarized in this paper and discussed in detail in separate papers at this conference<sup>13, 14</sup>. The Phase I experiment at NLR concentrated on the evaluation of a workspace optimized algorithm and the TsAGI experiment concentrated on a perception optimized algorithm.

The evaluation of the experimental test pilots indicated that the modifications to the motion drive algorithms had made a small improvement in the perceived motion strength – for both the workspace optimized and perception optimized algorithms. In the assessment of the overall motion cueing there was a large spread of ratings for the conventional cueing filter with motion cues rated as absent or insufficiently recognizable. For the optimized algorithms these ratings improved. The assessment of false cues in the perception optimized filter in particular demonstrated that there were practically no false cues perceived by the pilots.

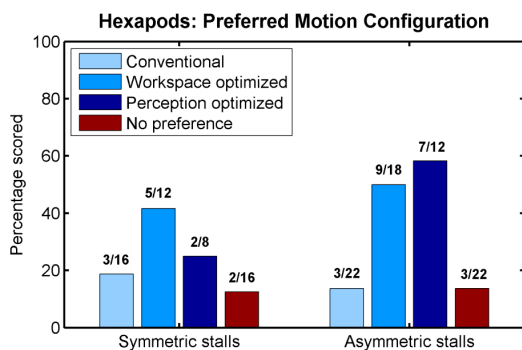


Figure 8. Preferred Motion Configurations - Hexapod

On both the NLR and TsAGI hexapod platforms motion cue strength was consistently rated as too weak for classic motion, but ratings improved with the SUPRA workspace/perception optimized cueing. When indicating the preferred motion configuration the workspace optimized filter was selected for the less dynamic symmetric stall scenarios, while the perception optimized filter was preferred for dynamic scenarios (Figure 9). On both of these hexapod platforms the expert pilot consistently preferred the SUPRA motion cueing over the conventional motion cueing algorithms<sup>13, 14</sup>.



4. *DESDEMONA results*

Regarding the stall scenarios, pilots commented that especially the large roll-off maneuvers in the DESDEMONA simulator felt excellent and were considered a big advantage over current hexapod simulators. Also they rated the buffet cueing motion as very realistic in both the DESDEMONA and GRACE hexapod simulator. Motion cueing in “Fixed/buffet only” was consistently rated as too weak on all simulators. The Onset Cueing on the DESDEMONA yielded a slight improvement in strength ratings but a large spread can be observed, especially during the unloading phase of the upset; G-cueing seemed to reproduce key motion cues at appropriate magnitude (Figure 9).

For DESDEMONA the key motion cue ratings for “Buffet Only” and “Onset Cueing” were acceptable with considerable or slight deficiencies respectively, while “G-cueing” received a median rating of 1, which is “equivalent to the real airplane”. This however comes at a price, as can be seen in Figure 10: “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. It appeared that in 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. In addition, these cues were mainly in the pilots lateral plane and were more congruent to the lateral aircraft motion during the stall. 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 asymmetric stalls 90% of the pilots chose “G-cueing” as their preferred option (8 out of 9 pilots). No pilot chose “Buffet Only”.

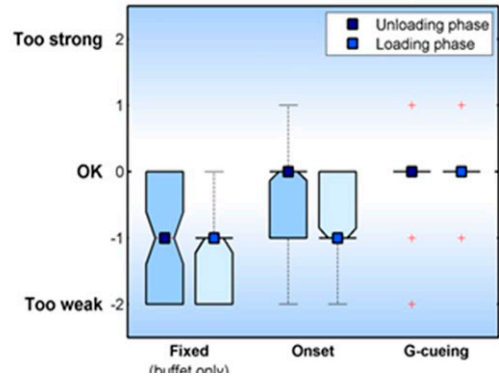


Figure 9. Rated motion magnitude in DESDEMONA

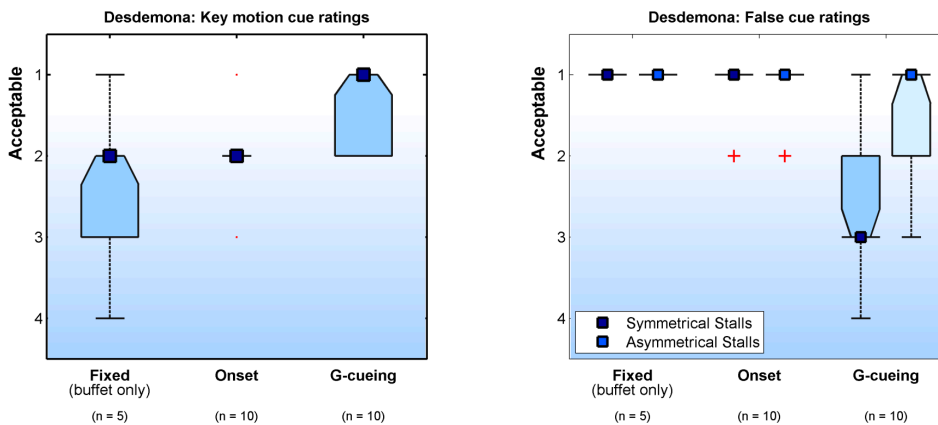


Figure 10. Overall motion ratings obtained in DESDEMONA for key motion cues (left) and false cues (right).

**B. Phase II: line pilots**

The second phase of the SUPRA evaluation used line pilots that had not had any experience of stalls or upsets in the aircraft. The intention of these experiments was to investigate the effect of the different forms of motion cueing on the performance of pilots in recovering the aircraft when exposed to an aircraft upset or stall. Three sets of experiments were conducted on the simulators at Desdemona, TsAGI and NLR.

1. *TsAGI Hexapod motion cueing experiments*

The goal of the experiments at TsAGI using the PSPK-102 simulator was to substantiate the advantages of the modified SUPRA drive algorithms over “classical” filters. The evaluation therefore addressed the following research questions. First, to demonstrate that the modified algorithm is objectively better than “classical” motion filters. Second, to demonstrate that the modified algorithm has an impact on pilot control activity and flight controlled parameters. Thirdly, an additional experiment was carried out to investigate the effect of G-load and angle-of-attack visualization on the pilot control behavior during upset recovery maneuvers. The detailed results and discussion of this research are presented in a separate paper at this conference<sup>13</sup>.

The first research question was addressed by the comparison of the “classical” and SUPRA filters’ outputs. An analysis of the “classical” filters showed that distortions were present in the reproduction of the key motion cues: (1) phase distortions (e.g. time delays) in the reproduction of longitudinal and lateral accelerations; where the lateral accelerations are more problematic; (2) angular motion is accompanied by large false cues, which is perceived by the pilot as motion in the opposite direction – in some cases this exceeds the onset cues; the most problematic is the roll axis due to large angular rates and, as a consequence, large false cues. In addition to this type of false cues, there are also false specific forces due to cockpit tilting while reproducing angular motion.

These distortions could be compensated by adjusting the filter settings according to the motion fidelity criteria established in the project. The introduction of a complementary low-pass filter into the lateral acceleration reproduction path also contributed to the compensation in the new filters. It has been observed that the development and optimization of any motion drive algorithms must be based on the acceleration perception and the role of motion cues in the pilot task. The adjustments in the SUPRA algorithms for this experiment investigate the effect of G-load on the motion perception for other degrees of freedom. This objective analysis of the cues from the SUPRA motion drive algorithms compared to the “classic” filters indicated that there was a better reproduction of the lateral cues, and an increase in the motion envelope.

The analysis for the second research question consisted of the comparison of the frequency spectra and standard deviations of the pilot control actions and flight controlled parameters for two cases: Motion-off and SUPRA-motion. The data collected shows that, despite the lack of large normal G-loads on hexapods, the cockpit motion affects the pilot’s control activities and flight controlled parameters: the high-frequency components in the frequency spectra decrease, standard deviations decrease. There is an effect on performance – both objectively and subjectively. In addition to the objective measurements – the performance measures and analysis of motion irregularities – the experiment included subjective assessment using pilots’ ratings, which indicated that the SUPRA motion cueing is more clear and less inaccurate.

This experiment demonstrated that the effect of the SUPRA optimized motion filters was to reduce the magnitude of high-frequency components in pilot control activity and reduce the variance and standard deviation of control inputs. This suggests that the pilot’s ability to control the recovery maneuver is improved by the motion filtering. In addition, the number of secondary stalls decreased with the motion. These experiments also demonstrated that pitch-tilt can be used to improve the G-load and pitch simulation in conventional simulators.

The third research question was included to evaluate the effect of G-load and AoA instruments in the cockpit. AoA indicators have been standard in many Russian aircraft. The (high) angles of attack are the reason for aircraft upset/stalls. That is why the direct information about approaching critical AoA may be useful for the pilot to undertake the necessary actions. At present, there are two methods to provide direct indication to the pilot of critical AoA: stick shaker and AoA indicator. According to pilots’ comments, a stick shaker provides a pilot with the tactile information, which is direct and does not depend on pilot’s attention or workload. At the same time, AoA-indicator shows angle-of-attack dynamics, and the information on current AoA helps to adequately select the upset recovery strategy: at small AoAs the bank angles are controlled with a wheel, at high AoAs the ailerons are not effective and pedals must be applied.

To objectively assess AoA instrument advantages, number of secondary stalls was selected as an objective metric. It was shown that for all the pilots who participated in experiments, the number of secondary stalls reduced for AoA indications: in some cases the secondary stalls did not appear at all, in the other cases their number was halved. This suggests that the direct information provided by the AoA indicator is a useful method to prevent the approach to critical AoA and assist in recovery; it may therefore be a reasonable alternative to stick shaker for the aircraft not equipped with the latter.

According to pilots’ comments, G-meter helps to control altitude loss and to optimize the trajectory of recovery and is reliable display when flying with a high speed. The objective measurements recorded during experiments (the maximum G-load and the loss of altitude) were not as consistent as the subjective pilot’s comments. For three of the five pilots, the indication of Gs resulted in less altitude loss and less Gmax; for the other two the altitude loss increased. Thus, the experiments conducted and the statistics collected did not allow us to make any final conclusion on the effectiveness of G-meter. Further experiments should be conducted.

The experiments on the PSPK-102 hexapod conclude that the improved SUPRA motion drive algorithms demonstrated an objective increase in the motion envelope compared to the “classical” filter, including better reproduction of the lateral cues. The pilot control activity was improved by the modified motion algorithms by reducing the variance and high frequency elements of control inputs. The evaluation of the AoA-meter and the G-meter indicated a potential improvement in the recovery trajectory. This demonstrates that the pilot training for upset recovery maneuvers can be conducted on moving-base hexapods, and that modifications can be made to improve the motion cueing in these maneuvers.



## 2. GRACE Hexapod motion cueing experiments

The investigation on the GRACE simulator focused on two aspects of the UPRT motion cueing: the stall buffet cueing, and the “maneuver” cueing. The experiments evaluated four questions for the SUPRA motion research – the application of (hexapod) motion to the upset and stall maneuvers; the ability to make an objective difference to the motion cueing; the effect of the modified motion cueing on the performance of the pilots; and the effect of modifications to the simulation of the stall buffet cueing on stall recognition and recovery. While the subjective opinions of the pilots were included, the emphasis of the Phase II experiment was the objective analysis. What follows next is a summary of the results. More details and discussion of this research are presented in a separate paper at this conference<sup>14</sup>.

The GRACE experiments were carried out with 20 line pilots. All of the pilots had some experience in URTA training from their airlines on their own simulator facilities. The experimental set up was divided into three parts:

- Familiarization with the simulator and aircraft model
- Stall recognition experiment (evaluating the buffet cueing)
- Upset and Stall recovery experiment (evaluating the “maneuver” cueing)

In both of the experiments the pilots flew all of the experimental conditions in a balanced experimental set up to control the learning effect of flying multiple maneuvers across the different conditions. The buffet experiment evaluated the difference between Classic Buffet (set up according to existing simulation guidelines) and SUPRA Buffet (improved modeling of stall buffet following new ICATEE guidelines). The pilots also flew the maneuvers in a No Buffet condition as a control. Two different stall characteristics were used as the basis of the maneuvers, and the pilots were requested to recover at first indication of stall. The stall warning system (stick-shaker) was disabled in this experiment. The upset and stall recovery experiment evaluated the difference between three motion conditions: Fixed Base, Classic Filter, SUPRA Filter. The SUPRA filter represented the improved hexapod cueing filter combining the research carried out NLR and TsAGI (Section III). The experiment consisted of four maneuvers representing one upset condition, and three different stall maneuvers to evaluate the effect of the motion filtering across a spectrum of upset and stall maneuvers that could be included in UPRT. In a similar way to the maneuvers flown in Phase I and in the other SUPRA experiments, the pilots flew the aircraft into the upset/stall, and recovered the aircraft when commanded to by the simulator operator.

The first experiment of the GRACE evaluation was to investigate the modifications made to the stall buffet simulation. Within the work of the Royal Aeronautical Society’s International Committee for Aviation Training in Extended Envelopes (ICATEE) there has been an investigation into the simulation of stall buffet. This identified the need for improvement to the current threshold and characteristic of the stall buffet cueing in FFS. The SUPRA Buffet condition that was evaluated in the GRACE experiment was designed to follow the guidelines that are in development within ICATEE. The ICATEE research is reported in a separate paper. The experiments on GRACE demonstrated that the modifications to the buffet cueing had a positive effect on the stall recognition and recovery of the pilots. The SUPRA buffet cueing resulted in a faster recognition of the stall, and a faster recovery. It is therefore suggested that this could form a valuable improvement to the facilities for UPRT.

The GRACE upset and stall recovery experiment’s first element was to investigate whether motion had a detrimental effect on the performance of the pilots during UPRT – to address the question of whether motion cueing should be applied on a hexapod simulator. The assessment of the pilot’s performance and the ratings of the pilots suggest that there was no immediate negative effect of applying motion during the maneuvers. The limitations of the hexapod motion platform did not introduce false cues that were noticeable or affected the pilot’s recovery handling.

The second element was optimally tuning the GRACE’s “classical” motion algorithm to use the abilities of the motion platform envelope to a fuller extent. With this approach it was possible to better match the onset accelerations of the aircraft model. This was particularly true in the lateral axes. The longitudinal axes, and in particular the normal acceleration – or G-load – effects were harder to reproduce. While early experiments on the platform during the project showed promise, it is suggested that more research into this is required. The tuning of the classical motion filter therefore can have an objective effect on the reproduction of aircraft accelerations and onset cues for upset recovery maneuvers on a hexapod simulator.

The third element was the analysis of the pilot’s performance measures in the experiment to compare the effect of the three motion conditions – fixed base, classic filter, and SUPRA filter. The performance measures that were used were chosen to identify the speed of the recovery maneuver, the amount of pilot control inputs, and the aircraft dynamics during the recovery maneuver. These measures assessed the time to recovery, altitude

loss, G-loading, pilot control inputs, Angle of Attack and number of secondary stalls. The objective results of the experiment show that there was no significant objective difference in the performance measures between the motion conditions; the motion had neither a negative or positive objective effect. The subjective input of the pilots however indicated that the pilot's perception of the motion was preferred, perceived as more realistic, for the improvements in the SUPRA motion filter.

The GRACE experiments demonstrate that it is possible to improve the motion cueing on existing hexapods for upset and stall recovery maneuvers, and that the hexapod motion did not negatively affect performance. These modifications appear to have an effect on the pilot's perception of the maneuver, though this is not reflected in the objective performance of the recovery maneuver. It is recommended that this be further investigated for a training facility as the pilot's perception can be an important contributing factor in training, something that was outside the scope of this experiment. The evaluation of modifications to the simulation of aerodynamic stall buffet motion effects showed that the modifications have an effect on the stall recognition time. This suggests that the ongoing investigation into modified stall buffet requirements for Full-Flight Simulators is worthwhile and should be considered in future simulator model developments.

### 3. *DESDEMONA motion cueing experiment*

The goal of the Phase II experiment on DESDEMONA, was to investigate the effect of motion cueing (onset-cueing compared to g-cueing) on pilot performance in recovery from a nose-down attitude caused by an asymmetric stall. For the Phase II evaluation in DESDEMONA the following research questions were addressed. First, how do line-pilots initially recover from an asymmetrical stall, by comparing initial behavior with behavior after explaining recovery procedures? Second, what effect has motion cueing (onset compared to g-cueing) on line-pilot performance in recoveries from an asymmetrical stall? Third, what effect has a g-awareness session on line-pilot performance in recoveries from an asymmetrical stall by comparing a pre-test and post-test. Fourth, can tilt coordination be used to induce the perception of unloading and loading during recovery from an asymmetrical stall? And finally, is the perception of control loading influenced by the presence of g-cueing?

The experiment started with a fixed base familiarization trial to familiarize pilots with the aircraft model and simulator environment. After the familiarization the Initial Exposure test took place, in which pilots were asked to recover twice from an asymmetrical stall in onset cueing "at first sight", i.e. without explaining the appropriate upset recovery procedure. After the Initial Exposure test, the correct recovery procedures were explained, and then recovery performance was tested in four more experimental trials: the so-called 1) Pre-test, 2) G-awareness session, 3) Posttest, and finally the 4) Tilt coordination. These first three sessions served to investigate a possible effect of a G-awareness session, in which pilots received feedback on the g load they experienced in the centrifuge condition, by comparing recovery performance in before (Pretest) and after (posttest) the G-awareness session. The latter condition (Tilt coordination) investigated the usefulness of pitch tilt to create the illusion of loading/unloading the aircraft.

In the Pre-test the pilots were asked to recover twice from an asymmetrical stall based on the explained recovery procedures. This test was done in onset cueing as well as g-cueing. The two motion settings were balanced over subjects to compensate for order effects. After the session the pilots rated perceived inaccuracies/false-cues. Also they were asked to give a self-rating on meeting the procedures-, speed limits- and g-limit objectives. Finally they were asked to rate the heaviness of the control loading during the recovery. After the Pre-test the pilots were asked to fill out a workload questionnaire on mental-, physical-, and temporal demand, as well as performance-, effort-, and frustration workload. These questions were asked for the onset cueing condition, as well as the g-cueing condition.

During the G-awareness session, the pilots were asked to fly three parabolas in g-cueing with a g-meter to create g-awareness (seat-of-the-pants). After these three parabolas the g-meter was turned off and the pilot was asked to recover a parabola at 2.0g to test if g-awareness was improved. If the recovery was performed within +/- 0.1g the test was completed, otherwise another parabola was executed.

In the Post-test the pilots were asked to recover twice from an asymmetrical stall. The setup was similar to the pre-test, as well as the procedures, ratings and questionnaire.





Finally, the pilots performed an upset recovery from an asymmetrical stall in normal onset cueing and one recovery in onset cueing with tilt coordination to simulate g-load (Onset+). They were asked to rate the motion

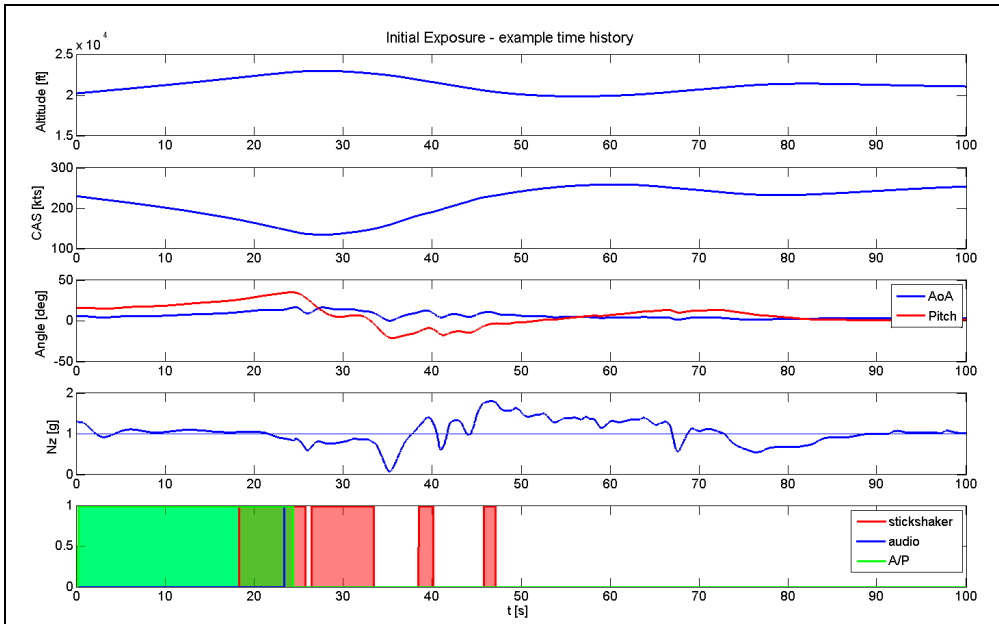


Figure 11. Example time history of a recovery from asymmetric stall during initial exposure

fidelity in both cases. To prevent from order effects, again its order was balanced over all subjects. After the session the pilots were asked which condition (Onset vs. Onset+) gave the best feeling of unloading, loading, and pitch. Finally they were asked which solution they preferred. At the end of the experiment, the pilots were asked to fill out a debriefing questionnaire on their experiences, preferences, future usability and on what they learned.

For illustration purposes, in Figure 11 an example time history is shown of an initial upset recovery exposure to an asymmetrical stall. From statistical analysis it can be concluded that pilots initially show inexperience with upset recovery (comparison of initial exposure with pre-test). Initially, recovery takes longer (12.5%), shows a higher number of secondary stalls (90.0%), where smaller pitch rate is applied (40.0%), and shows more flying into the stick-shaker (87.0%).

From the DESDEMONA Phase II experiment it can be concluded that pilots recover more conservative with G-cueing (compared to Onset cueing), as shown in Figure 12. With G-cueing, recovery takes longer (13.8%), lower G-load is applied (4.8%), increasing airspeed (3.4%), with more altitude loss (6.5%), at lower pitch rate (33.9%), and with less initial unloading.

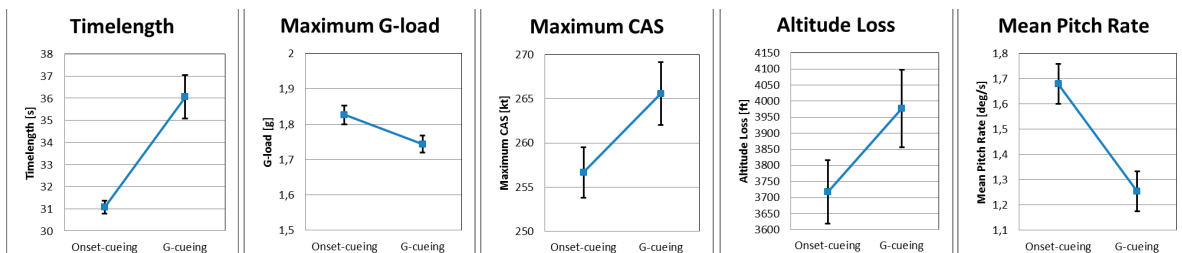


Figure 12. Effect of cueing (onset- vs. g-cueing) on duration, maximum g-load, maximum CAS, altitude loss, and mean pitch rate during recovery from asymmetric stall.

Besides that, it can be concluded that after the G-awareness session (Post-test compared to Pre-test) recovery becomes faster (G-cueing condition only) (17.5%), at a higher G-load (3.9%), with less secondary stick-shaker events (G-cueing condition only) (22.5%), at a higher pitch rate (21.0%), while vertical speed increases more (G-cueing condition only) (10.8%), while flying less in the stick-shaker (trend for G-cueing condition only) (15.1%). From subjective ratings on cueing preferences, Onset+ (tilt coordination to simulate G-load) is preferred over conventional onset cueing, especially during the loading phase. Pilots rate their mental workload higher in the pre-test (35.0%) and in the G-cueing condition (20.6%). Besides, their physical workload is rated higher in the G-cueing condition (55.5%), as well as their effort workload (21.0%) and frustration workload (34.0%). However, a G-awareness session lowers the pilots' physical workload (G-cueing condition) (19.9%).



According to general subjective ratings, pilots rate less false cues in the onset cueing condition compared to the G-cueing condition (19.1%). Secondly, pilots rate their procedures performance worse in the pre-test compared to the post-test (9.1%), and their performance to stay within speed limits better in the onset-cueing condition compared to the G-cueing condition (10.1%). With respect to control loading, pilots rate the control loading heavier in the G-cueing condition compared to the onset cueing condition (15.6%). Overall, pilots unanimously preferred the G-cueing condition over the onset cueing.

From the DESDEMONA Phase II experiment it can be concluded that pilots initially show a lack of experience in upset recovery, recover more conservative in the g-cueing condition, fly more safely after the g-awareness session, perceive higher control loading in the g-cueing condition, rate higher workload (mental, physical, effort and frustration) in the g-cueing condition, while the perceived physical workload can be decreased by providing a g-awareness session. Pilots prefer Onset+ cueing (tilt coordination to simulate G-load), especially during the loading phase, and although pilots rate higher false cues, all subjects did unanimously prefer the g-cueing condition.

## V. Conclusions

The piloted evaluations showed that the SUPRA aircraft simulation model is representative of a conventional jet transport with under wing mounted engines, a fuselage mounted horizontal stabilizer and an operating weight of approx. 100 tons. This means 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.

Further it was 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 dependent 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 was found superior to the conventional hexapod motion cueing. Moreover, the study showed no negative effects of conventional hexapod motion versus no-motion simulation on UPRT.

Reproduction of *g* cues in centrifuge-based simulators was rated 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 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.

It is important to note that the SUPRA project did not aim at developing an actual training program to fight the risk of loss of control in flight. Instead, the project attempted to develop technological 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. 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.

Finally, the Industry Upset Recovery Training Aid already provides simulator scenarios for upset recovery from unusual attitudes which all stay within critical values of AoA. Now the SUPRA simulator model allows for extending these upset exercises with post-stall scenarios.

## Acknowledgments

The authors would like to thank all of the pilots involved in the evaluation of the SUPRA simulation on the simulators. We would also like to thank the members of the SUPRA expert group for their valuable guidance throughout the project.

The SUPRA project was funded under the European Union Seventh Framework Programme, FP7, Grant Agreement no. 233543. The authors thank all of the SUPRA partners who have indirectly contributed to this paper through their enthusiastic research in the project.

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