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Motion Simulation of Transport Aircraft in Extended Envelopes: Test Pilot Assessment

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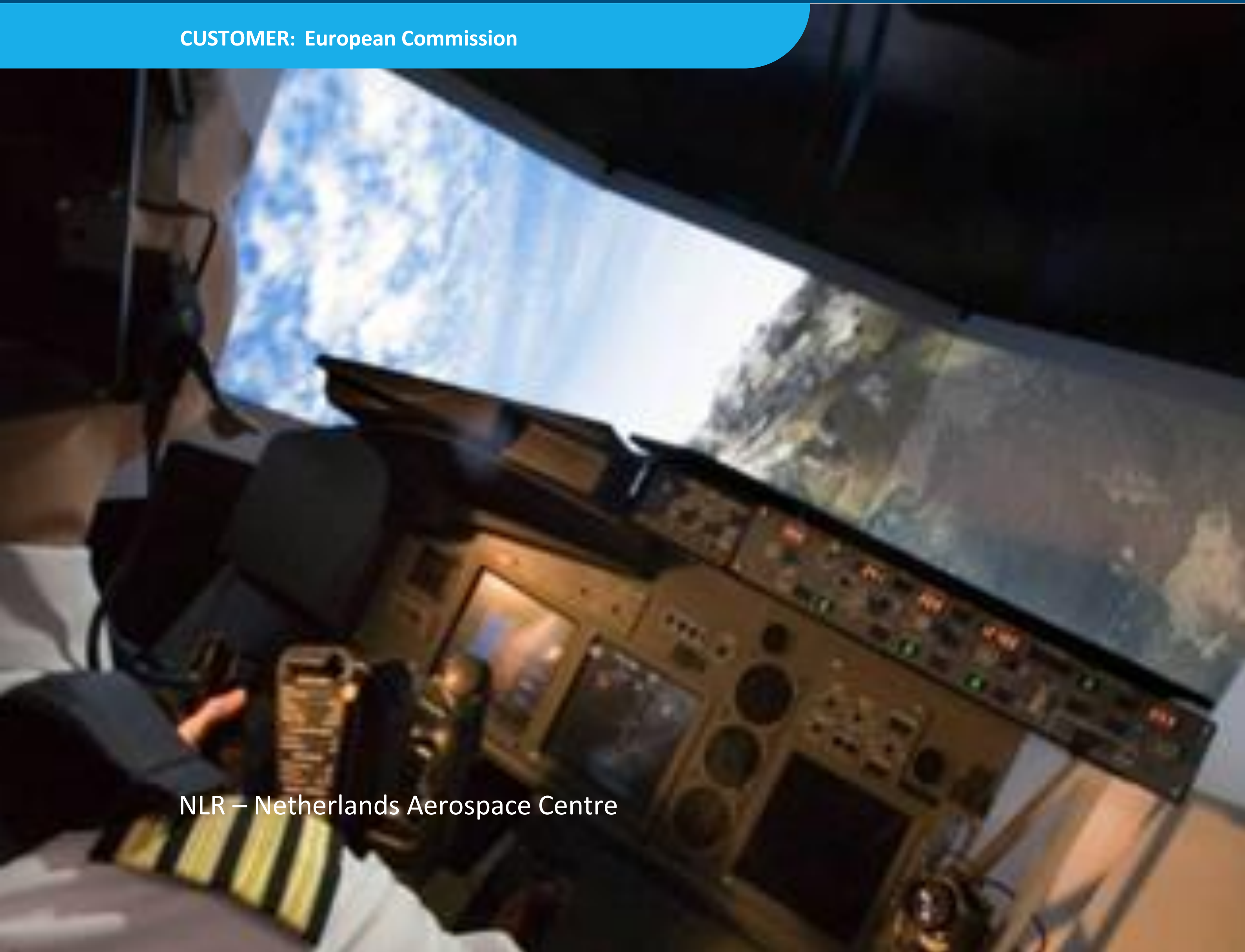

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EXECUTIVE SUMMARY

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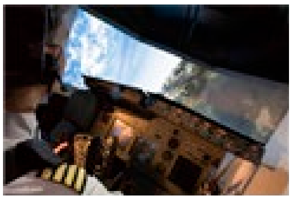

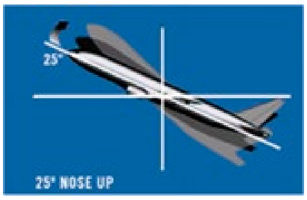

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AUTHOR(S)
M.H. Smaili
S.A.E. Nooij
M. Wentink
L. Zaichik
E.L. Groen

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Problem area

Loss of control in flight (LOC-I) remains one of the major sources of fatal accidents in commercial aviation over the last years. One of the significant factors leading to LOC-I is the entry of an aircraft into an upset, which refers to a situation in which an aircraft unintentionally exceeds the parameters normally experienced in line operations or training. Recovery to a stable flight path should be initiated as soon as a developing upset condition is being recognized. However, because many pilots lack the experience with such rare events, there is a risk that they fail to recognize the situation and/or are not able to recover in a safe way. In addition, pilots may be unfamiliar with the nonnormal control response of the airplane during aerodynamic stall, which may further complicate recovery. It is generally agreed that the availability of ground-based flight simulators capable of reproducing upset conditions can greatly contribute to upset prevention and recovery training (UPRT) programs for commercial pilots. However, today's commercially operated full flight simulators have several major limitations that should be taken into account when exercising UPRT. One of those limitations, apart from the aerodynamics model, is that the motion envelope of the conventional hexapod type motion platform (the so-called Stewart platform) is too limited to replicate the motion cues that occur during upsets.

Description of work

The European research project SUPRA (Simulation of Upset Recovery in Aviation) expanded the flight simulation envelope, by developing and assessing new simulator improvements including an improved aerodynamic model and novel motion cueing strategies. The SUPRA project addressed several motion cueing solutions, involving not only a hexapod-type platform, but also a more advanced, centrifuge-based motion platform, capable of replicating sustained g-loads that occur during certain upset recoveries. A test-pilot evaluation of both the SUPRA aircraft model and the SUPRA motion cueing solutions was conducted. Because the motion cueing solutions were developed for two very different simulators, with different very motion characteristics, motion envelopes, and cockpit environments, simulators were not compared against each other in the test pilot evaluation. Instead, the capabilities of each simulator were exploited to search for optimal solutions. Within each simulator the novel motion cueing solutions were evaluated against their respective baselines.

Results and conclusions

The SUPRA aerodynamic model was judged representative for a generic transport aircraft both inside and outside the normal flight envelope. Concerning the motion simulation the test pilots agreed that a hexapod simulator, with appropriate motion cueing, is suitable to appreciate and understand the aerodynamic behavior of the aircraft beyond the normal envelope. Nevertheless, despite improvements in motion filters, motions cues were not as pronounced as those obtained in the centrifuge-based platform. Experiencing the correct physical stimulation, and especially the g-loading during recovery, was found important. With careful selection of the scenario, centrifugation can be applied without unacceptable false cues. This way, commercial pilots can be exposed to realistic, highly dynamic, high-workload flight scenarios within the safe environment of the simulator. The test pilots concluded that a ground-based g-cueing device has added value for upset recovery training, which fills in the gaps identified by international authorities as ICAO and ICATEE.

Applicability

The results of the SUPRA project are applicable as complementary guidelines for flight simulator manufacturers and international authorities for certification and improvement of upset prevention and recovery training.

GENERAL NOTE

This report is based on a paper published in the AIAA Journal of Guidance, Control and Dynamics Special Issue on Aircraft Loss of Control, April 2017, by AIAA.

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AUTHOR(S):

M.H. Smaili	NLR
S.A.E. Nooij	Desdemona
M. Wentink	Desdemona
L. Zaichik	TsAGI
E.L. Groen	TNO

NLR - Netherlands Aerospace Centre

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Contents

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Motion Simulation of Transport Aircraft in Extended Envelopes: Test Pilot Assessment

S. A. E. Nooij* and M. Wentink†
Desdemona B.V., 3769 ZG Soesterberg, The Netherlands
H. Smaili‡
National Aerospace Laboratory, 1006 BM Amsterdam, The Netherlands
L. Zaichik§
Central Aerohydrodynamic Institute, Zhukovsky, Moscow Region 140180, Russia
and
E. L. Groen¶
TNO Human Factors, 3769 ZG Soesterberg, The Netherlands

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The European research project SUPRA ("Simulation of Upset Recovery in Aviation") produced an extended aerodynamic model for simulation of a generic transport aircraft, capturing the key aircraft behavior beyond aerodynamic stall. As described in the current paper, a group of 11 test pilots with in-flight experience in stall conditions assessed the validity of this aerodynamic model, in combination with new motion cueing solutions in a conventional hexapod platform as well as a centrifuge-based device. Results showed that the SUPRA model was considered representative outside the normal flight envelope, and on both simulators the enhanced cueing solutions received higher subjective ratings than the comparison condition. The pilots unanimously rejected exercising these conditions without motion. It is concluded that the SUPRA model successfully demonstrates upset conditions, including stall, and that conventional hexapod motion cueing can be improved for the purpose of upset simulation. If available, a ground-based *g*-device is recommended to provide *g*-awareness training.

I. Introduction

LOSS of control in flight (LOC-I) remains one of the major sources of fatal accidents in commercial aviation over the last years [1]. One of the significant factors leading to LOC-I is the entry of an aircraft into an upset, which refers to a situation in which an aircraft unintentionally exceeds the parameters normally experienced in line operations or training [2]. This generally includes inappropriate pitch attitudes (greater than 25° nose up or 10° nose down), bank angles (greater than 45°), or an airspeed inappropriate for the flight conditions [2]. Recovery to a stable flight path should be initiated as soon as a developing upset condition is being recognized. However, because many pilots lack the experience with such rare events, there is a risk that they fail to recognize the situation and/or are not able to recover in a safe way. In addition, pilots may be unfamiliar with the nonnormal control response of the airplane during aerodynamic stall, which may further complicate recovery [3].

It is generally agreed that the availability of ground-based flight simulators capable of reproducing upset conditions can greatly contribute to upset prevention and recovery training (UPRT) programs for commercial pilots [1,4,5]. However, today's commercially operated full flight simulators have two major limitations that should be taken into account when exercising UPRT [6]. First, the available aerodynamic models (i.e., the mathematical model describing the aircraft behavior in response to pilot inputs and external disturbances) have not been developed, or validated, outside the normal flight envelope. This may render the simulation unrealistic in the poststall regime. Second, the motion envelope of the conventional hexapod-type motion platform (the so-called Stewart platform) is too limited to replicate the motion cues that occur during upsets. The European research project SUPRA (Simulation of Upset Recovery in Aviation) expanded the flight simulation envelope, by developing an extended aerodynamic model, as well as novel motion cueing strategies. The SUPRA-extended aerodynamic model is built onto a data package representing a generic transport aircraft, and reproduces the typical behavior of a transport aircraft at high angles of attack (AoA) and sideslip [7,8]. It captures the longitudinal and lateral instabilities, and degraded controllability. Its adjustable parameters allow for simulating various types of departures, as described in previous papers [7,8].

The current paper addresses SUPRA's motion cueing solutions, involving not only a hexapod-type platform, but also a more advanced, centrifuge-based motion platform, capable of replicating sustained *g*-loads that occur during certain upset recoveries. This paper concludes with the results of the test-pilot evaluation of both the SUPRA aircraft model and the SUPRA motion cueing solutions. Because the motion cueing solutions were developed for two very different simulators, with different very motion characteristics, motion envelopes, and cockpit environments, simulators were not compared against each other in the test pilot evaluation. Instead, we took advantage of the differences between the simulator facilities and exploited the capabilities of each simulator to search for optimal solutions. Within each simulator the novel motion cueing solutions were evaluated against their respective baselines.

II. Motion Cueing Challenges

The SUPRA project included an analysis of the typical aircraft motions occurring in various upsets: recoveries from nose-high or nose-low attitudes; symmetric, wings-level stalls; and asymmetric stalls involving a wing drop [9]. The magnitudes and frequency ranges of the typical motion cues occurring in the different scenarios

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*Sr. Research Scientist; suzanne.nooij@tuebingen.mpg.de.

†Technical Director; mark.wentink@desdemona.eu.

‡Sr. R&D Engineer, Training, Simulation & Operator Performance; hafid.smaili@nlr.nl.

§Head of Section; zaichik@tsagi.ru. Member AIAA.

¶Sr. Scientist, Perception and Cognition; eric.groen@tno.nl. Member AIAA.

were estimated based on expert analysis and experience with flight tests at the Gromov Flight Research Institute (Zhukovsky, Russia) [9], as well as simulations performed with the SUPRA aerodynamic model [10]. The results showed that especially the fully developed stalls involve strong motion cues that may exceed the capabilities of conventional flight simulators. For the angular degrees of freedom (DoF) the minimal motion frequency is around 1–2 rad/s, with pitch and yaw rates up to 10–15°/s. Roll rates up to 20°/s were observed for fully developed symmetric stalls, and up to 60–100°/s for asymmetric stalls. For comparison, the maximum roll rate of a typical simulator is around 30°/s. Stall recoveries also involved pronounced variations in g-load, that is, the acceleration along the aircraft's normal axis. g-loads lower than $1g$ (about $+0.5g$, or even lower) typically occur during the unloading of the aircraft, which is achieved by pushing forward on the controls so as to lower the nose and reduce AoA [9]. Increased g-loads occur during "loading" of the aircraft, which is needed to recover from a nose-low attitude, and is achieved by pulling on the controls for several seconds. The g-load can go up to the limit load of the aircraft, which is $+2.5g$ for Part 121–certified transport aircraft in clean configuration. Teaching pilots how to estimate the load limit is important so that they do not overstress the airframe, or have a delayed recovery.

As mentioned above, current full flight training simulators operate hexapod-type motion platforms. The motion driving algorithms that transform aircraft motion into simulator motion commonly consist of classical washout filters [11,12], which scale and filter the aircraft motion to fit it to the simulator workspace. Although many studies investigated methods to improve the classical washout filter and the selection of the filter parameters (e.g., adaptive coordinated washout [13,14], optimal control [15,16], or predictive algorithms [17]), most commercial training simulators still use the classical washout scheme with filter settings that are typically tuned for a broad range of maneuvers within the normal flight regime. This approach does not fully exploit the simulator motion space, and may result in too conservative motion settings for specific maneuvers involving larger aircraft motions. This was demonstrated previously for the simulation of the lateral acceleration occurring during a decrab maneuver on landing with crosswind [18]. As the same problem may also occur with the simulation of upset maneuvers, the SUPRA project investigated whether the motion space of a conventional hexapod platform can be improved by maneuver-specific tuning of its washout filter. This approach is referred to here as "workspace optimization." (Note that the term *optimization* indicates a general improvement rather than optimization in the mathematical sense.) However, because of the limited stroke length, hexapod-type platforms can generate linear accelerations only for a very brief period. Hence, they are not suitable to reproduce sustained g-loads that accompany upset recoveries. For example, a stall recovery can involve a normal load of $+2.5g$ lasting for 8–10 s, whereas a hexapod system with an actuator stroke of 1.8 m and typical motion filter reaches its limits in 0.7 s. A recent study of Ledegang et al. [19] illustrated the importance of presenting pilot with the physical g-load during the simulation of upset recovery. When the g-load was *not* reproduced by the simulator — as in a conventional hexapod flight simulator — airline pilots tended to overload the aircraft, and exceed the limit load. On the other hand, when the g-load was reproduced by means of centrifugation, the pilots did not load the aircraft enough for an efficient recovery. Presenting pilots with representative g-cues during recovery is therefore believed to be of great value in simulator training of upset recovery. Therefore, the other optimization approach within SUPRA focused on using a centrifuge-type simulator to reproduce the sustained g-loads. Currently, special ground-based g-cueing devices are available with a main purpose of demonstrating spatial disorientation effects to pilots [20]. The DESDEMONA facility (DESorientation Demonstrator Amst) is such a device, and it was used within SUPRA to investigate how its centrifuge capability can be used to generate g-loads while minimizing the false cues, such as tumbling sensations, that typically occur in centrifuges [21]. This approach will be referred to as "centrifuge optimization."

In addition to the maneuver-based motion cueing development, special attention was paid to realistic replication of the aerodynamic buffet occurring when the aircraft approaches maximum AoA, which can provide the flight crew with an important cue to recognize the impending stall.

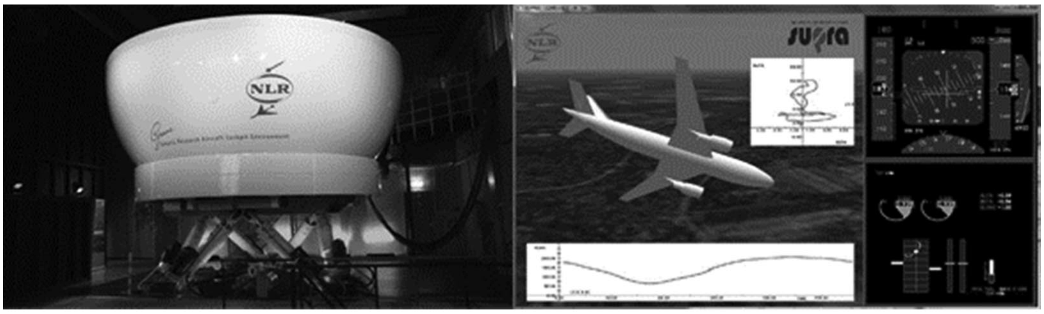
III. Simulator Facilities

The NLR simulator facility used was the Generic Research Aircraft Cockpit Environment (GRACE) [22] (Fig. 1a). Its electrically driven hexapod motion platform (Bosch-Rexroth, The Netherlands) allows for excursions of ±0.55 m in surge and sway ($a_{\max} = 6\ \mathrm{m/s^2}$) and ±0.44 m in heave ($a_{\max} = 8\ \mathrm{m/s^2}$). Pitch and roll excursions are ±17° ($\omega_{\max} = 30°/\mathrm{s}$), whereas the yaw excursion is ±22° ($\omega_{\max} = 40°/\mathrm{s}$).

For the SUPRA experiments GRACE's flight deck was configured as a Boeing large transport aircraft type (e.g., B767, B777, and B747). The simulator's electronic control loading system comprised a column/wheel, pedals, and a throttle station. Control loading characteristics were representative for a large Boeing transport aircraft, and included stick-shaker dynamics. The visual system comprised a four-window collimated CGI system, offering each pilot a field of view of 89° (horizontal) and 27° (vertical). As shown in Fig. 1b a dedicated visualization tool was developed at NLR to facilitate the evaluation of the aerodynamic model and aircraft motion. The example in Fig. 1b shows an upset recovery maneuver of the SUPRA model and flight envelope graph with AoA excursions up to 20° and sideslip up to minus 3° and 4°.

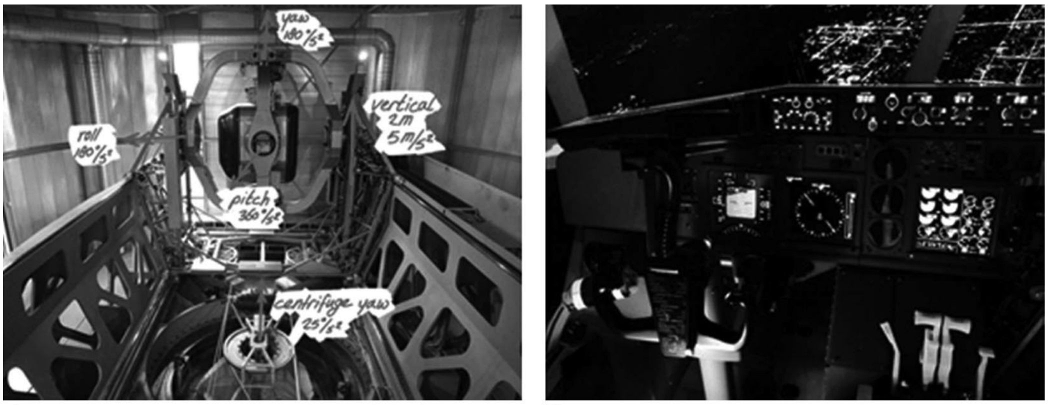
The DESDEMONA facility (manufactured by AMST Systemtechnik Gmbh) at TNO (Soesterberg, The Netherlands) combines a centrifuge with a gimbaled cabin, enabling the reproduction of sustained g-loads, sustained and/or high angular rates, as well as high angular accelerations that could occur during upsets (Fig. 2). The cabin is capable of rotating >360° about any axis in space ($\omega_{\max} = 180°/\mathrm{s}$), and is mounted on a linear motion base allowing for vertical (2 m) and horizontal motion (8 m). In both planes, maximum linear acceleration is $4.9\ \mathrm{m/s^2}$. The whole system can be rotated about a main centrifuge axis, generating a maximum g-load of $3g$ when the cabin is positioned at the end of the horizontal track. A detailed description of the simulator is provided in [23].

For SUPRA the cockpit was configured with a captain-side B737 instrument panel and throttle quadrant. Control loading, including stick shaker dynamics, was present on the wheel/column. The



a) b)

Fig. 1 GRACE hexapod simulator (a) and the visualization tool for the assessment of the aerodynamic model and aircraft motion (b).



a) b)

Fig. 2 DESDEMONA simulator in the neutral position (A). The pilot in the cabin is facing to the left. Panel B shows an impression of the 737NG style cockpit (left seat only) inside the cabin.

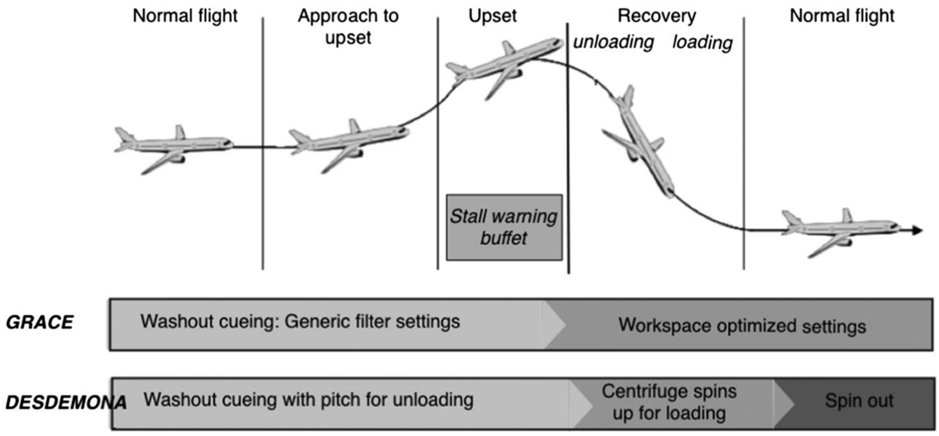


Fig. 3 Overview of the flight phases and the motion cueing regimes for the workspace optimized cueing (GRACE) and the centrifuge cueing (DESDEMONA).

instrument panels were modeled after a B737NG and displayed on three monitors integrated in the cockpit panel. A PC-based computer-generated image system was used to render the outside visuals. In the cabin, three computers generated real-time images with an update rate of 60 Hz. Five projectors (resolution 1024×768 pixels) projected the image on a three part flat screen, placed approximately 1.5 m from the eye reference point, creating an out-of-the-window field-of-view of about 180° horizontally and 32° vertically.

IV. Novel Motion Cueing Solutions

The development of the new motion cueing strategies was based on the assumption that each scenario followed a well-defined structure. Because the initial development of the upset scenario was predetermined, the movement of the aircraft and hence the required motion cues were also predetermined. This allowed us to optimize the motion cueing algorithms for each specific phase in each specific scenario, with smooth fading in between the different motion cueing regimes. Figure 3 gives an overview of the different phases, and the combination of different motion cueing regimes within one scenario. Detailed information is provided in the following sections.

A. Workspace Optimization for Hexapod Simulator

A modular concept was developed that enabled smooth fading between the classical washout filter settings for normal flight and the stall-specific filter settings, which were applied during the stall and its recovery (Fig. 3). The transition from normal flight to stall-specific parameters occurred during approach to stall, and the onset of the aerodynamic buffet. The maneuver-specific filter settings were obtained by first identifying the main motion components for each phase of the SUPRA upset scenarios [10], and subsequently prioritizing simulator motion in the corresponding degrees of freedom [24]. For the selected scenarios (see Sec. V.C) the prioritized axes were heave and sway (to enhance normal g-loading and lateral roll-off cues) and, depending on the stall type, pitch and roll (for symmetric or asymmetric stalls, respectively). The washout filter settings were tuned for the prioritized DoF, using both objective and subjective methods, where the default filter settings for the normal flight regime were used as a starting point (see Table 1). In the offline objective tuning the gains, damping factors and cutoff frequencies of the four prioritized axes (heave, sway, pitch, and roll) were adjusted to provide better step/sinusoidal responses while staying inside the GRACE motion workspace. The other parameter settings remained the same. The offline-tuned setting was then fine-tuned by two experienced test pilots during three piloted sessions in the GRACE simulator. Both pilots were experienced test pilots familiar with real-aircraft upsets and stall buffets, which allowed subjective assessment of the representativeness of the optimum motion cueing algorithm (MDA) for the relevant stall upset maneuvers. Filter settings for both normal flight and stall are summarized in Table 1.

The effect of the new filter settings is illustrated in Fig. 4, showing the replication of the lateral force and roll rate for a level wing stall with roll-off. The motion reference point was at the level of the pilot's head. The time traces of the optimized filter produced lateral specific forces and roll rates that better match those of the aircraft model than the original motion filter.

B. Centrifuge-Based Optimization

For the DESDEMONA simulator a motion cueing scheme was developed that resembled a hexapod platform, while also utilizing the simulator's unique motion capabilities. This will be referred to as the

Table 1 Conventional washout filter settings for normal flight and optimized for stall

Filter parameter	Flight phase	High-pass rot. acc. (φ, θ, ψ)	High-pass lin. acc. (x, y, z)	Low-pass lin. acc. (x, y, z)
Gain	Normal flight	0.5	0.5	0.5
	Stall optim.	0.85 (φ, θ)	1.0 (z)	— —
Cutoff freq. [Hz]	Normal flight	0.0625	0.25	0.8
	Stall optim.	0.0795 (φ, θ)	0.75 (y)	— —
Damping coeff.	Normal flight	2.0	2.0	1.0
	Stall optim.	1.0 (φ, θ)	1.5 (z)	— —
Tilt rate limit [rad/s^2]	Normal flight	n.a.	n.a.	0.0349
	Stall optim.			— —

Note: Stall optimized parameters are only indicated for the DoF to which they apply; otherwise parameters are equal to those for normal flight.

adapted washout mode. This mode was combined with centrifugation (i.e., centrifuge mode) during recovery (see Fig. 3).

1. Adapted Washout Mode

The DESDEMONA simulator has six cascaded DoF. This makes it possible to accelerate the cabin upward (heave), forward (surge) and in pitch, roll, and yaw. Because the cabin was locked at a radius of 4 m in the 3G-centrifuge mode, the cabin could not be accelerated sideways (sway) along the radial track. Therefore, the adapted washout mode used five axes to generate acceleration onset and tilt cues: heave, surge, pitch, roll, and yaw. Surge was generated using centrifuge yaw acceleration (simulator cabin is positioned 4 m from the center) with simultaneous counterrotation of the cabin yaw. Motion limits in the adapted washout mode are shown in Table 2.

The motion filters that were designed for the adapted washout mode are based on the classical washout structure, producing a sum of high-pass-filtered onset cues, and tilt coordination cues to render sustained accelerations [12,13]. However, instead of a single-input/single-output (e.g., acceleration) second- or third-order high-pass filter used in conventional washout, the filter structure in DESDEMONA takes position, velocity, and acceleration as inputs, and combines them into a single output (acceleration, which is then integrated to output position and velocity). All motion channels in DESDEMONA use this new filter. Basically, the filter consists of a second-order low-pass filter from input to output position. The input velocity and acceleration are fed into the low-pass filter as feed-forward signals. As a result, the transfer of input to output position has a low-pass characteristic, and the transfer of acceleration has a high-pass characteristic. Therefore, this filter structure is well suited to combine prepositioning signals with acceleration onset cues into a single coherent output to drive each simulator DoF.

When the input position, velocity, and acceleration are coherent (integrals of acceleration), the output of the adapted washout filter is exactly equal to the input (one-to-one transfer). If the position and velocity signals are set to zero, then the transfer function of the filter is equal to a second-order high-pass filter. However, in the SUPRA adapted washout cueing the position input was a prepositioning signal to enhance the normal g-loading motion cues. The prepositioning signal was determined by a look-up table for the vertical specific force from the aircraft model. The simulator moved down (to

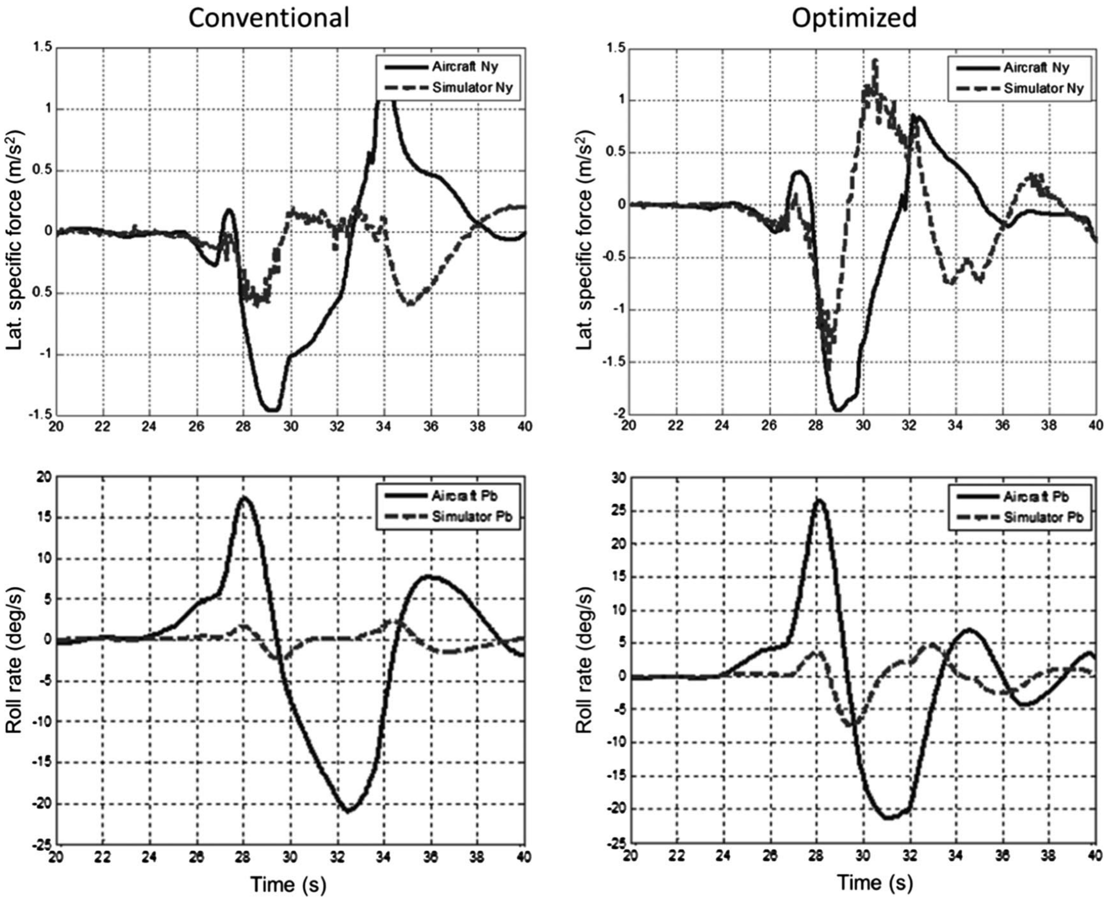


Fig. 4 Example time traces showing lateral specific force during wings level stall entry and roll-off for conventional filter settings (left) and SUPRA optimized filter settings (right).

Table 2 Operational limits in the DESDEMONA adapted washout mode

DoF	Acceleration (m/s^2, $°/s^2$)	Velocity (m/s, $°/s$)	Position (m, °)
Surge, m/s^2	1.75	5 m/s	Inf. (no washout)
Sway, m/s	Tilt coordination only (no rate limit)		
Heave, m	5	2.2	±0.9
Cabin roll, deg $/s^2$	90	90	±60
Cabin yaw, deg $/s$	45	30	±90
Cabin pitch, deg	60	45	±60

a minimum of -0.9 m at $0.5g$) in the case of unloading, and up in the case of loading the aircraft (to $+0.9$ m at $1.7g$).

In addition to prepositioning, the perception of loading and unloading of the aircraft was further improved by a so-called g-load tilt mechanism. Using the normal g-load of the aircraft the pitch gimbal of the simulator was driven to a maximum of 30° nose up for loading and 30° nose down for unloading. This technique is similar to tilt coordination, where cabin pitch of the cabin is used to generate a sensation of *longitudinal* acceleration. During testing of the SUPRA g-load tilt mechanism it appeared that pitching up or down supports the perception of loading and unloading, respectively (see also Sec. VII). It was decided to incorporate this cabin tilt algorithm in the adapted washout mode.

The washout filter structure that drives the DESDEMONA pitch gimbal is shown in Fig. 5. It uses aircraft pitch acceleration ($\dot{\omega}_{yair}$), plus the longitudinal (f_{xair}) and vertical specific force (f_{zair}). The latter input is related to the g-load tilt mechanism, and adds to the simulator tilt required for the simulation of sustained longitudinal acceleration (normal tilt coordination). The resulting tilt signal is combined with the pitch acceleration signal in the washout filter block to generate the simulator pitch commands (θ_{sim}, $\dot{\theta}_{sim}$, $\ddot{\theta}_{sim}$).

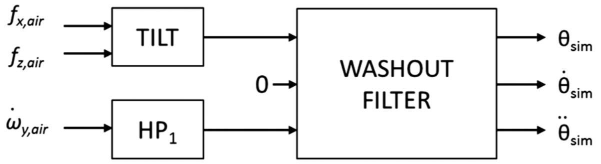


Fig. 5 Simplified schematic of the pitch cueing in DESDEMONA.

Figure 6 shows an example time response of the pitch washout filter and the effect of the g-load tilt mechanism. The left column shows the simulator response when the g-load tilt mechanism is inactivated for a simple pitch-step maneuver up to about 10 deg nose up and back again. The lower left panel shows that the tilt mechanism renders longitudinal specific force close to that in the aircraft. The right column shows the simulator response when the g-load tilt mechanism is enabled (as was the case in the current study). Here a maneuver is shown in which the pilot first unloads the aircraft, and then loads it to get the aircraft back to level flight (similar to a stall recovery). It can be seen in the lower right plot that, instead of actually increasing and decreasing the vertical specific force, the resulting *longitudinal* force is used to add body pressure into the back of the seat (loading), or body pressure against the seatbelt (unloading). Although these cues are normally used for simulating acceleration and deceleration, our findings imply that the way these cues are being perceived by the pilot largely depends on the context, for example, the flight maneuver and control inputs (e.g., whether he or she is applying power or pulling the yoke). Figure 6 shows that the simulated longitudinal force is highly correlated with the vertical specific force in the aircraft (in shape, not amplitude). As a consequence of the tilt mechanism, the pitch rate is larger in the simulator (top right panel) than in the aircraft, although the timing of the onsets is still correct. In an aircraft, the g-onset is determined by the pitch onset (and true airspeed).

2. *Centrifuge Mode*

During centrifugation the g-load is a function of rotation speed and radius. The latter was fixed at 4 m during SUPRA. Similar to common

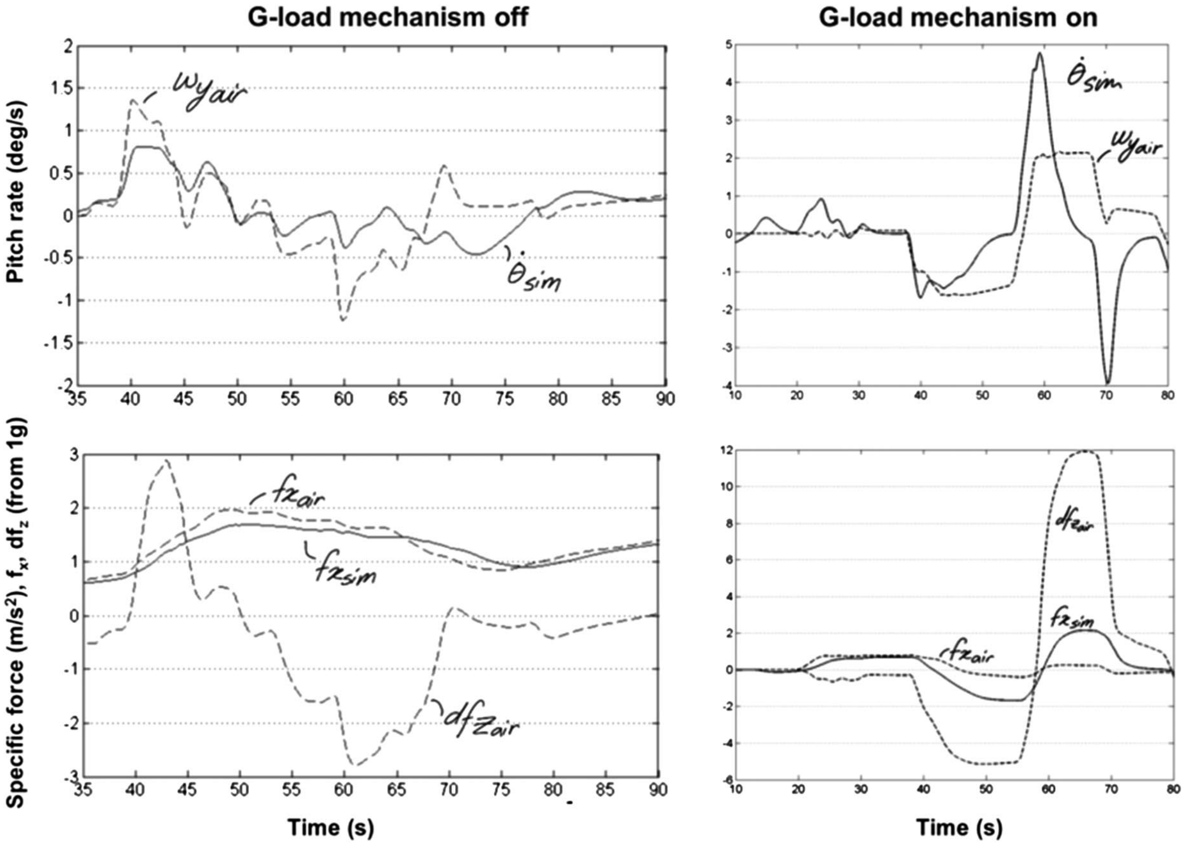


Fig. 6 Behavior of the pitch washout filter (depicted in Fig. 5) with the g-load tilt mechanism off (left column) or on (right column).

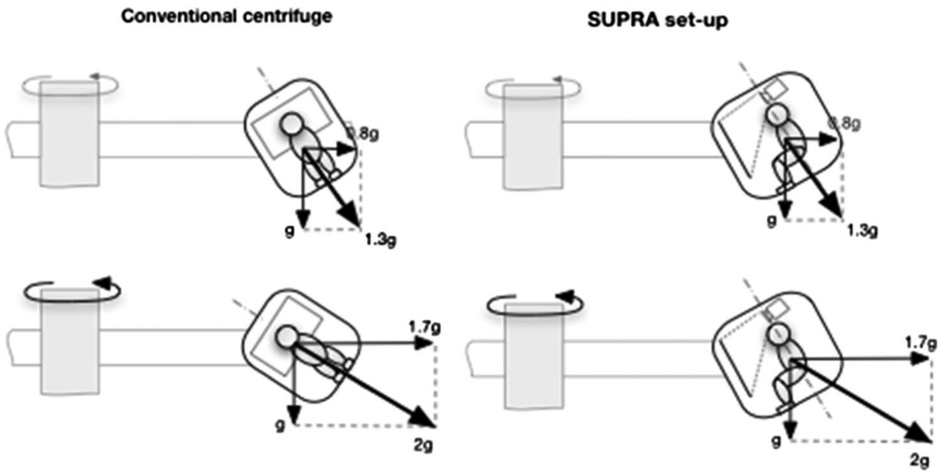


Fig. 7 Conventional centrifugation, using continuous cabin alignment with the total specific force (left), and the new configuration (right), with the pilot facing inward at a fixed attitude.

centrifuge-based flight simulation, the DESDEMONA centrifuge did not start from standstill, but was brought to a baseline rotation to enhance its responsiveness. The baseline rotation provided a new gravitational reference of $1.3g$, from which unloading and loading were simulated by decelerating and accelerating the centrifuge, respectively.

Usually, in centrifuge-based flight simulation the pilot is facing the direction of rotation (i.e., facing the tangent of the circle; see Fig. 7, left column), and the orientation of the cabin is continuously being aligned in the roll plane with the direction of the total specific force (see Fig. 6 left column). The latter is a major disadvantage of centrifugation as it induces strong tumbling sensations during head movements of the pilot, or during the alignment of the cabin with the specific force vector. In the SUPRA centrifuge motion cueing two measures were taken to minimize the tumbling sensation. First, the duration of centrifugation was minimized by having the centrifuge rotate only when needed, and, second, the orientation of the cabin remained fixed during centrifugation, with the pilot not facing the direction of motion, but looking inward (Fig. 7, right column). At the start of the scenario, all motion cues were provided by the washout cueing mode (Fig. 3), until the approach-to-stall and the buffet motion was initiated. The buffet motion was generated by the heave system (see Sec. IV.C). During this phase the pilot was still oriented tangentially to the centrifuge arm. Then the cabin was rotated slowly inward (i.e., with the pilot facing to the centrifuge axis), and the centrifuge was slowly accelerated to a baseline rotation. When the pilot initiated the recovery and unloaded the aircraft, the cabin pitched down to simulate unloading, according to the g-load tilt mechanism. This pitched-down orientation (40°) was then *maintained* for the entire recovery phase, during which the centrifuge speed was adjusted to provide the normal g-load exerted on the aircraft. Perfect alignment with the total specific force occurred at a g-load of $1.3g$ (see Fig. 7). After the loading phase the simulation was ended, and the centrifuge was slowly decelerated to standstill.

Pitching the cabin down in the transition phase served two purposes. It was used to generate a sensation of unloading, and at the same time, it put the cabin in a proper orientation during centrifugation. Keeping the cabin in fixed orientation prevented the disorientating cross-coupling effects, but came at the price of misalignment of the total specific force vector at g-loads different from $1.3g$.

C. SUPRA Stall Buffet Module

The current requirements for aerodynamic buffet simulation in a training simulator specify that the stall buffet onset must be matched with aircraft data [25]. The threshold for stall buffet onset used in the simulator is typically $\pm 0.5g$, which matches the aircraft certification initial buffet threshold. This is the AoA at which the buffet exceeds $\pm 0.5g$. However, the International Committee for Aviation Training in Extended Envelopes (ICATEE) working group has identified that this threshold may be too high and recommended a value of $\pm 0.03g$. Moreover, they indicated that the dependency of buffet amplitude on AoA is an important cue for recognition, which commonly is not accounted for. The dependency of buffet frequency on the AoA has been identified as a less critical cue. For both simulators a buffet module was developed that took these requirements into account. It was based on the assumption that increasingly higher frequency vibrations of the airframe are excited with an increasing AoA. The frequencies are harmonics, and the different amplitudes were subjectively tuned by a highly experienced test pilot, who was flying the simulator in and out of stalls. This resulted in a buffet model of which the amplitude was linearly dependent on the AoA (see Fig. 8), and that was representative for the class of aircraft under consideration.

V. Test Pilot Evaluation

The test pilot evaluation consisted of two parts. In the first part, the aerodynamic model was evaluated, both within and outside the normal flight envelope. The second part focused specifically on the motion cueing solutions. Before the experiment motion cueing algorithms, buffet motion, and the SUPRA aircraft model parameters were fine-tuned by a highly experienced test pilot, and two flight test engineers from the GROMOV Research Flight Institute (Zuykovsky, Moscow). These experts were excluded from the formal evaluation described below.

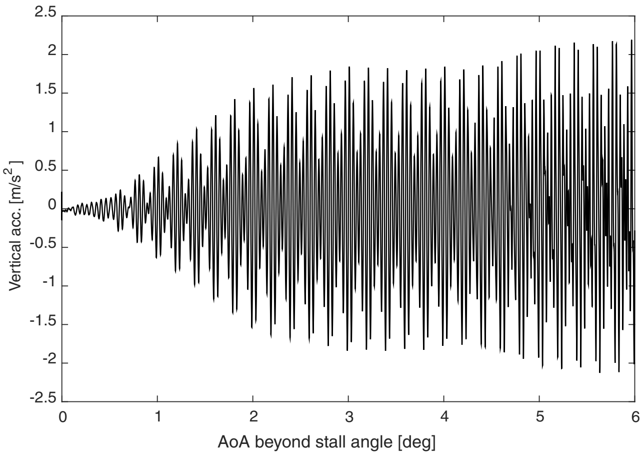


Fig. 8 Buffeting profile.

A. Participants

In total 11 highly experienced pilots, aged between 42 and 59 years, participated in this evaluation trial. They were either test pilots ($n = 7$), or experienced line pilots ($n = 4$) with type ratings on various Boeing, Airbus, or Fokker transport aircraft. All test pilots and one of the line pilots had inflight experience with upsets/stalls in transport aircraft ($n = 8$). The three line pilots without such inflight experience were involved in upset recovery training. All pilots had aerobatic experience. The total number of flight hours ranged between 7200 and 22,000 (average $= 12,800$ h). From all pilots, eight participated in the evaluation on both simulators, whereas two only evaluated DESDEMONA, and one pilot only evaluated GRACE.

B. Aerodynamic Model Evaluation

The modeled aircraft represented a commercial airliner in conventional configuration, with a maximum take-off weight of approximately 100 tons, having under-wing-mounted engines and a fuselage-mounted horizontal tail. The model was reconfigurable, meaning that a variety of representative upset behaviors could be achieved by modification of a limited number of parameters [7,8]. This allowed for implementation of the different upset scenarios (see next paragraph and Appendix A).

After briefing the pilots on the purpose of the study and the experimental procedures the pilots were familiarized with the simulator and the cockpit. Then the pilots first assessed aircraft behavior and handling for maneuvers within the normal flight envelope, and also three unusual attitude scenarios for which the AoA remained within the validated envelope. Subsequently, they evaluated scenarios outside the normal flight envelope, consisting of 1) approach to symmetric (i.e., level) stall; 2) approach to asymmetric stall; 3) developed symmetric stall with mild or nonexistent roll instability; and 4) developed asymmetric stall with mild and severe roll-off. All scenarios were taken from the Airplane Upset Recovery Training Aid (AURTA) and were performed with different entry conditions (see Appendix A). It was explained to the pilot that these different stall types were preset by the experimenter (by changing specific parameters in the model), and could represent different aircraft conditions (e.g., wing deformation, wing icing). It was also explained that the developed stall scenarios were included to demonstrate the behavior of the aircraft when no timely recovery was initiated. To evaluate whether the aircraft behavior was representative or not for the simulated class of aircraft, the pilots rated a set of specific items (representative Y/N?), which are summarized in Appendix B. They also indicated whether they found the scenario cluster valuable for training purposes by giving a rating on a three-point scale (highly, somewhat, or not relevant). After all exercises, the pilots gave an overall judgment on the aircraft model according to the four-point rating scale in Table 3, column A. During evaluation of normal aircraft behavior the simulator was operated in fixed base mode; otherwise, washout cueing was provided (conventional washout for GRACE and the adapted washout for DESDEMONA).

C. Motion Evaluation

Four representative stall scenarios were selected for the motion evaluation (see Appendix A). These included two symmetrical stalls with nonexistent or mild roll instability and two asymmetrical stalls with a mild (~45°) and severe roll-off (60–90°) to the right. The pilots were unaware of the preset roll-off direction. As will be explained further in the Sec. VII, the direction of the roll-off was related to the direction of the centrifuge rotation in the centrifuge based, as preliminary testing showed that rightward roll-offs induced less false cues than leftward roll-offs during counterclockwise centrifugation.

To start the maneuver the pilot set up the conditions for one of the four scenarios following a prescribed entry procedure. In the next phase (upset) the stick shaker, aircraft buffet motion, and stall warning alerted the pilot that the aircraft was stalling. The pilot was instructed to initiate recovery at an audio signal that was presented when the AoA reached a value of 15°. Note that no AoA or g-load indicators were visible to the pilot because they are also not available in many aircraft. The pilot was instructed to recover following the usual procedures, by unloading the aircraft to reduce AoA, rolling the aircraft back to wings level (if required) and subsequently load the aircraft to regain a normal pitch attitude, and adjust power to arrive at a normal airspeed.

Each scenario was flown with each different motion cueing algorithm. For GRACE this was the conventional washout cueing using conventional versus optimized filter settings, and for DESDEMONA this was the washout cueing without and with centrifugation in the recovery phase. As a control condition, half of the pilots also performed the evaluation in fixed base mode on the DESDEMONA simulator, with only the buffet motion present. The pilots always started with the symmetric stalls and ended with the two asymmetric scenarios. Within each scenario, motion cueing conditions were presented in random order.

For each scenario–motion cueing combination the pilot gave two general ratings that captured the overall characteristics of the motion cueing condition for that particular scenario. The first rating assessed the overall replication of the key motion cues for that specific maneuver, following the four-point scale shown in Table 3, column B. Here, key motion cues were defined as cues that are present in the actual aircraft and that should be felt (with appropriate strength) during the simulation. The second general rating assessed the overall presence of false cues, or inaccuracies, following the four-point scale shown in Table 3, column C. Inaccuracies were defined as cues that are *not* present in the actual aircraft, but are felt during simulation, for example, the feeling of the cabin moving back to its neutral position in the washout cueing or the centrifuge spinning up in the centrifuge cueing. It also included any inaccuracies in timing or dynamic behavior of the felt motion (i.e., motion cue coming too late, or building up too slow, etc.).

In addition to these overall ratings, more detailed ratings were provided on the appropriateness of the strength of the various motion cues, using a five-point scale ranging from -2 (too weak) to $+2$ (too strong). For the symmetrical scenarios, pitch and only the strength of the pitch cue and the normal g-load were evaluated, whereas for the

Table 3 Rating scales to express the overall acceptability for the aerodynamic model (A), the presence of the key motion cues (B), and the presence of false cues (C)

Rating	A) Aeromodel	B) Key motion cues	C) False cues	Acceptability
1	Representative of the class of airplane, minimal pilot adaptation required	Motion cues are equivalent to real airplane	False motion cues are not perceivable	Acceptable
2	Mostly representative of aircraft class, requires minor pilot adaptation	Key motion cues are present with similar magnitude and dynamics, i.e., are acceptable for training purposes	Some false cues are perceivable but do not adversely affect pilot experience of the maneuver	
3	Marginally representative of aircraft class, significant adaptation is required	Some key motion cues are not recognizable; modifications need to be made to be acceptable for training	Considerable false cues are present and mask key motion cues or considerably alter the experience of the maneuver. May cause slight discomfort	Not acceptable
4	Not representative of aircraft class, extensive adaptation is required	Key motion cues are not present	False cues are dominating and may cause unacceptable physical discomfort and entirely distract the pilot	

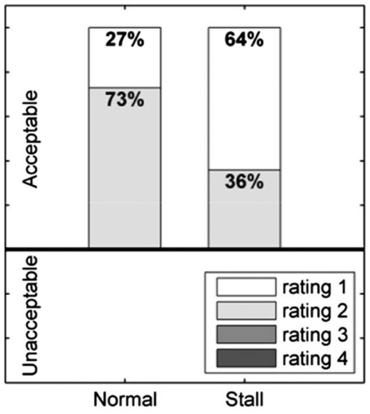


Fig. 9 Distribution of overall acceptability ratings ($n = 11$) for the aircraft behavior in the normal flight envelope (normal) and in the stall region (stall).

asymmetrical scenarios, roll and side force were also included. Inaccuracies or false cues were further specified verbally and individually rated on a similar scale. The reference for the magnitude and inaccuracy ratings was the aircraft motion as indicated by the flight instruments. After completing all motion cueing conditions for each scenario, the pilots indicated motion cueing preference by ranking.

VI. Results

A. Aerodynamic Model Evaluation

The distribution of the overall ratings for the SUPRA aircraft model is shown in Fig. 9, for the behavior both in the normal flight envelope and in the stall region. Ratings were comparable for the two simulators. The acceptable range in the figure (ratings 1 and 2; see Table 3, column A) qualifies the model's features for simulation and training, whereas the ratings 3 and 4 disqualify the model for simulation applications. Regarding aircraft behavior in the normal flight envelope, 27% of the pilots gave the best possible rating of 1, whereas the remaining 73% scored a rating of 2. The expert pilots agreed that the model exhibited acceptable normal basic flying qualities, comparable to a midrange wide-body aircraft (e.g., B737 to B777). Nevertheless, they indicated that there can be type-specific differences on certain aspects. For example, one comment was that the model was less sensitive in power/pitch relationship than some aircraft types, which can have an effect on upset recovery performance. Other comments concerned some lack of static stability, or somewhat slow recovery pitch rates.

The focus of the project lied, however, in extending the model to maneuvers outside the normal flight envelope. For these maneuvers, the model was rated with a score of 1 by 64% of the pilots, whereas 36% scored a 2. This indicates that all pilots found the SUPRA aircraft model representative for the class of simulated aircraft, capturing the key characteristics of aircraft behavior in the stall region. The aerodynamic buffet was also highly appreciated, and considered important for upset training. The SUPRA buffet simulation was considered better than buffet reproduction in conventional simulators, although buffet intensity was sometimes rated as too mild or too severe, depending on the experience of the test pilot with a particular aircraft. Buffet ramp and rate were found adequate. The scenarios flown were rated as being “highly relevant for training” in 82% of the cases. In the remaining 18%, the rating “somewhat relevant” was given.

B. Motion Cueing Evaluation

The results for the motion cueing evaluation for both simulators are summarized in Figs. 10 and 11. Figure 10 provides the distribution of

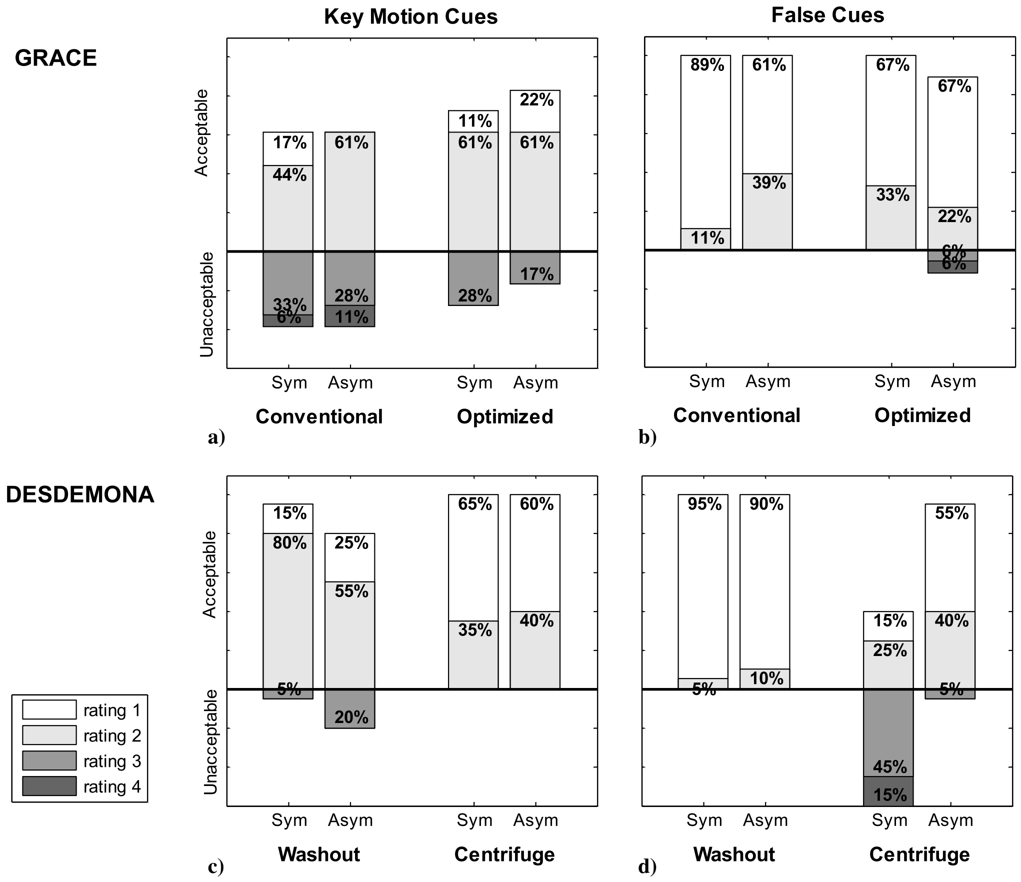
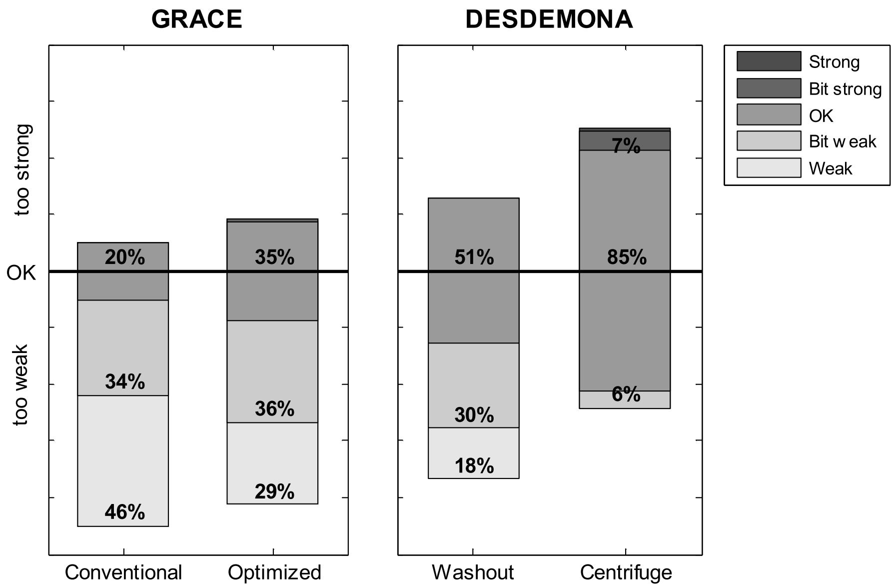


Fig. 10 Distribution of key motion cue ratings and false cue ratings for the two simulators, grouped per motion cueing condition and stall type (sym. vs asym).



a)

b)

Fig. 11 Distribution of motion strength ratings for the different motion cueing conditions. Values are collapsed over all motion cues and stall types.

the overall acceptability ratings regarding the reproduction of key motion cues (left column) and the presence of false cues (right column), for the symmetric and asymmetric stalls. Note that a score of 1 indicates the best possible rating, and a score of 1 or 2 is considered as acceptable (see also Table 3). Ratings for motion strength are tabulated in Appendix C and summarized in Fig. 11.

On the GRACE hexapod simulator, the pilots compared the washout cueing using conventional filter settings ("conventional") versus the workspace-optimized filter settings ("optimized"). When asked during the debriefing, pilots generally considered the conventional washout cueing representative of the industrial baseline used for pilot training. However, as expected, this cueing did not always adequately render the key motion cues. As can be inferred from Fig. 10a, for the conventional cueing 61% of the pilots gave a score of 1 or 2 for the overall rating for the key motion cues when both stall types are combined (i.e., $[44 + 17 + 61]/2$). This amounted to 78% in the workspace-optimized condition, which was a statistical significant improvement (Wilcoxon signed rank test, $z = -2.36$, $p = 0.018$). In line with this, Fig. 11a (see also Appendix C) shows that as a result of the workspace optimization a larger part of the motion cues was rated as being of appropriate strength, instead of too weak. When comparing the ratings on the different degrees of freedom, it was clear that this was mainly because of improvements in the lateral cueing (roll, side force), where 73% of the cases were rated as appropriate, versus 26% for the conventional washout. For the longitudinal motion components (pitch, normal g-load), values were comparable between the two conditions (~15% appropriate). In both motion cueing conditions, false cue ratings were within the acceptable range (scores 1 or 2), with the exception that in workspace-optimized cueing, false cues were rated as unacceptable in 12% of the asymmetric stalls (Fig. 10b). Here the simulator was operating close to the mechanical limitations of the simulator and reversal bumps were perceivable. Taken all together, the workspace-optimized cueing was preferred in 53% of the trials, whereas pilots preferred the conventional cueing in 35% of the trials. In the remaining 12% they were rated equal (i.e., no clear preference).

In DESDEMONA the effect of centrifugation during the recovery ("centrifuge") was compared with the adapted washout mode without centrifugation ("washout"). Five pilots also evaluated a fixed base condition, with only the aerodynamic buffet motion present. However, when compared with the other two motion conditions, this condition was unanimously rated as unsuitable for training in all scenarios, and will not be discussed further. The key motion cue ratings (Fig. 10c) show that the adapted washout cueing received a rating of 2 in the majority of cases (68%, when combining both stall types), but also 1 (20%) and 3 (12%). The centrifuge condition, on the other hand, received better ratings, with the highest score of 1 in 63% of the cases. This improvement was highly significant ($z = -3.46$, $p = 0.01$). No differences between stall types were observed.

The ratings on perceived motion strength (see also Appendix C) corroborated these overall ratings. Centrifuge cueing provided cues of appropriate strength in 89% of the cases (Fig. 11b). Only a small number of cases was rated as too weak (3%), or too strong (8%). In the adapted washout condition, motion strength was rated as appropriate in 49% of the cases and too weak in the remaining 51%. The most important cue that was reported to be lacking in the adapted washout condition was the normal g-loading, which was rated as too weak in 70% of the cases (compared with 7% in the centrifuge condition). Pilots commented that the onset was adequate, but that they missed the sustaining cue. In addition, roll and side force were also rated as too weak in about 50% of the cases for the adapted washout condition (compared with 11% in the centrifuge condition), whereas the strength of the pitch cue was rated appropriate in the majority of the cases (75%, compared with 92% in the centrifuge condition).

Regarding false cues, the picture was quite different: whereas false cues were largely absent in the washout cueing, they were clearly perceived in the centrifuge mode (Fig. 10d), with 33% of all scenarios rated as generating unacceptable false cues. This effect of motion cueing condition on the false cue rating was highly significant ($z = 4.29$, $p < 0.001$). The reported false cues were all related to the angular acceleration of the centrifuge, causing a false sensation of yaw rotation, and in some cases side force. The latter was because the pilot was facing inward, so that the tangential acceleration associated with the acceleration of the centrifuge acted in the pilot's lateral direction. To our surprise, the misalignment of the specific force during centrifugation was not reported as a false cue.

Interestingly, a clear distinction could be made between stall types: the asymmetric stalls received significantly better ratings (i.e., less false cues) than the symmetric stalls ($z = -3.22$, $p = 0.001$). Whereas for the symmetric stalls the false cues were acceptable in only 40% of the cases, this amounted to 95% in the asymmetric stalls. As a consequence of this distinction between stall types, the centrifuge cueing was the preferred cueing for the asymmetric stalls in 89% of the pilots, whereas for the symmetrical this was only by 44%. The rest preferred the washout cueing.

VII. Discussion

Airplane upsets remain rare, but potentially dangerous events that justify training of flight crews to — first of all — recognize, and if necessary, recover from these situations in a safe and controlled environment. For this training to be valuable, both an adequate aircraft model and adequate motion reproduction are required [5,9]. The results of the pilot evaluation show that the SUPRA project successfully extended the simulation envelope with respect to both requirements. Although the SUPRA project did not directly aim at developing training, test pilots agreed that the technology is clearly suitable to extend the simulator envelope for upset recovery training. The SUPRA simulation technology enables not only demonstration of the development of a stall with the indications for early recovery, but also demonstration of the consequences of late recoveries.

A. Aerodynamic Model

As no type-specific aircraft model was available, the SUPRA aerodynamic modeling comprised building an extended model onto a data package representing a generic transport aircraft. Hence, the SUPRA model can be considered “class representative.” The expert pilots agreed that the model exhibited acceptable normal basic flying qualities, comparable to a midrange wide-body aircraft (e.g., B737 to B777). That the behavior in the normal flight envelope was not rated equally well as the behavior in the stall region is most likely because a generic model for the normal flight envelope was used, which was not optimized further. Another factor that could have contributed to the difference is the fact that the normal flight envelope was evaluated without simulator motion, whereas for the upset maneuvers the simulators operated in washout mode. This was done to facilitate the recognition of the key events during the upset scenario and to stress the dynamic nature of the maneuvers.

The results show that the extension of the model outside the normal flight envelope, in particular its behavior during fully developed aerodynamic stall, was well appreciated by the pilots. The eight pilots who had done real stall flight tests in transport aircraft recognized the typical handling qualities and dynamics that occur during the different phases of the stall, that is, the entry of a stall, and its recovery, including secondary stalls. Also, the aerodynamic buffet was highly appreciated.

A few other studies have dealt with improving simulator models for upset recovery (e.g., [26,27]). In a collaborative study between NASA and Boeing, the flight model of a large Boeing transport aircraft was extended to cover high AoA, large sideslip, and large angular rates. The data used for extension were from a series of wind tunnel tests conducted at NASA Langley Research Center using subscale models of a generic commercial transport aircraft [26]. This approach is more exact than the phenomenological approach adopted in the SUPRA project. However, an advantage of this approach is that the generic model has adjustable free parameters to simulate a variety of different aircraft behaviors. The test pilots found the SUPRA aerodynamic model representative for the class of aircraft and suitable for training applications. It was stressed by several pilots that the aircraft behavior in the stall region (especially the large roll-off maneuvers) is a key innovation that is not present in the aircraft aerodynamic models they were familiar with.

B. Motion Simulation on Hexapod Simulators

The subjective evaluation shows that maneuver-specific motion cueing can improve the reproduction of key motion cues in a conventional hexapod flight simulator for the purpose of upset and stall maneuvers. This does not necessarily introduce unacceptable false cues, depending on the stall scenario. In particular the highly dynamic entry of an asymmetric aerodynamic stall that involves a wing drop and roll-off is perceived as more realistically with the maneuver-specific motion cueing.

Previous studies also investigated the limitations of the classical washout filter for the purpose of upset recovery simulation [28,29]. These investigations identified potential limitations concerning the reproduction of upset scenarios on a hexapod simulator. Especially the results for the roll upset are interesting because it shows large false cues in the lateral specific force, which is one of the key motion cues in such a scenario. The approach adopted in the current study identified the important motion components for each scenario to adapt the filter settings such that this particular DoF was prioritized by maximizing the platform excursions in this DoF. The experiments on the GRACE hexapod simulator showed that reproduction of onset cues is most important for a small to medium-sized simulator. Furthermore, the lateral specific force occuring during large roll motions can be matched quite well to the actual aircraft motion (Fig. 4). The pilot evaluation also showed that false cues that are present in the simulator motion are not always perceived by the pilots. As will be further discussed below, the highly dynamic nature of the upset events most likely contributes to this.

As could be expected, the results of the GRACE simulator also showed that the lack of sustained g-cueing is a limiting factor in simulating the recovery phase of the stall upset. Research performed at TsAGI suggests that both the unloading and loading effects may be further improved with respect to the pilot’s motion perception [18,19]. Their approach takes into account the knowledge that the pilot’s sensitivity to motion cues (e.g., angular rates) is suppressed in the presence of higher g-loads. During the SUPRA project the research team at TsAGI implemented this approach in their hexapod simulator by making the gain of the rotational channels in the washout filter inversely proportional to the computed g-load. This way the pilot perceives less aircraft pitch and roll motions even though no actual g-load is present. The concept was tested with a limited number of pilots ($n = 4$), and the results indicate that it resulted in a more realistic motion strength and reduction of false cues in the recovery phase of the upset maneuver [24,30].

The motion research at DESDEMONA produced a new method, the g-load tilt mechanism, using simulator pitch tilt to simulate a sustained feeling of loading and unloading. This method is similar to tilt coordination and may be applicable in hexapod simulators. The majority of pilots commented that it provided a more realistic sensation of the g-loading cues than what they were used to from their conventional training simulators, which makes it a promising solution to provide a feeling of sustained loading/unloading in hexapod simulators. Future studies should substantiate this claim by a direct comparison between a classical washout filter with and without the g-load tilt mechanism active. Note that the simulator tilt merely creates an *illusion* of loading/unloading: the actual change in the gravity component along the pilot’s vertical body axis is relatively small (i.e., a reduction of 13% at a tilt of 30°), and the resulting component will always be smaller than $1g$ for both forward and backward tilt. Therefore it is, in our opinion, more likely that the change in the pressure distribution on the body creates the sensation of (un)loading: Forward cabin tilt decreases the pressure on the seat and increases the pressure on the shoulder belts, similar to what happens during actual unloading. Likewise, backward cabin tilt presses the pilot into the seat, inducing a sensation of loading. This simulator tilt also supports the actual aircraft motion during the two recovery stages, that is, nose down during unloading and nose up during loading.

C. Pros and Cons of Centrifugation

Whereas the g-load tilt mechanism mentioned in the previous paragraph may induce an *illusion* of (un)loading, centrifugation provides the actual *physical* stimulus. Several studies showed that presenting sustained g-loads during recovery is beneficial for proper recovery [19,31]. The test pilots in the present study judged that centrifuge-based g-cueing generated cues of appropriate strength, producing the highest motion fidelity ratings. In some cases this came at the cost of false cues related to the spinning up and down of the centrifuge. Still, there were also conditions in which these sensations remained unnoticed, or were rated as acceptable. Apart from intraindividual differences in motion sensitivity between pilots, a possible explanation for this is that the centrifuge was only accelerated during the onset of buffet motion, masking the false cues. This is in line with other research showing that human sensitivity to a particular motion component is decreased when concurrent motion in another degree of freedom is present [32–34].

The results also showed that less false cues were reported in the asymmetrical scenarios. We explain this by the fact that, during

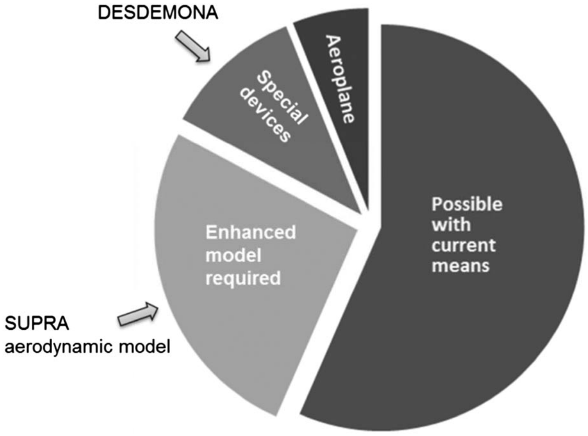


Fig. 12 Contribution of SUPRA innovations to the UPRT training envelope as defined by ICATEE (adapted from [35], with permission).

centrifugation, the pilot was facing the center of centrifugation. Consequently, the tangential acceleration caused by speeding up the centrifuge acted in the pilot's lateral direction. As the asymmetrical scenarios also involved lateral motion cues (roll/side forces), the parasitical lateral acceleration caused by the centrifuge acceleration was interpreted as a key motion cue rather than a false cue. The improved strength scores of the lateral motion cues in the centrifuge condition seem to confirm this: they were rated as too weak in 50% of the cases for the adapted washout versus 11% for the centrifuge cueing. Another factor that may have affected the perception of false cues in the asymmetrical scenario is the increased complexity of the motion stimulus, and the dynamical nature of the scenario.

D. Addition to Existing Training Devices

The ICATEE, coordinated by the Royal Aeronautical Society between 2009 and 2012, defined a matrix of 176 training tasks involved in UPRT, and mapped these onto different training devices [35]. As Fig. 12 shows, 99 of these tasks (56%) can be performed using existing technology approved by International Civil Aviation Organization (ICAO). Fifty-four of these tasks (31%) involve academic training not requiring a device, and 45 tasks (25%) can be delivered with current type III, V, or VII devices. However, the remaining 77 tasks (44%) in the training matrix require an upgrade of, or addition to, existing flight simulation training devices (FSTD); 46 of these (26%) can be performed with an extension of the FSTD's aerodynamic model, whereas the remaining 31 tasks (18%) involving spatial disorientation and g-load management should be performed on airplane, or, alternatively, using special ground-based devices. A centrifuge-based device like DESDEMONA offers a ground-based alternative for on-airplane training with a focus on g-awareness. The arrows in Fig. 12 show that both SUPRA innovations (aerodynamic aircraft model and g-cueing) addressed the extension of the UPRT training. The DESDEMONA simulator equipped with the SUPRA model and flight deck provides a close approximation of the upset environment of large transport aircraft. As one experimental test pilot noted directly after completing a stall recovery in the centrifuge mode: "it was an absolutely perfect feel of the airplane."

VIII. Conclusions

The SUPRA aerodynamic model was judged representative for a generic transport aircraft both inside and outside the normal flight envelope. Concerning the motion simulation the test pilots agreed that a hexapod simulator, with appropriate motion cueing, is suitable to appreciate and understand the aerodynamic behavior of the aircraft beyond the normal envelope. Nevertheless, despite improvements in motion filters, motions cues were not as pronounced as those obtained in the centrifuge-based platform. Experiencing the correct physical stimulation, and especially the g-loading during recovery, was found important. With careful selection of the scenario, centrifugation can be applied without unacceptable false cues. This way, commercial pilots can be exposed to realistic, highly dynamic, high-workload flight scenarios within the safe environment of the simulator. The test pilots concluded that a ground-based g-cueing device has added value for upset recovery training, which fills in the gaps identified by international authorities as ICAO and ICATEE.

Appendix A: Scenarios

Appendix B: Scoring Items

Appendix C: Strength Scores

Table A1 Description of scenarios included in the aeromodel evaluation

Scenario	Stall case[a]	Entry procedures	Recovery
Approach to stall	11	FL130, level flight, decel. at 3 knts/s up to stall	At stick shaker
Approach to stall	41	FL130, level flight, decel. at 3 knts/s up to stall	At stick shaker
Developed stall	10[c]	FL130, level flight, decel. at 3 knts/s up to stall	At full buffet.[b] Using bank
	10	FL130, pitch 30 deg, throttle idle	At full buffet
	10	FL330, pitch 30 deg, throttle idle	At full buffet
	10	FL130, level turn 30, decel. at 3 knts/s up to stall	At full buffet
Developed stall	11[c]	FL130, level flight, decel. at 3 knts/s up to stall	At full buffet. Using pitch
	11	FL130, pitch 30 deg, throttle idle	At full buffet
	11	FL330, pitch 30 deg, throttle idle	At full buffet
	11	FL130, level turn 30, decel. at 3 knts/s up to stall	At full buffet
Developed stall	31	FL130, level flight, decel. at 3 knts/s up to stall	At full buffet
	31	FL130, pitch 30 deg, throttle idle	At full buffet
	31[c]	FL330, pitch 30 deg, throttle idle	At full buffet
	31	FL130, level turn 30, decel. at 3 knts/s up to stall	At full buffet
Developed stall	41	FL130, level flight, decel. at 3 knts/s up to stall	At full buffet
	41[c]	FL130, pitch 30 deg, throttle idle	At full buffet
	41	FL330, pitch 30 deg, throttle idle	At full buffet
	41	FL130, level turn 30, decel. at 3 knts/s up to stall	At full buffet

FL, flight level (in feet × 1000).

[a] Explanation of stall cases: 10 = symmetric stall with no roll instability; 11 = symmetric, level stall with mild roll instability; 31 = asymmetric stall with mild wing drop; 41 = asymmetric stall with heavy wing drop.

[b] Recovery was performed upon an audio signal provided by the experimenter, when the AoA ≥ 15 deg.

[c] Scenario selected for motion evaluation.

Table B1 **Scoring items (representative Y/N?) to assess aircraft handling and aerodynamic behavior in the normal flight envelope (top row) and in the stall region (bottom row)**

Normal handling	Unusual attitudes
Elevator response, pitch	Nose-high wings level
Stabilizer response, trim	Nose-high bank
Aileron response, roll	Nose-low high-bank
Rudder response, yaw	
Thrust response, power	
Thrust response, pitch	
Control loading pitch	
Control loading roll	
Control loading rudder	

Approach to stall (symmetric)	Approach to stall (asymmetric)	Developed stall (symmetric)	Developed stall (asymmetric)
Pitch response	Pitch response	Buffet magnitude & freq.	Roll-off at stall AoA
Roll response	Roll response	Pitch unloading	Roll rate
Stick-shaker onset		Pitch loading	Roll unloading
Buffet onset			

Table C1 **Distribution of ratings (number of times observed) for perceived motion strength for all cueing conditions, collapsed over all maneuvers and flight phases**

GRACE		Conventional settings				Optimized settings			
		Roll	Pitch	Lateral	Normal g-load	Roll	Pitch	Lateral	Normal g-load
Too weak	−2	26	25	18	39	14	17	7	31
Bit weak	−2	14	30	10	26	9	42	3	32
OK	0	14	17	10	6	31	13	29	9
Bit strong	+1	0	0	0	0	0	0	2	0
Too strong	+2	0	0	0	0	0	0	0	0
Total		54	72	38	71	55	72	41	72
DESDEMON		Adapted washout				Centrifuge			
		Roll	Pitch	Lateral	Normal g-load	Roll	Pitch	Lateral	Normal g-load
Too weak	−2	11	2	6	24	0	0	1	0
Bit weak	−2	13	17	10	31	6	1	2	6
OK	0	20	57	18	25	34	71	27	65
Bit strong	+1	1	0	0	0	2	5	2	7
Too strong	+2	0	0	0	0	0	0	0	2
Total		45	76	34	80	42	77	32	80

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NLR

Anthony Fokkerweg 2
1059 CM Amsterdam, The Netherlands
p) +31 88 511 3113 f) +31 88 511 3210
e) info@nlr.nl i) www.nlr.nl