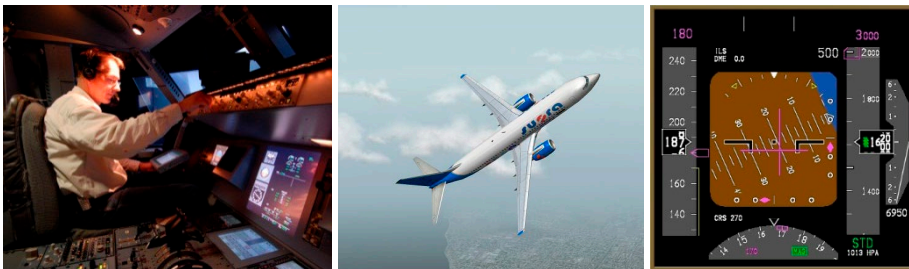




Executive summary

Developing Upset Cueing for Conventional Flight Simulators

SUPRA: NLR Experiments



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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. Of particular interest to the industry is what the possibilities are to improve existing training facilities – such as Full Flight Simulators – for upset prevention and recovery training.

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 NLR work within the project supported the aerodynamic and motion cueing developments. This paper reports the development that was carried out together with the TsAGI and GFRI institutes on optimizing the motion cueing of conventional hexapod based flight simulators for upset recovery training.

The experiments carried out for this phase of the SUPRA project applied test pilots and line pilots to examine the differences in perceived realism as well as performance in recovering the aircraft from upsets and stalls.

Results and conclusions

The experiments carried out at NLR demonstrated that improvements to the motion cueing on conventional simulators can be beneficial to the training environment.

Buffet cueing improvements had a positive effect on the recovery prior to stall. An improvement in the cueing match with the aircraft accelerations was also possible through modifications to the cueing algorithm.

The results demonstrated that the conventional flight simulator is a valuable facility for recurrent upset prevention and recovery training.

Applicability

The discussion presented in this paper applies to motion based training on hexapod simulator platforms. The paper is focused on upset recovery training, but includes general principles of motion based simulation.

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Abbreviations

AoA	Angle of Attack
FFS	Full flight simulator
ICATEE	International Committee for Aviation Training in Extended Envelopes
LOC-I	Loss of control - In-Flight
Ny	Lateral specific force
Pb	Roll rate
SUPRA	Simulation of Upset Recovery in Aviation
UPRT	Upset Prevention and Recovery Training
URTA	Upset Recovery Training Aid



Developing Upset Cueing for Conventional Flight Simulators

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As a part of the SUPRA project, NLR has been developing motion cueing for Upset Prevention and Recovery Training on conventional full flight simulators. This paper describes the concept development, implementation and piloted evaluation of modified motion cueing on the GRACE hexapod simulator. The focus of these developments was to improve the motion cueing with minimum impact on the existing hardware and software of the simulator. Two different strategies were applied within the motion cueing solution – workspace and perception optimised. The workspace strategy aimed to improve the fidelity by maximising the use of the simulator’s motion envelope. The perception strategy reproduced the g-load perception effects on the acceleration onset cueing. In addition, a modification to the stall buffet cueing effect was developed. Two phases of experimental evaluation were carried out consisting of a subjective validation by experimental test pilots and an evaluation with current line pilots. The outcome of these experiments indicated that the onset cueing could be objectively improved. The perception of the motion cueing in the upset and stall recovery scenario’s was enhanced, without introducing false cues. The stall buffet modifications resulted in reduced stall recognition times. These experiments at NLR demonstrated that the hexapod based flight simulator forms a valuable training facility for Upset Prevention and Recovery Training.

Nomenclature

<i>AoA</i>	=	Angle of Attack
<i>FFS</i>	=	Full flight simulator
<i>ICATEE</i>	=	International Committee for Aviation Training in Extended Envelopes
<i>LOC-I</i>	=	Loss of control - In-Flight
<i>N_y</i>	=	Lateral specific force
<i>P_b</i>	=	Roll rate
<i>SUPRA</i>	=	Simulation of Upset Recovery in Aviation
<i>UPRT</i>	=	Upset Prevention and Recovery Training
<i>URTA</i>	=	Upset Recovery Training Aid

I. Introduction

The increasing demand for upset prevention and recovery training in conventional civil flight simulators is raising questions about the effectiveness of the motion systems of these devices. The training for recovery from upsets and stalls may result in aircraft dynamics that are outside the normal operational envelope of civil transport aircraft. Civil flight simulation training devices have motion cueing algorithms that are designed for normal flight operations, and may therefore not provide the most effective motion feedback during stall and upset manoeuvres. While current civil flight simulators are used for upset recovery training, some advocate their use only as fixed base devices due to the risk of negative cueing from the limitations of the motion platforms. Most civil flight simulators are equipped with conventional hexapod, or Stewart Platform, motion systems and as such have only limited travel and motion cueing capabilities. The algorithms that drive the platforms are often based on “classic” motion filter design.

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The Simulation of Upset Recovery in Aviation (SUPRA)* project, which is funded by the European Commission as part of the Seventh Framework Programme, has been developing improvements to simulation models to address the current concerns for upset and stall simulation. This includes developments in aerodynamics, motion perception modelling and motion cueing¹. The focus of the research is into the simulation facility, as a contribution to the industry discussion of how training to prevent Loss of Control -In-Flight (LOC-I) can be improved.

The Royal Aeronautical Society's International Committee for Aviation Training in Extended Envelopes (ICATEE) was established in 2009 as an industry working group to define and develop recommendations for Upset Prevention and Recovery Training (UPRT). This group consists of a wide cross-section of the industry and is currently working with the International Civil Aviation Organisation (ICAO) on industry UPRT recommendations. A part of these recommendations includes modified requirements for Full Flight Simulators (FFS). ICATEE is developing a list of training tasks for UPRT, as well as analysing the training facilities that are required for these tasks². This work is still in development, but currently indicates that approximately 80% of the UPRT tasks could be carried out on existing simulators, or with minor upgrades to existing hexapod-based training devices. It is therefore interesting to identify the potential for improving conventional flight simulators for future UPRT.

II. UPRT Motion cueing objectives

Within the SUPRA project NLR and TsAGI have been investigating the possibilities of developing improvements to motion cueing that can be applied to conventional civil flight simulators. The primary aim of this research has been to develop motion cueing solutions for upset prevention and recovery training that can be applied short term, and are acceptable and deployable for the flight simulator industry, operators and aviation authorities. The civil aerospace industry is conservative and strictly regulated for safety considerations, so adjustments and new developments for motion cueing should have as minimal operational risks as possible. These risks can be kept to a minimum by ensuring that any new solution can be easily embedded or linked to the existing motion drive algorithms without harming the integrity of the current architecture. The basic design principles that have been applied to realize this, in line with current industrial practices, are the following:

- Developing a switchable add-on to the current classic filter for an upset motion drive algorithm
- Maximizing the usage of the current Stewart Platform motion space by exploiting gains and positioning for particular upset manoeuvres

These principles enable the current motion cueing solution for the normal flight conditions to remain intact. This ensures that there is minimal impact on the simulator certification for normal flight crew training, and minimizes the development time and cost. Additionally, it allows existing flight simulators to be modified simply with an update, rather than an intrusive update to replace the basic motion algorithms or a replacement of the hardware motion platform, which is costly and requires major re-certification. These developments are based on a theoretical analysis of aircraft upset profiles and the associated dynamics of the aircraft in combination with the perception of the pilots. The algorithm developments have been implemented and evaluation on the conventional hexapod research simulators at NLR and TsAGI. The evaluation of the motion cueing combined the objective analysis of the motion system performance with subjective feedback from the pilots.

III. UPRT Motion cueing concept

A. Motion analysis of upset scenarios

The underlying concept for the UPRT motion filter design is to optimise the motion cueing dependent on the phase of the upset recovery scenario. For this purpose the SUPRA project has developed several types of scenarios as training exercises for manoeuvre based training in upset recovery³ and can be classified into two groups for motion cueing purposes: stall induced upsets and externally induced upsets. The assumption is that these scenarios are activated in response to an input from the simulator instructor. Since the initial development of the upset scenario is pre-determined, the movement of the aircraft, and hence the motion cues, are also pre-determined. It is therefore possible to adjust the MDA accordingly to optimise the cues for the phase of the scenario. These upset and recovery manoeuvres have been analysed from the perspective of the motion cueing

* The SUPRA consortium consists of the following partners: TNO, NLR, Boeing Research & Technology Europe, AMST Systemtechnik, TsAGI, De Montfort University, Gromov Flight Research Institute, Max-Planck Institute, Dinamika and Desdemona B.V.
(www.supra.aero)

that is required. For this purpose, we have identified five phases of the manoeuvre scenario. These are illustrated in Figure 1.

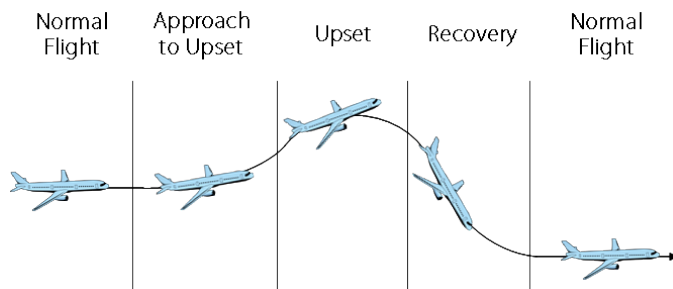


Figure 1. Motion cueing phases of the upset recovery training scenario.

Within the five phases that have been identified for the upset recovery manoeuvre, the motion drive algorithm is adjusted to optimise the cues that are required by the pilot. In the normal flight phase the standard or existing classical motion drive algorithm of the simulator is used. During the approach to the upset or stall phase, the buffet cueing will be the primary motion effect that is required by the pilots. During this phase the standard motion drive algorithm is transitioned to the UPRT algorithm. In the upset phase, the simulator

is required to respond to a known manoeuvre of the aircraft – in response to the scenario selected. Therefore, it is possible to optimise the motion of the simulator to this manoeuvre. The motion drive algorithm should then be adjusted to prioritise the primary cue that is required, dependent on the aircraft motion in the upset (Table 1). This limits the motion system to cueing in a single axis, or coupled axis pair – for example in pitch & heave.

Scenario	Description	Degree of freedom	
		Primary	Secondary
1.1	<i>Nose-high, zero bank</i>	Roll	Sway
1.2	<i>Nose-high, bank angle $45^\circ < \phi < 90^\circ$</i>	Roll	Sway
1.3	<i>Nose down, bank angle $45^\circ < \phi < 90^\circ$</i>	Heave	Roll
1.4	<i>Nose down, high bank $\phi > 90^\circ$</i>	Heave	Roll
2.1 a	<i>Clean Config, Straight & Level</i>	Pitch	-
2.1 b	<i>Clean Config, turn</i>	Roll	-
2.2 a	<i>Landing Config, Straight & Level</i>	Roll	Sway
2.2 b	<i>Landing Config, turn</i>	Roll	Sway
3.1 a	<i>Wing stall, Clean Config, turn</i>	Heave	Roll
3.1 b	<i>Pitch Up stall, Clean Config, Scen. 1.2</i>	Heave	Pitch
3.2 a	<i>Wing stall, Landing Config, turn</i>	Heave	Roll
3.2 b	<i>Pitch Up stall, Landing Config, Scen. 1.2</i>	Heave	Pitch

Table 1. Motion Cues – Prioritised Degrees of Freedom.

During the recovery phase, the motion cues that are required are dependent on the response of the pilot to the upset. It is therefore not possible to predict the cues that will be required. However, during recovery the g-loads experienced by the pilot may reach average levels between 1.8 to 2.2g. The TsAGI motion perception studies showed that under g-loads the motion perception of the pilot reduces. This effect can be captured by an analytical model which adapts the motion filter gains (i.e. prioritizes each motion axis contribution) as a function of the aircraft g-load during the recovery phase. This “perception” based optimization was adopted as the strategy for the recovery phase under g-loads higher than +0.3g. More on these findings can be found in a separate AIAA paper⁴. As the accelerations and velocities of the aircraft model return to normal, and the aircraft returns to a normal flight attitude, the motion drive algorithm settings should turn to the initial standard or existing classical motion drive algorithm settings.

B. Description of upset motion filter architecture

The primary objective of the NLR within the SUPRA project was to develop a short-term motion cueing concept, which serves as an add-on for existing classic motion drive algorithms in combination with a conventional hexapod motion system. The UPRT motion cueing add-on developed by the NLR is schematically depicted in Figure 2 and comprises five modules that will be discussed in the next subsections.

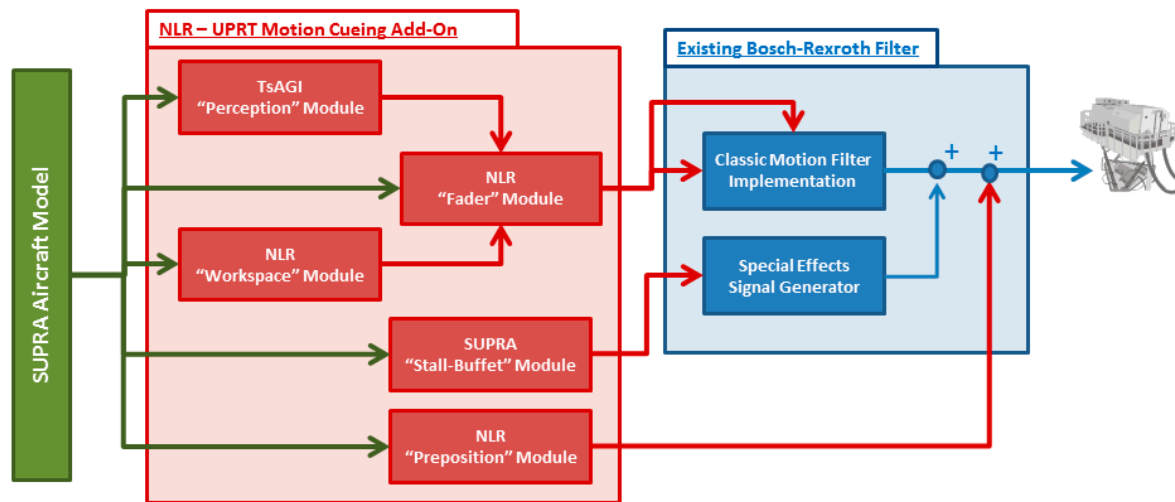


Figure 2. NLR SUPRA Motion Cueing Filter Architecture.

Perception, Workspace and Fader Modules

The TsAGI perception and NLR workspace modules in combination with the NLR fader module form the heart of the UPRT motion cueing add-on developed by NLR. The TsAGI perception module implements the g-load perception effects on the acceleration onset cueing that results from their human perception research⁴. This module takes the SUPRA aircraft model specific forces and angular accelerations as its input to adaptively scale and filter these signals before they are fed to the fader module. The NLR workspace module implements the prioritised axis motion cueing approach, while optimally using the workspace of the motion system. This is accomplished by an algorithm that modifies the classic motion filter gain settings in real-time according to the SUPRA aircraft model state, upset recovery scenario and phase. A single and optimised set of motion filter parameters (i.e. gains, damping and cut-off frequencies) has been established for this module (See section III-D). The fader module implements an algorithm that smoothly switches between both the perception and workspace modules based on the SUPRA aircraft model produced g-loads during the execution of an upset or stall recovery manoeuvre.

1. NLR Pre-position Module

The pre-position module algorithm aims at optimizing the hexapod motion space in heave to better simulate the g-break sensation in an upset or stall scenario. This module takes the SUPRA aircraft AoA to move the motion platform up to a pre-position pose in heave such that the onset heave cue during g-break can be accentuated more (i.e. more downward travel). The pre-position module algorithm embodies low pass filter behaviour with such a setting that the motion platform is moved to the pre-position pose without violating the human motion perception thresholds. This means that the transition to the pre-position pose is not detectable by the pilot. The pre-position pose is an additional position signal that is added to the classic motion filter heave output signal.

2. SUPRA Stall Buffet Module

The current requirements for buffet simulation in a training simulator specify that the stall buffet onset must be matched with aircraft data. The threshold for stall buffet onset used in the simulator is typically ± 0.5 g, which matches the aircraft certification initial buffet threshold. This is the angle of attack at which the buffet exceeds ± 0.5 g. Moreover, the buffet amplitude is a constant value. However, the ICATEE working group has identified that this threshold may be too high and amplitude variation is an important cue for recognition. This working group established new requirements for stall buffet simulation for the following buffet characteristics:

- the onset angle of attack (± 0.03 g)
- the variation in amplitude (as a function of AoA)

The frequency variation has been identified as a less critical cue. Therefore, the SUPRA Stall Buffet Module implements these new key characteristics, and used a representative frequency variation typical for an existing

large transport aircraft. The SUPRA stall buffet module algorithm drives an existing buffet signal generator using both the SUPRA aircraft AoA and onset angle of attack as its input.

C. NLR's GRACE simulator facility implementation

The Generic Research Aircraft Cockpit Environment (GRACE) is the NLR transport cockpit research simulator facility.

The GRACE simulator features a two-seat flight deck typical of a transport aircraft. The instrumentation panel installed in the cockpit is equipped with large liquid-crystal displays that can be configured to represent the avionics systems of different aircraft types. Furthermore, the flight control hard- and software can also be configured to represent different aircraft. For the SUPRA experiments described in this paper the flight deck was configured as a Boeing large transport aircraft type (e.g. B767, B777, B747). The simulator's electronic control loading system comprised two column/wheel and pedals and a throttle station. The control loading model characteristics was configured to be representative for a Boeing large transport aircraft type, and comprised stick-shaker dynamics. The GRACE visual system comprises a four-window collimated CGI system. The system offers each pilot a field of view of 89° (horizontal) and 27° (vertical).



The system offers each pilot a field of view of 89° (horizontal) and 27° (vertical).

The NLR GRACE simulator has an electrically driven hexapod motion platform delivered by Bosch-Rexroth. Its performance capabilities are representative for today's commercially used motion platforms (Table 2). However, as can be seen from Table 2, its motion space is smaller compared to such commercial used platforms and the one that has been used by TsAGI for the SUPRA experiments⁴.

Degree of Freedom	Excursions (pos, min)	Acceleration	Velocity
Surge	660 [mm], -557 [mm]	± 6.0 [m / s ²]	± 0.855 [m / s]
Sway	553 [mm], -553 [mm]	± 6.0 [m / s ²]	± 0.855 [m / s]
Heave	446 [mm], -414 [mm]	± 8.0 [m / s ²]	± 0.611 [m / s]
Roll	17.75 [°], -17.75 [°]	± 130.0 [° / s ²]	± 30.0 [° / s]
Pitch	16.60 [°], -17.25 [°]	± 130.0 [° / s ²]	± 30.0 [° / s]
Yaw	22.05 [°], -22.05 [°]	± 200.0 [° / s ²]	± 40.0 [° / s]

Table 2. NLR's GRACE Motion Platform Characteristics.

For the implementation of the SUPRA motion filter concept described in the previous section, Bosch-Rexroth's motion drive algorithms and software were used as the starting point for the SUPRA motion drive algorithms. These motion drive algorithms are Bosch-Rexroth's implementation of the classical motion filter as developed by Reid and Nahon⁵. Configured with a conventionally tuned parameter set, these Bosch-Rexroth motion drive algorithms are assumed to be representative for a conventional hexapod motion cueing as nowadays is deployed by airline training facilities. This base-line motion drive algorithm implementation is referred in this paper as the "classic" motion filter.

The Bosch-Rexroth motion software interface allows for runtime modification of motion drive algorithm parameters, and injection of additional external platform positions and attitudes (Figure 2). This interface has been used to develop a Matlab-Simulink implementation of the SUPRA motion filter concept, which in run-time adapts the Bosch-Rexroth parameters in relationship to the actual aircraft state and "workspace/perception" schedule depicted in Figure 1. In this manner the "SUPRA" filter meets the criteria of being a switchable "add-on" to an existing "classic" filter, without modifications to the existing Bosch-Rexroth motion drive algorithm that harm its structure or integrity (Section II).

D. Objective and subjective tuning

For the tuning of the newly developed "SUPRA" filter both objective and subjective methods have been used⁵. The start-point for the "workspace" optimised tuning was the baseline "classic" filter setting. From this base-line the offline objective tuning was performed using the results of the motion analysis of the upset



scenario's (Section III-A). This means that the gains, damping factors and cut-off frequencies of the four prioritised axis (heave, sway, pitch and roll) were adjusted to provide better step/sinusoidal responses while staying inside the GRACE motion workspace. The other motion drive algorithm parameter settings remained the same. This offline-tuned setting was taken to the GRACE simulator. On the simulator three separate fine-tuning sessions were held with two test-pilots. These pilots were experienced flight test pilots familiar with real-aircraft upsets and stall-buffets.

The first session comprised the evaluation of the heave pre-position approach to better simulate the g-break sensations. Though this pre-positioning showed promising results in our objective motion analysis on the g-break cues, the subjective assessment of the two test pilots was that it was limited. In addition, the pre-positioning resulted in severe false cues when the simulator motion platform reached its limits in the other aspects of the motion space. This was caused by the dynamic nature of the recovery manoeuvre, which meant that it was difficult to tune the pre-positioning such that the pilot didn't exceed the motion space, in particular if an aggressive control strategy was used to recover. Therefore, it was decided to remove the heave preposition algorithm from the "SUPRA" filter prior to the second fine-tuning sessions.

In the second session the pilots flew the same scenarios again and were asked to assess each of the four prioritised motion axis separately. Based on their comments the filter parameters were modified by systematically changing and subjectively evaluating responses between two settings. Due to the software interface, parameter settings could be changed online back and forth from one setting to the other. Meanwhile, real-time monitoring and objective analysis was done on the difference between the aircraft model produced specific force vector and angular rates and the ones produced by the motion system. Furthermore, the usage of the motion space was monitored in real-time. After fine-tuning each axis, possible perceivable negative cross-coupling effects in high and low pass channel (i.e. false cues) were assessed by small perception tests where one pilot closed his eyes and the other pilot gave a random step input in either roll or pitch. Finally, as a final check the overall perceived motion fidelity by the test pilot crew was assessed for all upset and stall scenarios and compared to the original "classical" motion filter. This fine-tuned "SUPRA" motion filter was stored.

Several days later the same test pilot crew was invited for a third session to assess this workspace optimised filter setting again following the same procedure, except that the "SUPRA" motion filter was used as the starting point. Only very minor gain changes in high pass pitch and roll were made, showing that their input was consistent and resulted in a stable motion filter setting. During the third session also the integration (i.e. fade-in/fade-out algorithm) with TsAGI's perception optimised filter part was assessed and fine-tuned⁴. Furthermore, a subjective assessment was made by the test-pilot crew of the effect of the cut-off frequencies (i.e. middle frequency) of the four high-pass channels and the low-pass channels (i.e. tilt coordination) as recommended by the TsAGI perception study. The TsAGI recommended parameter setting of 0.22 Hz was rated to provide slightly better motion sensations compared to the other two assessed middle frequency settings (0.19 and 0.25hz).

IV. Experimental evaluation

A. Experimental design

The final experiments in the SUPRA project were coordinated between the research institutes (TNO, NLR, TsAGI and Max-Planck Institute). Each institute used the SUPRA aircraft model as the basis for the simulation and investigated specific research questions related to the facility. The work of NLR using the GRACE simulator focused on the application of the SUPRA simulation models to conventional flight simulators.

1. Research objectives

The primary goal of the experiments at NLR was to evaluate the effect of the modifications to the motion drive algorithms. The research hypothesis was that the fidelity of the motion cueing can be improved by modifying the existing algorithms – this would be evaluated through both subjective and objective analysis.

The evaluation of the simulation was split into two phases. Phase 1 consisted of a subjective evaluation of the aerodynamic model and motion cueing modifications using expert test pilots with experience in upsets and/or stalls in an aircraft. These expert pilots validated the aerodynamic model in normal handling conditions, as well as several upset and stall scenarios. The modified motion cueing configuration was evaluated for four stall scenarios in the phase 1 experiment. This was used as a validation of the aerodynamic and motion cueing modifications prior to the larger-scale line pilot experiment.

The second phase of the evaluation focused on the objective analysis of the motion modifications and an investigation of the effect on pilot performance in upset and stall recovery. The phase 2 experiment was carried



out with line pilots who were asked to fly the manoeuvres but were not specifically tasked with a subjective analysis.

The following research questions were addressed:

- 1) Does the modified low speed buffet motion simulation have an effect on the recognition of stall compared to the conventional buffet profile?
- 2) Does simulator motion have an impact on the performance of pilots in upset recovery training, compared to fixed-base?
- 3) Does the modified motion cueing have a positive effect on the performance in the recovery manoeuvre compared to the classical cueing?
- 4) Can an objective improvement to the fidelity of the motion cueing be made through the modifications to the algorithms?

1. Experiment participants

Two groups of pilots were used in the evaluation. The pilots used in the first phase were experimental test pilots and pilots from the SUPRA expert group. The requirement for the experimental test pilots was that they had experience in upset/stall recovery in transport aircraft. These were pilots from aircraft manufacturers and certification authorities that have been involved in the flight test campaigns for transport aircraft. In addition to these experimental test pilots a small group of the SUPRA expert pilots were used that have extensive experience of the current upset recovery training in simulators or light aircraft. In total nine pilots were involved in the Phase 1 experiment on the GRACE.

The phase 2 pilots were current line pilots in active service with airlines. In total 20 pilots participated, with a cross-section of long- and short-haul experience. All of the pilots had undergone basic upset recovery training as required by their airlines on the airline training simulators. No pilots had experience of upsets or stalls in the real aircraft. The experiment applied a balanced design so that all pilots flew all of the motion conditions for all of the upset and stall manoeuvres. The learning effect of flying multiple scenarios was countered by balancing the sequence of the motion conditions across the participants.

2. Method

The subjective evaluation consisted of questionnaires to record the assessment of the pilots. The primary subjective analysis took place in phase 1 where rating scales were used by the test pilots to assess the aerodynamics and motion cueing. The aerodynamic rating was used to assess whether the aerodynamics were representative of the aircraft class that was simulated. The handling rating also assessed whether pilot adaptation was required in handling the aircraft for normal manoeuvres as well as upset and stall manoeuvres. The aerodynamic model consisted of several different stall models, so the evaluation included an assessment of the handling characteristics for each of the four selected stall models in approach to stall and developed stall manoeuvres. The manoeuvres were derived from the Upset Recovery Training Aid (URTA)⁶.

The phase 1 motion evaluation consisted of questionnaires after four stall manoeuvres. The test pilots were asked to identify the key motion cues for each manoeuvre, and rate the magnitude and inaccuracies present. Five point rating scales were used for this assessment – assessing the magnitude between “too weak” and “too strong” compared to the aircraft motion. Finally, the pilot was asked to rate the overall motion cueing fidelity for the key motion cues and false cues for each configuration and manoeuvre. The overall key motion fidelity rating was based on a comparison with the expectations of the real aircraft and acceptability for training. The false cues rating assessed whether any false cues were perceived, and the level to which they were distracting in flying the simulator.

In phase 2, two experiments were carried out to evaluate the buffet motion cueing, and the upset motion cueing modifications. For the buffet evaluation experiment the pilot’s task was to recognise the stall and recover at first indication of stall. For this experiment, the stick-shaker was disabled and the pilot therefore relied on the instruments and aerodynamics of the aircraft for recognition. Three conditions were evaluated: “No Buffet – fixed base”, which was the control condition, and then the experimental conditions “Classic buffet”, and the modified “SUPRA buffet”. The simulator recorded parameters to assess the performance.

For the upset motion cueing experiment the pilots were asked to fly four manoeuvres (one upset manoeuvre, and three different stalls). In this experiment the pilot was instructed to fly the aircraft into the upset/stall by the simulator operator and recovered the aircraft when commanded. The pilot’s task was to recover the aircraft as quickly and safely as possible. A subjective assessment of the motion cueing was made relative to the pilot’s expectations from the instruments and outside visual cues. This assessment was therefore not a comparison with the actual aircraft cueing, since the line pilots had no experience of upsets or stalls in the aircraft.



B. Subjective results

The subjective evaluation of the ‘‘SUPRA’’ motion cueing filters aimed to assess the effect of the SUPRA developments on the motion perception during the upset and stall conditions, compared with the ‘‘Classical’’ motion filter approach.

The experimental test pilots rated all motion filters using an acceptability scale. A rating of 1 or 2 indicates that the motion cueing is an acceptable representation of the aircraft motion for training purposes. A rating of 3 or 4 indicates that the lack of expected cues or the presence of false cues leads to unacceptable motion. The results are presented in Figure 4[†]. The results show a progressive improvement of the perceived key motion cues across the motion cueing conditions. The modified cueing on the GRACE simulator is indicated by the ‘‘workspace optimised’’ ratings, which show less variation and is within the acceptable ratings. The conventional cueing shows a wide variation of acceptability amongst the pilots. The false cue ratings are shown split between the symmetrical and asymmetrical stall scenarios (two of each were flown). The workspace optimised modified cueing shows a tendency to higher false cue ratings for the asymmetric stalls.

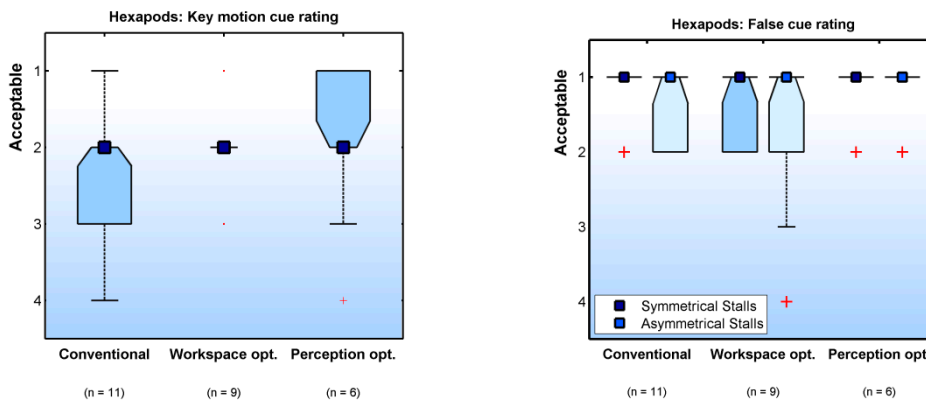


Figure 4. Phase 1 acceptability ratings for key motion cues (left) and false cues (right). Combined results for the SUPRA hexapod evaluation on the NLR GRACE simulator (workspace) and TsAGI PSPK-102 simulator (perception).

The experimental test pilots assessed their preferred motion cueing configuration. The results for these assessments are illustrated in Figure 4, divided for symmetrical and asymmetrical stall cases. The motion preference is indicated in the figure by means of the percentage that the particular motion configuration was preferred compared to all evaluated cases. These results show that the modified cueing was preferred over the classical cueing.

The assessment results for the magnitude of the motion cues during the upset and stall recovery manoeuvres did not exhibit differences between the motion conditions. There was a trend towards an improved rating for the workspace modified motion cues, with ratings tending to increase to ‘‘slightly weak’’ or ‘‘okay’’. For the modified cueing, the key motion cues were rated as representative in more cases compared to the classical cueing.

Examining the magnitude assessments in more detail for each of the motion cues indicated that the modifications to the motion cueing tended to have a more noticeable effect in the lateral axes than in the longitudinal axes. The lateral axes were rated as representative in 60% of the cases for the modified cueing, compared to 25% of the cases for classical filters. The differences were less pronounced for the longitudinal axes.

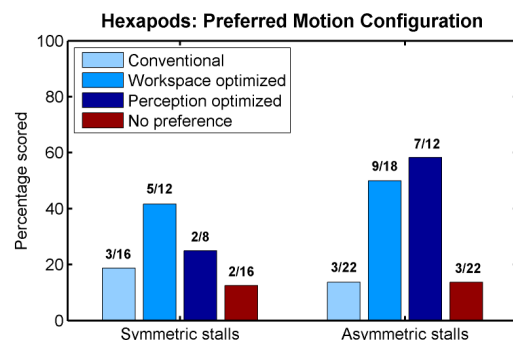


Figure 5. Preferred motion assessment results.

[†] The figures show the results for the workspace optimised and perception optimised results. The perception optimised results are reported and discussed in a separate paper at this conference⁴.

The results of the phase 2 subjective evaluation are shown in Figure 6. During this phase fourteen of the twenty line pilots rated the acceptability of the different motion conditions according to their expectations. The results indicate that the modified motion cueing (identified as SUPRA-3 MDA in the figure below) was preferable. The false cue ratings were comparable for all conditions.

C. Objective results

The objective evaluation of the motion cueing modifications consisted of two parts: a comparison with the aircraft model, and an evaluation of pilot performance.

2. Objective comparison with aircraft model

By comparing the angular rates, accelerations and specific forces produced by the “Classic” and “SUPRA” motion filters directly with those from the aircraft model, an objective assessment of their level of fidelity can be made. The assumption is that the higher level of motion cueing fidelity will match the aircraft dynamics during the stall manoeuvre better given the capabilities of the GRACE motion system. The subjective assessment

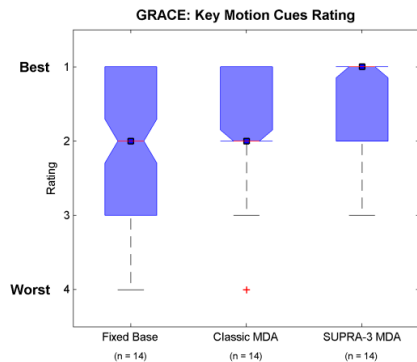


Figure 6. Phase 2 acceptability ratings for key motion cues.

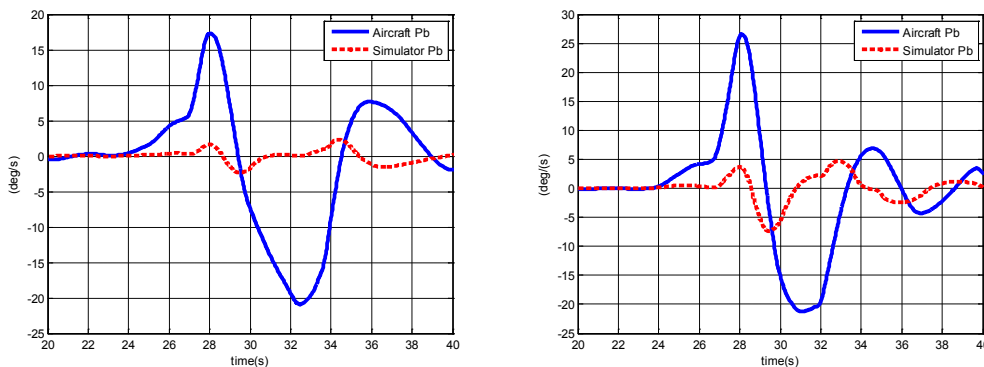


Figure 8. Comparison of aircraft and simulator roll angular rates during wings level stall entry and roll-off for Classical motion filter (left) and SUPRA motion filter (right).

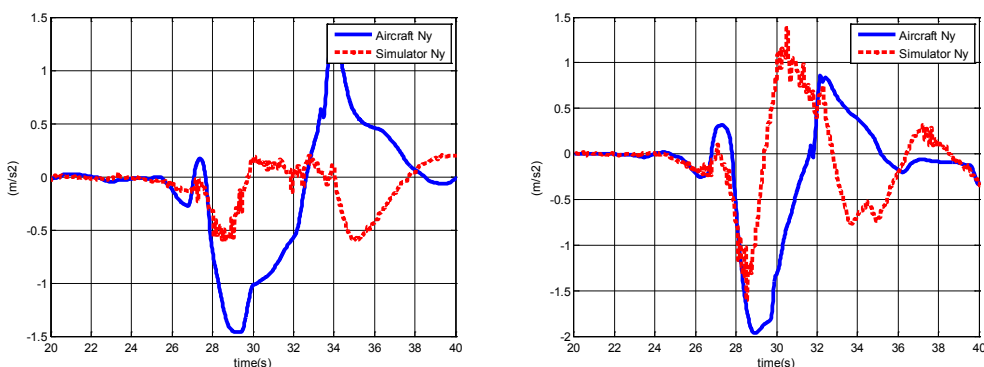


Figure 7. Comparison of aircraft and simulator lateral specific force during wings level stall entry and roll-off for Classical motion filter (left) and SUPRA motion filter (right).

discussed in the previous section showed that the “SUPRA” motion filter was preferred over the “Classical” motion filter for UPRT by the airline pilots. The objective comparison with the aircraft model substantiates this result by showing that the “SUPRA” filter produced angular rates, accelerations and specific forces that match those of the aircraft model better than the “classical” motion filter for the same UPRT scenario. Figure 7 and Figure 8 show an example of the main lateral cues that play a role during the stall entry unloading phase for a wings level stall. In this example scenario, the SUPRA aircraft modelled a reduced lateral aerodynamic stability in the fully developed stall.



3. Pilot performance

The objective evaluation of pilot performance examines the effect that the motion cueing has on the overall outcome, i.e. does a modification to the motion affect the end-result, or how does the pilot fly the manoeuvre? The parameters that were monitored in the experiments are intended to measure the effectiveness of the recovery manoeuvre. While there is no definition of the “ideal” recovery manoeuvre, certain parameters have been identified to give an indication of an acceptable manoeuvre, or a better manoeuvre. These parameters, listed below, were identified together with the development test pilots during the motion cueing development and testing.

- Time to stall recognition: the required time for the pilot to take action at the first indication of stall (e.g. buffet, speed, AoA, deceleration)
- Time to recovery: the time to re-establish stable flight
- Altitude loss: maximum altitude lost during the upset and recovery manoeuvre
- Maximum g-load: maximum g-load during the recovery manoeuvre
- Maximum pitch rate: maximum pitch rate during the recovery manoeuvre
- Maximum calibrated airspeed: maximum calibrated airspeed during the recovery manoeuvre
- Maximum AoA: maximum angle-of-attack during the recovery manoeuvre (e.g. measuring risk of secondary stall)
- Number of secondary stalls: number of secondary stalls during the recovery manoeuvre
- Longitudinal & Lateral control inputs: pilot control activity evaluated using root mean square error, and frequency spectrum analysis

The primary parameter where an effect was expected was in the time to recovery (and time to stall recognition for the buffet experiment). The hypothesis for the experiment suggested that a difference would be observed between the motion conditions. The other performance indicators were included to give measures of the aggressiveness of the recovery manoeuvre, the amount of control inputs that were required, and the effectiveness of the manoeuvre.

4. Enhanced buffet motion simulation

The goal of this experiment was to investigate the effect of the modified buffet cueing compared to the current classical buffet cueing. While the statistical analysis of the buffet motion simulation was used to identify the differences in performance between the “Classic” buffet condition and the “SUPRA” buffet condition, the “No buffet” condition was included in the experiment and a statistically significant difference was noted for all of the performance measures between the “No buffet” condition and the other buffet conditions.

An independent samples *t* test compared the time to stall recognition for the “Classic” buffet condition

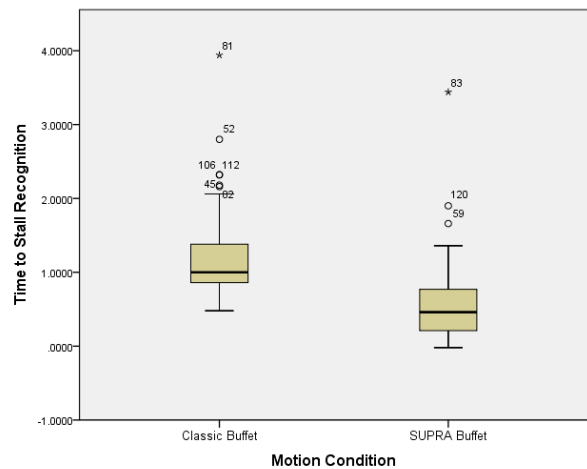


Figure 9. Buffet Experiment: Time to Stall/Buffer Recognition.

($M = 1.25750$, $SD = .70203$) with the “SUPRA” buffet condition ($M = .62667$, $SD = .67653$). This comparison was found to be statistically significant, $t(77) = 4.067$, $p < .001$. This is illustrated in Figure 9.

For the time to recovery the results do appear to indicate that there was a difference in the spread of the data, while the mean time to recovery did not differ significantly. For the “Classic” buffet condition ($Mdn = 2.75000$, $IQR = 5.1450$) there was a larger spread of results compared to the “SUPRA”

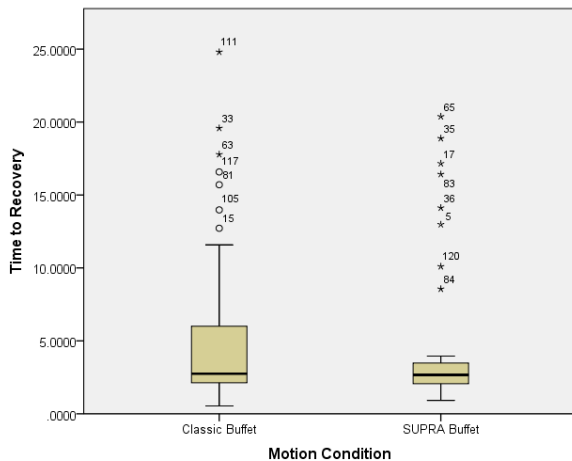


Figure 10. Buffet Experiment: Time to Recovery.

buffet condition ($Mdn = 2.67000$, $IQR = 1.4400$). This is illustrated in Figure 10.

No statistically significant difference was observed in the other performance indicators.

5. Upset recovery performance

The goal of this experiment was to investigate the effect of the modifications to the motion cueing for upset and stall recovery manoeuvres. In this analysis a Univariate analysis was used to compare the performance indicators for the three motion conditions: Fixed, Classic and SUPRA. There was no statistically significant difference observed in the performance indicators between the different motion conditions.

Examination of the results indicates that there was a larger effect on the performance indicators between the different stall conditions than between the motion conditions. The differences for the performance indicators between the stall conditions were statistically significant. For example, in Figure 11 (b) the difference in Time to Recovery is illustrated between the Upset and Stall scenarios – where the mean time to recovery for the Pitch Up Stall scenario is almost double that for the Upset scenario.

V. Discussion

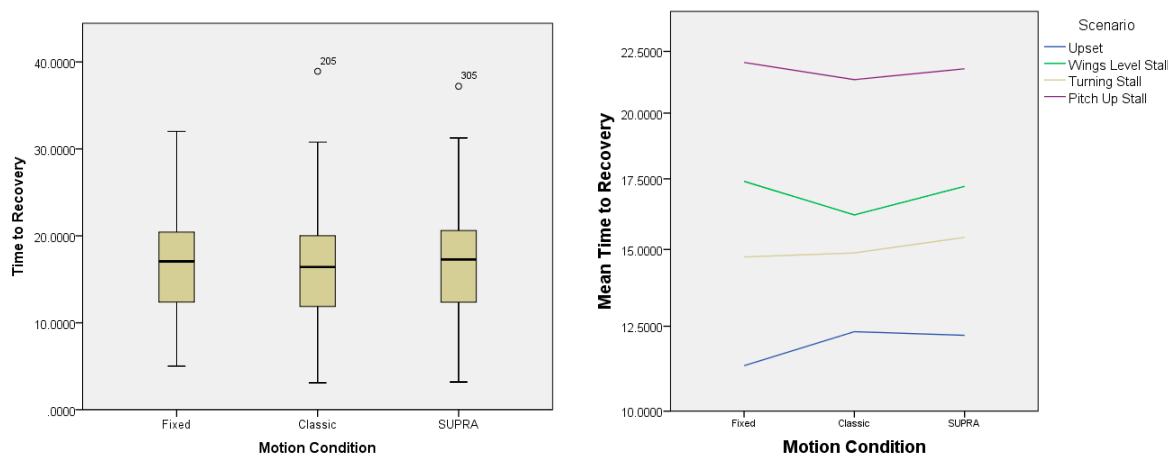


Figure 11. Motion Experiment: (a) Time to Recovery (Overall). (b) Mean Time to Recovery (per Scenario).

This paper focuses on the motion cueing related aspects of the SUPRA experiments carried out at NLR. The results of the evaluation determined that it was possible to tune the motion cueing on a conventional hexapod simulator to achieve an improvement in onset cueing. The pilots involved in the evaluation rated the modifications to the motion cueing better for the upset and stall manoeuvres than the classic or fixed-base motion conditions. While no objective difference in performance for the recovery manoeuvre was observed in the final evaluation, these results should be considered in the wider context of the upset cueing modifications to the simulation.

A. Phase 1 Experiment

The subjective evaluation by experimental test pilots of the modified motion cueing in the Phase 1 experiments indicated a preference for the modified cueing over the classical and fixed-base cueing.

The pilot's subjective assessment of the motion indicates that for the perception the modified cueing represents the best solution to represent the acceleration onset cues that are expected for the upset and stall manoeuvres. Individual comments and ratings from pilots indicate that in some cases a difference was felt during the unload phase of the manoeuvre, particularly with respect to the integrated cueing (instruments, visual and motion). The modifications to the filters also did not lead to the introduction of false cues, and for some manoeuvres tended to reduce the false cues.

There were some differences in the ratings observed between the symmetrical and asymmetrical stall scenarios at NLR. The ratings from the asymmetrical scenarios exhibited a trend towards more unacceptable false cues in the pilot's ratings. Examining the motion of the simulator in these cases would seem to indicate that the simulator reached its mechanical limits. In the dynamic nature of these manoeuvres the handling of the pilots during the recovery can lead to large accelerations. By modifying the motion cueing to optimise the use of the motion envelope there was a risk that the number of false cues would be increased.



The subjective evaluation results show that the motion cueing of the conventional hexapod flight simulator can be improved to better capture the key motion cues for upset and stall manoeuvres without introducing any unacceptable false cues. In particular it was shown that the highly dynamic entry phases of the upset, for example the aircraft wing drop and roll off, can be reproduced realistically. The results on the GRACE simulator for the recovery phase of the manoeuvre exhibited less effect, where the lack of sustained g-cueing is a factor. The TsAGI research indicates that both the unloading and loading g effects can be improved with respect to the pilot's perception of the motion⁴. The pilot's ratings indicate that the motion modifications on the GRACE simulator resulted in an improved simulation of the upsets and stalls, and contributed to the overall upset cueing improvements achieved by the SUPRA developments on the simulator.

B. Phase 2 Experiment

The results of the Phase-2 experiments demonstrated that it is possible to improve the level of fidelity of the motion cues produced by a conventional full-flight simulator during upset and stall recovery scenarios. The developed UPRT motion cueing add-on for a classical motion filter (Figure 2) resulted in a better match (i.e. fidelity) between the specific forces and rotational accelerations of the SUPRA aircraft model and the ones replicated by the total motion system configuration (i.e. SUPRA motion filter and hexapod). Despite this increased level of motion cue fidelity of the SUPRA motion filter compared to the Classical motion filter and the Fixed-base condition, this didn't result in a significant differences in performance in the recovery manoeuvres. This could be due to a number of contributing factors or combinations thereof:

- No particular recovery manoeuvre was specified or instructed to the pilots. It was left to pilot to decide how they recovered. Therefore, there was more variation in the recovery manoeuvres due to the pilots' recovery strategies than due to the motion system conditions.
- Adaptability of the pilots to the different motion system conditions (i.e. adjusting their control or recovery strategy) could be a contributing factor why there is little difference in performance.
- The GRACE hexapod has a relatively small motion space compared to today's full-flight simulator industry standards. This could mean that the fidelity improvements in motion cues compared to the aircraft model are too small (e.g. in duration and magnitude) to make a significant difference from a human perception or control behaviour point of view in the used UPRT scenarios.

Defining an "ideal" recovery manoeuvres is not a sinecure. The discussions with the SUPRA consortium test pilots led to the definition of the key performance indicators, but an "ideal" target profile was not defined. This is partially because it was decided that the line pilots should be free to recover as they would "in operations". The line pilots were asked during the experiment to recover the aircraft as quickly *and* safely as possible, so it was expected to see a difference (i.e. a reduction), in the time to recovery. This effect was not observed. It was indicated by the SUPRA test pilots that this could be due to the aim of flying a "safer" manoeuvre, so a smoother recovery given the fact that there was sufficient safe altitude and airspace to do this.

The research at TsAGI indicates that significant performance effects can be observed with a similar SUPRA cueing filter implementation applied to their full-flight simulator which has a motion space twice as big as the one of the GRACE simulator⁴. Both hexapod systems have similar motion performance capabilities in terms of maximum accelerations and velocities (Table 2), which are representative for today's full-flight simulator industry standards. The tuning of the SUPRA motion filter was carried out to get the maximum level of motion cueing fidelity for the SUPRA aircraft (model) flight dynamics given the available motion space of GRACE simulator. The aim of the NLR research was to explore the extent to which existing facilities could be modified to improve the motion cueing for UPRT, and to develop knowledge and lessons-learned that could be directly applicable to today's flight simulator industry and airlines. Major modifications to the hardware of the system such as larger actuators or different motion frame configurations were therefore not included in this part of the SUPRA research. The application of a possible other type of motion platform for UPRT was assessed in another experiment within the SUPRA project and is reported in a separate paper¹.

C. Further remarks

The motion improvements that were applied for the Phase 2 experiment had a limited effect on pilot performance, but the fidelity analysis and subjective evaluation do show that the hexapod platform has potential for improvement. The overall results with the motion activated confirm that the hexapod simulator can be used for UPRT. Given the expected ICATEE recommendations for the development of UPRT, applying current Level VII simulators as well as enhancements to these simulators, the existing hexapod FFS has an important role to play. Other simulation devices that are being considered such as G Awareness Devices, Spatial



Disorientation Devices and Training Aircraft make up the remaining 20% of the training tasks to provide the complete suite of UPRT facilities.

The modifications to the motion effect for stall buffet cueing show promise demonstrating a difference in recognition of stall using aerodynamic buffet. This supports the investigation work that is being carried out in ICATEE. The final buffet threshold and cueing criteria are still being defined by the ICATEE group, but the experiment on GRACE indicates that a modification to reduce the activation threshold and include a variation in the amplitude with AoA can be recognised by the pilots. This had a positive effect on the stall recognition of the pilots reducing the recognition time. This could make a valuable contribution to the training of stall awareness and recognition for aircraft where aerodynamic buffet is a noticeable warning of impending stall[‡].

The motion cueing in the SUPRA project was developed as part of an integrated upset cueing model for the simulator – from the aircraft model, to the motion cueing, to the simulator hardware and the pilot. The experiments at NLR also demonstrated the value of the extended aerodynamic model (reported in a separate paper¹). The motion cueing developments reported in this study should therefore be regarded as a part of the overall system modifications – the simulation as a whole can only be as strong as its weakest link. The SUPRA research focused on the development of the simulation facility – the aerodynamics, motion perception and cueing – and did not examine the training case for UPRT. These experiments suggest that the motion cueing that is possible with conventional flight simulators has value for UPRT.

VI. Conclusions

The research conducted at NLR into motion cueing as part of the SUPRA project leads us to several conclusions relative to the use of the hexapod motion platform for the simulation of upset and stall manoeuvres.

- Modifications to the buffet cueing had a positive effect on the stall recognition.
- No negative effect was observed when upset or stall manoeuvres were flown on motion compared to fixed base, this suggests that motion can be applied for UPRT on conventional simulators.
- There was no objective difference in pilot performance due to modified motion cueing, though the modifications did lead to a better subjective analysis of the motion cueing, and overall upset cueing.
- Objective analysis of the onsets shows that it is possible to better match the aircraft model onsets than Classic motion suggesting an improvement in the fidelity of the motion cueing. The subjective evaluation by the pilots indicates that the perception of the modifications was also better.

The conventional flight simulator is a valuable training facility for Upset Prevention and Recovery Training, particularly if it is upgraded with aerodynamic and buffet cueing modifications. As part of the integrated UPRT system modifications, the motion system can be beneficial to the fidelity of the acceleration onset cueing, which leads to an improved perception of the manoeuvres as a whole.

6. Acknowledgments

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[‡] It is important to note here that not all aircraft exhibit recognisable stall buffet, and that the buffet onset can vary. It is suggested that the buffet cueing should therefore be representative of the simulated aircraft.



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