Executive Summary:

Recent aviation safety reviews list Loss of Control In-flight (LOC-I) as the most common category of fatal accidents in transport aircraft. In the period between 2001-2010 LOC-I accounted for 20 accidents (1756 fatalities) world-wide, of which 9 fatal accidents in EASA Member States, whereas the rate of LOC-I accidents in the Russian states increased from 16% to 41% in the last three decades.

A large number of LOC-I accidents have been attributed to a lack of the crew's awareness and experience in recovery from extreme flight conditions, or upsets, including unusual attitudes (such as a high roll angle of more than 45 deg), or stall. Typically, when an aircraft inadvertently entered an upset, inadequate recovery by the pilot has allowed the situation to become critical, resulting in loss of the aircraft. While these situations do not occur on a regular basis, their results are invariably catastrophic.

By making upset recovery training mandatory, as is now foreseen by the certification and regulatory authorities, pilots may be better prepared to deal with unusual attitude and stall conditions. Real flights in large aircraft are considered impractical for this purpose, as this would be expensive and unsafe. Therefore, it is generally recognized that a ground-based flight simulator, capable of accurately reproducing extreme flight conditions in a representable flight deck environment, would significantly improve the effectiveness of upset recovery training programmes. An additional advantage would be that commercial pilots already receive their recurrence training in a flight simulator. Hence, combination with upset recovery training in the same simulator sessions would be cost-effective.

However, current flight simulators are considered inadequate for the simulation of upset conditions, since commonly the aerodynamic models only provide high fidelity within the normal flight envelope. This is not representative for upset conditions, where the aircraft behavior may become highly unstable, non-linear and unpredictable. Furthermore, conventional flight simulators, featuring standard hexapod-based motion systems, are unable to reproduce the high accelerations, angular rates, and sustained G-forces needed for upset recovery.

The FP-7 research project SUPRA (Simulation of UPset Recovery in Aviation) aimed to overcome these technical limitations that prevent widespread use of simulators for upset recovery training. The project successfully applied innovative engineering methods to extend a generic aerodynamic model which captures the non-linear aerodynamic behaviour of transport aircraft beyond the conventional flight envelope. Based on judgments of highly experienced test pilots it was demonstrated that current hexapod-type simulators can be improved to provide realistic feedback on the motion cues during upset and stall conditions, without introducing new unacceptable false cues. In addition, the pilots judged the centrifuge-based simulator with gimbaled cabin DESDEMONA extremely useful in reproducing the higher g-loads of up to +2.5g which are associated with recoveries from nose-low attitudes. This shows that ground-based g-devices can be used to enhance the pilot's g-awareness in a transport category cockpit. The SUPRA project succeeded in pushing the boundaries of state-of-the-art flight simulation to address the new requirements for upset and stall recovery training while complementing the UPRT training material that is already available in the airline and training industry.

Project Context and Objectives:

Although aviation safety has been greatly enhanced by technical improvements and new training concepts during the last decades, Loss of Control in flight (LOC-I) continues being the leading cause of fatal accidents in commercial aviation , accounting for 85 accidents and 1756 fatalities worldwide in the last 10 years (Figure 1 1). A large number of LOC-I accidents have been attributed to a lack of pilots awareness and experience in extreme flight conditions. While pilots are familiar with the handling characteristics of their airplanes during normal operations, characteristics might change dramatically when the airplane is taken to the edge of the flight envelope and beyond. It has been shown that when entering a loss of control situation chances of successful recovery are decreasing with the time spent outside the normal envelope. Hence, once a LOC situation has not been avoided, timely recognition and recovery from an upset, that can be reason or result of a loss of control situation, are essential.

Accident analysis shows that a sizeable percentage of LOC accidents occur with airplanes that are in flyable condition, i.e. did neither suffer a system nor structural failure. This is pointing at improved awareness and recovery training as a potential remedy. Real flights in large aircraft are impractical for this purpose, as this would be expensive and unsafe. Therefore, it is generally recognized that a ground-based flight simulator capable of accurately representing extreme flight conditions would significantly improve the effectiveness of upset recovery training. An additional advantage would be that commercial pilots already receive their recurrence training in a flight simulator. Hence, combination with upset recovery training in the same simulator sessions would be cost-effective. The need to improve flight crew awareness and proficiency in this area was realized by industry and regulators more than a decade ago and lead, amongst other things, to the development of the Upset Recovery Training Aid (URTA) . The URTA aims at improving the flight crews academic knowledge of aerodynamic and flight dynamics principles for flight around the edges of the envelope as well as providing demo and training scenarios for upset recovery training in full flight simulators. However, the simulator part of the training remains limited to scenarios within the normal envelope. As the simulation models within this envelope are derived mostly based on flight validated data the simulator behaviour reliably represents the behaviour of the airplane. Outside this envelope, an area which is naturally relevant to upset recovery training, simulator behaviour might not be representative of the highly unstable behaviour of real aircraft, posing the risk of negative training .

Yet another limitation of the hexapod motion base full flight simulators is the limited motion space making it hard to reproduce large or sustained accelerations or angular rates which are sometimes associated with upsets or recovery from upsets. This limitation can obviously only be overcome completely with in-flight training or advanced motion platforms. However, pertinent improvements might be feasible by optimizing the motion cueing algorithms - those are the filters that are translating simulated aircraft motion into simulator cabin motion - for upset manoeuvres instead of the typical training manoeuvres.

The SUPRA project has taken on the challenge of advancing the state-of-the-art of flight dynamics modelling and motion cueing to address these two gaps currently prohibiting the wide-spread use of ground-based simulators for upset awareness and recovery training. In both areas the project is basing its work on previous efforts that were hosted within and outside the SUPRA team: the flight dynamics modelling is based on wind-tunnel techniques that have been used very successfully to predict the behaviour of fighter aircraft in flight regimes relevant to SUPRA and is supplemented by novel computational fluid dynamics methods; motion cueing improvements have been developed based on targeted motion perception research and include conventional hexapod-type motion platforms as well as novel centrifuge based platforms (Figure 1 2). The entire cycle of SUPRA developments is depicted in Figure 1 3. In the first work package the occurrence and characteristics of upset conditions were investigated. The term upset' comprises a multitude of flight regimes not typically encountered during normal flight operations of commercial transport airplanes. Upset conditions involve unusual attitudes (pitch angles in excess of +10/-25 deg, bank angles above 45 deg); stalls, including spins; and exceeding maximum airspeed or structural limits. Typically, depending on flight crew actions an upset situation can quickly evolve from one type into another which makes formulation of upset scenarios rather difficult. In cooperation with the SUPRA Expert group it was decided that upset recovery training should provide subject pilots with the necessary tools to recover at ideally any point in time of a dynamically evolving upset situation. Consequently the starting point for SUPRA were the unusual attitude scenarios described in the URTA, which stay all inside the validated flight envelope, and extend those exercises by approach-to-stall and stall scenarios, including fully developed spin for demonstration purposes.

The objective of the flight dynamics and aerodynamic modelling within SUPRA was to extend the normal flight envelope and reproduce the non-linear aerodynamic effects that may dramatically change aircraft behaviour in high incidence flight conditions. Using a phenomenological approach previously applied successfully to similar problems with military aircraft, supported by wind tunnel and Computational Fluid Dynamics (CFD) methods, SUPRA developed a reconfigurable, class-specific model of transport aircraft, which can be reconfigured rapidly to represent different stall departure characteristics. The model is capable of reproducing key aerodynamic non-linearity's that occur at high angle-of-attack and side-slip angles, as well lateral-directional instabilities (autorotation).

The human motion perception work was aimed at improving understanding of pilot sensitivity to certain motion cues during flight in upset regimes. The team could draw upon experience from relevant research in the fields of spaceflight, aviation and maritime applications. Several knowledge gaps have been filled during the project by targeted experiments using ground-based simulator hardware at TNO, NLR, TsAGI and MPS, as well as Gromov Flight Research Institute's (GFRI, Russia) flying test-bed. The newly gained knowledge of motion perception was applied to the development of novel motion cueing solutions (the next work package in the cycle).

Motion cueing developments within SUPRA involved both standard hexapod platforms at NLR and TsAGI, as well as the one-of-a-kind DESDEMONA centrifuge-based simulator at TNO. Although hexapod motion systems are adequate for simulating normal flight manoeuvres, their limited physical motion space makes it difficult to reproduce the large accelerations or angular rates associated with upset recovery. Furthermore, motion driving algorithms those are the mathematical filters that translate simulated aircraft motion into simulator cabin motion normally have conservative parameter settings. Hence, the motion cueing research on hexapod systems was aimed at optimizing the motion cueing algorithms for upset manoeuvres without changing the hardware. The motion cueing research on DESDEMONA investigated the usefulness of reproducing the physical effects of higher G-loads associated with upset recovery. Since centrifuge-based generation of G-loads may introduce additional false cues such as Coriolis-forces, this work was supported by detailed pilot motion perception experiments which were aimed at optimizing the simulation of G-loads while simultaneously minimizing false cues.

Early 2012 the extended aerodynamic model and the optimized motion cueing algorithms were integrated into the hexapod- and centrifuge-type research simulators of SUPRA for the final evaluation. Flight deck characteristics such as displays and controls were brought to a common generic commercial transport standard facilitating comparison of evaluation results between simulators. A group of 12 highly qualified experimental test pilots (42-61 years; between 7,200-22,000 flight hours), familiar with upset situations from real flight, participated in the validation of the simulator concept. These expert pilots rated the stall behaviour of the SUPRA aerodynamic model as quite accurate and acceptable for pilot training. Regarding motion fidelity, the pilots noted that the enhanced buffet motion cueing at the onset of aerodynamic stall was very realistic both in the hexapod simulator and in DESDEMONA. The optimized motion cueing in the hexapod was rated higher than the standard cueing, and did not introduce additional false cues. In DESDEMONA, the large roll-off manoeuvres were especially judged realistic and were considered a big advantage over current hexapod simulators. The g-cueing seemed to reproduce key motion cues of appropriate magnitude, rated as equivalent to the real airplane. Although the spin-up and spin-down of the centrifuge caused some false cues which were noticeable during symmetrical stall scenarios, they were masked by the dynamic cueing environment related to asymmetrical stall scenarios. As a result, g-cueing was selected as the preferred cueing option for asymmetric stalls by 90% of the pilots.

Considerable effort has been made to coordinate the work of the SUPRA project with past and on-going related efforts. Especially in the field of extended envelope modelling SUPRA engaged with key NASA and Boeing experts who were part of the U.S. Extended Upset Recovery Simulation (EURS) project about a decade ago. Further, SUPRA ensured future applicability of the R&D performed by direct involvement in the Royal Aeronautical Society's ICATEE (International Committee on Aviation Training in Extended Envelopes), a group currently developing guidelines for improved upset training and facilities which are being proposed to ICAO for inclusion in future regulatory material.

In conclusion, the SUPRA project succeeded in developing a new generic concept to provide the required enhancements to the state-of-the-art simulation of advanced upset conditions, including stall and spin. The results of the expert pilot evaluation showed that the out-of-the-envelope aerodynamic model and improved motion cueing (including enhanced buffet cueing) were able to replicate the key dynamics that typically occur during an upset or stall. It was demonstrated that the acceleration onset cueing of conventional hexapod motion simulators can be optimized for better replication of the lateral/directional cues during a stall without introducing new unacceptable false cues. The correct replication of the physical strain on the human body during an upset was demonstrated using centrifugation as a simulator solution. In this sense, the centrifuge can be applied as tool to familiarize pilots with the physical demands during an upset recovery and the effect on their judgment, situational awareness and control behaviour.

Project Results:

The S&T activities within SUPRA produced foreground knowledge in the following five areas, which will be described in separate sections of this chapter:

1. Upset scenarios
2. Aerodynamic modelling
3. Motion cueing
4. Motion perception
5. Pilot evaluation

The Industry Airplane Upset Recovery Training Aid (URTA) provides the following definition of an airplane upset:

An upset is defined as an airplane in flight unintentionally exceeding the parameters normally experienced in line operations or training: pitch attitude greater than 25 degrees nose up or 10 degrees nose down, bank angle greater than 45 degrees, or within these parameters, but flying at airspeeds inappropriate for the conditions.

The attitudes that constitute an upset as described above, also called unusual attitudes are depicted in Figure 1 4.

As the definition above is hinting at, the term upset is used in a wider scope than only for unusual attitudes. In SUPRA we included the following four basic conditions: unusual attitude; stall; excess speed and load; and spin (as a special kind of post-stall rotation). As Figure 1 5 illustrates, upsets are typically rather dynamic conditions, which, depending on the cause of the upset and flight crew actions, can transition swiftly between the various types of upsets.

In general terms an aircraft is stalled when the lift produced is no longer enough to sustain the weight of the aircraft or the aircraft becomes aerodynamically uncontrollable. This typically occurs when the angle of attack (AoA) exceeds a critical value (Figure 1 6). A stall condition can typically be recognized by one or more of the following aspects: aerodynamic buffeting, which can be heavy at times; inability to arrest descent rate; lack of pitch authority; lack of roll control; lateral-directional instability. As a special, dynamic type of stall which constitutes an equilibrium rotating motion of the airplane with angles of attack beyond stall, the spin shall be mentioned here. The character of spinning motion is defined by the equilibrium AoA value and the involved steady rotation rate.

Whereas stall and spin represent a condition exceeding the normal flight envelope on the low end, exceeding the maximum safe operating speed or Mach number represents an exceedance on the high end. In such situations compressibility effects can either adversely affect handling and controllability or cause aero elastic effects putting high stress on the airplane, such as high speed buffet, or reaching high airspeeds can cause high aerodynamic forces exceeding structural limits. Similarly exceeding design limit load factors can overstress the airplane compromising structural integrity.

1.3.1.1 Database search

Early in SUPRA data was collected on upset accidents and incidents with commercial transport aircraft. The objective was to support the selection of representative upset scenarios that should be simulated. A search run on the publicly available NTSB-accident and incident database with a search time window from January 1980 until September 2009 using the keyword loss of control delivered 13 relevant events between 9/6/1985 and 5/12/2005, of which 12 are involving jet airplanes. The scope of SUPRA was limited to jet airplanes, hence turbo-prop aircraft were not considered for further analysis. Also a manual search on the data provided on the Russian website http://www.airdisaster.ru was run. The website lists all USSR and Russian Federation accidents and incidents with available information starting from 1951. The search produced 15 events between 7/10/1985 and 9/14/2008, 12 of which involved jet aircraft. A further automated search was run on the NLR Air Safety Database in the Occurrence Category Loss of Control In-Flight within the time window 1970 until 2009. The search produced an additional 7 events, 5 of which involved jet aircraft. In total the search of the various sources produced 35 events between 1979 and 2008, 29 of which involving jet aircraft.

1.3.1.2 Upset Classification

Based on the probable cause and full narrative provided in the accident / incident reports a classification of the events was performed in terms of: 1) triggering event; 2) initial attitudes; 3) stall occurrence; and 4) aircraft configuration or phase in flight. The results are visualized in four different pie charts in Figure 1 7.

Analysis of the triggering event (upper left plot), showed that equipment failures and improper crew actions are common causes for upset events, while icing and other environmental events were less represented in the collected data. Some of the icing-related events were considered unrecoverable (UR in the plot). The analysis of the initial attitude (upper right plot) showed that about 30% of LOC-I events commenced as pure roll events; approximately 25% initially were pure unusual attitudes in pitch, mostly involving a nose high attitude. A relatively small fraction of the events (approx. 10%) commenced with a combined roll and pitch unusual attitude. About 25% of the cases did not commence with an unusual attitude. It has to be kept in mind that this analysis does not allow any statement on the development of the upset situation; only the entry into the LOC-I condition was evaluated. Analysis of the presence of stall (bottom left plot) showed that about 50% of the LOC-I events started with a stall. A small fraction of the stall events, occurring after take-off and icing-related, was considered unrecoverable. Further analysis showed that LOC-I events occurred with a relatively even distribution across all phases of flight and corresponding aircraft configurations (bottom right plot). A rather small fraction of LOC-I cases was found related to go-around (G/A). However, it has to be kept in mind that go-arounds occur only once every few hundred cycles, i.e. the probability of entering a LOC-I condition during a go-around maneuver may be disproportionately higher. Of 21 flights 13 flight were piloted manually when entering the upset; in 8 cases the flight was either fully or partially controlled by the auto flight system (autopilot and/or auto throttle).

The events were evaluated concerning its containment within the normal flight envelope considering parameters such as vertical load factor, angular rates and angle of side-slip. The objective of this preliminary evaluation, solely based on expert judgment, was to have a first idea of what fraction of LOC-I events in the data base merit an extension of the aerodynamic and flight dynamics simulation models as planned in SUPRA. An event was considered inside the normal envelope if the initial upset event as well as proper and timely initiated recovery actions by the crew would remain within the flight envelope for which validated simulation models currently exist. Out of 27 events which could be evaluated with sufficient confidence 9 were considered to remain within the normal envelope, whereas 18 were considered to leave this envelope.

1.3.1.3 Scenario selection

During the Forum Discussion with the SUPRA Expert Group it was argued that it may not be desirable to focus too much on actual upset cases, since the pilots will most certainly encounter a different upset in real life. This supports the idea to develop basic, somewhat abstract upset conditions. It was recommended to use the URTA as starting point for the scenarios of SUPRA, since it is widely accepted by the industry and authorities as currently the most achievable way to educate pilots to recognize and recover from upset events. The URTA describes simulator exercises for recovery from unusual attitudes which take into account the limitations of current flight simulator technology concerning the aerodynamic models and the motion capabilities. These exercises are not suitable to demonstrate the unsteady behavior at high angles of attack. Hence, the main challenge of SUPRA was to extend simulator models to adequately reproduce stall conditions, so as to demonstrate how aircraft behavior changes when no timely recovery action is initiated.

Based on these considerations, it was concluded that the SUPRA scenarios should include: 1) Unusual attitudes (nose-high, nose-low, with small and large bank angle); 2) Approach-to-stall (cruise and landing configuration, straight and turning flight); 3) Stall (cruise and landing configuration, straight and turning flight).

Figure 1 7. Cross sections of SUPRA database search on upset accidents.

1.3.2 SUPRA aerodynamic modelling

Flight simulation is essentially time-dependent modeling of the aircraft's flight dynamics associated with variation of aerodynamic forces and moments related to the aircraft's state and deflection of control surfaces. The aerodynamic forces and moments may be considered as functions of the aircraft motion parameters such as flight altitude (or the atmospheric density), airspeed (or the Mach number); angle of attack (AoA), sideslip and angular rates; and also on deflection of aerodynamic control surfaces, for example, stabilizer, elevator, ailerons, rudder, trailing edge flaps, etc. Altogether, the mathematical flight dynamics and aerodynamic model can be considered the heart of modern flight simulators. For Level D certified Full Flight Simulators (FFS) the model outputs accurately match aircraft responses measured in-flight for conditions within the normal flight envelope. However, outside this envelope, an area which is naturally relevant to upset recovery training, simulator behavior might not be representative of real aircraft behavior. From the scenarios described in the previous section it follows that aerodynamic models should be extended into high AoA, to include stall. This is illustrated in Figure 1 8 for the dependency between lift and angle of attack. Current pilot training is focused of staying within normal and safe part of the flight envelope, i.e. at AOA's below the stall warning for which simulator fidelity is high (green area in Figure 1 8). Training may also include approach-to-stall exercises, for which the simulator data are derived from wind tunnel data (yellow area). However, for stall conditions beyond critical AoA no reliable data exist (red area). The aerodynamic model of SUPRA was aimed to extend the simulator data beyond critical AoA, to allow airline pilots to recognize unexpected upset situations and practice appropriate control strategies to recover the aircraft.

Figure 1 8. Different levels of simulator fidelity depending on angle of attack (AoA) (courtesy drawing Telegraaf).

At the onset of SUPRA it was investigated which aerodynamic data were available and how these should be extended to simulate the high incidence flight conditions. The backbone of the SUPRA aerodynamic model includes experimental wind tunnel data obtained in TsAGI for a generic airliner configuration with a typical low-wing two engines configuration. These aerodynamic data, as usual for all industrial applications, were obtained in different wind tunnels with low and high Reynolds numbers, low subsonic and transonic Mach numbers using different experimental facilities. Figure 1 9 shows the typical regions of AoA and Mach number where aerodynamic data are available. On the one hand, aerodynamic dependencies on a wide range of Mach number (M=0.2..0.8) were available in the yellow region for a limited range of angle of attack (m=0..20°). On the other hand, knowledge of higher AoA was available from special low-speed wind tunnel tests but only at low Mach numbers (blue region in Figure 1 9). The indicates the area with moderate and cruise Mach numbers and where stall conditions can occur below aerodynamic and structural limits, but wind tunnel data are not available. Computational fluid dynamics (CFD) can help to cover this unknown part of the flight envelope extend the envelope by a combination of large sideslip, angle of attack and rotational speed. In SUPRA this was done for forced coning motion of a T-Tail configuration at sideslip angles of up to 40° and AoA up to 26°. Another approach was to replace the commonly used two-dimensional look-up tables with aerodynamic data as a function of AoA and Mach number by a so-called phenomenological model. This approach has previously been successfully applied for military aircraft, and allows for a smooth and physically justifiable interpolation between high angle of attack dependencies available in the blue region and the high Mach numbers in the yellow region . The model will be explained in more detail in the next sections.

Figure 1 9. Availability of aerodynamic data for extended angles of attack and Mach numbers.

Flight conditions at high AoA may cause a number of non-linear aerodynamic effects which may result in uncontrolled motions as well as unconventional aircraft responses to pilot control inputs. The most important non-linear aerodynamic effects that should be captured by the SUPRA aerodynamic model are described in Table 1.

Aerodynamic effect Description

Non-linear loss of lift Due to flow separation the aircraft stalls beyond critical AoA, which can be felt by pilot as the g-break.

Dynamic aerodynamic hysteresis Results from time delays in the development of flow separation which may lead to dynamic instability in pitch, roll, and yaw.

Aerodynamic buffet Preceding flow separation structural vibrations may occur, which is an important warning signal for the pilot.

Autorotation Asymmetrical development of flow separation is an important phenomenon affecting lateral/directional stability and controllability.

Vertical tail shadowing Deterioration in static and dynamic lateral/directional stability.

Control surface shadowing Loss of control efficiency (pitch, roll, and yaw channels).

Pitching up moments Longitudinal instability due to interaction between swept wing and horizontal tail.

Table 1. Key aerodynamic effects at high incidence flight.

1.3.2.1 Phenomenological model

Basically, an aerodynamic model provides the aerodynamic forces Lift (CL), Drag (CD), and Side force (CY). The SUPRA aerodynamic model included an unsteady aerodynamic phenomenological model describing the unsteady nonlinear variations of aerodynamic lift and pitching moment coefficients in the stall region. The above-mentioned decoupling of aerodynamic dependencies ((blue and yellow regions in Figure 1 9) is a promising way to smoothly extrapolate high angles of attack data and high Mach numbers data into the region. For example, the approximation of the lift coefficient can be given as: where is the dependence of the lift coefficient for zero incidence upon Mach number, is the experimental dependence on angle of attack of the lift coefficient measured for M=0.4, and are empirical coefficients identified to approximate experimental dependencies at various Mach numbers. Really only coefficient should be identified, since a connection exists with the second coefficient:

A similar decoupling was applied in the SUPRA extended aerodynamic model for longitudinal and lateral/directional aerodynamic coefficients. At stall conditions the flow separation is associated with characteristic time delays for readjustment, which substantially affect the aerodynamic loads and dynamic stability (dynamic hysteresis) . Hence, an additional dynamic contribution was introduced which (in many cases) can be described by a simplified differential equation, for example a first order differential equation:

where is the characteristic time of flow readjustment processes and is a nonlinear function which should be identified to match experimental dependencies of aerodynamic coefficient on frequency of oscillations. Figure 1 10 shows a rather close match between the lift coefficient predicted by the phenomenological model and CFD, adequately capturing the dependence on frequency and amplitude of oscillations of angle of attack in the stall region (green line).

1.3.2.2 CFD modeling

Computational prediction of aerodynamic loads using CFD methods has now well been validated for the normal flight envelope, e.g. for evaluation of the lift-to-drag ratio. Prediction of stability and controllability derivatives is also rather reliable. In the stall region CFD methods provide good agreement with experimental wind tunnel results; however they need more consistent validation especially beyond stall conditions. CFD modeling is considered as a complementary source for generation of important aerodynamic data in addition to the wind tunnel data obtained in TsAGI. The CFD computations within SUPRA were based on NLR's ENFLOW , using a rigid body approximation, and a computational multi-block grid consisting of 918 blocks (Figure 1 11).

Figure 1 12 shows an example of a CFD simulation for an aircraft with a T-tail configuration which is prone to a deep-stall when the tail surface is submerged in the wake of flow separation from the wing.

Figure 1 12. CFD simulation of the wake of separated flow impinging the horizontal tail surface.

Figure 1 13 presents a comparison between CFD results and wind tunnel dependencies on angle of attack for the drag, lift and the pitching moment coefficients. CFD captures very well the magnitude and location for the maximum value of the lift coefficient at stall conditions and also the tendency in the pitching moment coefficient for pitch-up instability.

Figure 1 13. Comparison between CFD results and wind tunnel experimental data.

Figure 1 14. 3-D visualization of the SUPRA flight envelope, showing multiple aircraft modes.

Validation of aerodynamic models is well-developed for normal flight conditions at low angles of attack, where air flow is attached and aircraft dynamics behave linearly. This allows for a good match between simulated and flight test time histories. At high angles of attack the aircraft dynamics become non-linear, showing multiple attractor dynamics and strong dependence on initial conditions and control commands. This makes validation much more difficult and in many circumstances practically impossible. A good match between simulated and flight test time histories for one particular case does not guarantee that the same agreement will be achieved for other initial conditions and command inputs. For this reason, the SUPRA aircraft model was validated in two alternative ways. First, a mathematical validation was performed to check whether the aircraft model shows correct departure intensity and spin behavior in different modes, i.e. in normal and critical flight regimes. Figure 1 14 shows a 3-D cross section of the SUPRA flight envelope. Second, the SUPRA aircraft model was subjectively validated by expert test pilots with experience in stall conditions in the real aircraft. The results of this validation are described in section 1.3.4.1.

In summary, the aerodynamic modelling in SUPRA combined wind tunnel data, CFD, and a phenomenological modelling principles to produce a representative/generic aerodynamic model that representatively captures multiple phenomena which are possible at stall/post-stall flight conditions. The SUPRA model can be considered a generic, or class-specific type of model, in agreement with the recommendations by ICATEE . The SUPRA model is also reconfigurable, meaning that a variety of representative high angle of attack behaviors can be achieved by modification of a limited number of parameters. This allows for implementation of different upset scenarios. The SUPRA aerodynamic model was validated by expert pilots in piloted simulation, who judged whether the model provides acceptable performance, stability and handling qualities in the normal flight envelope, and also is representative in terms of dynamics at stall and beyond stall flight conditions. The results of this evaluation are described in section 1.3.5.

1.3.3 SUPRA motion cueing

Full flight simulators employ a moving base to provide the pilot with inertial motion feedback about the aircraft's motion. Since the motion space of a simulator motion platform is obviously much more confined than the motion space of the real aircraft, the output of the aircraft model must be scaled down and filtered, in order to keep the simulator within its physical boundaries. This is done by so-called motion cueing software or motion driving algorithms. This software usually comprise a set of high-pass filters to reproduce only the aircraft accelerations, or onset cues, and filter out longer displacements. In itself onset cueing concurs nicely with the fact that the human sensory systems that signal self-motion are sensitive to angular and linear changes in self-motion. Nevertheless, motion driving algorithms inevitably create motion artefacts or false cues, for example by repositioning the simulator cabin between onset cues. Due to the conservative parameter settings of commonly used motion driving algorithms, and the benign aircraft motions in the normal training regime, these false cues usually cause no problems. However, simulation of motions that occur during upset events may cause problems. First, motion settings may be too conservative to reproduce the larger aircraft motions. Second, motion deformations caused by high-pass filtering may become enlarged and disturbing; and lastly, standard hexapod-type motion platforms are by definition incapable of reproducing sustained g-loads that are associated with upset recovery. Replication of these cues is considered important because the majority of the pilots have never experienced such a dangerous but rare event and have no idea about the nature of the motion cues arising in upset and upset recovery.

The objective of the motion cueing research in SUPRA was to investigate; 1) how the motion driving algorithms of conventional hexapod-type simulators can be optimized to adequately reproduce the typical aircraft motions during upset recoveries, and 2) what can be gained from reproducing sustained g-loads in an centrifuge-type simulator with a gimballed cabin.

1.3.3.1 Hexapod motion cueing

The hexapod-type flight simulators at NLR and TsAGI were used to develop motion cueing solutions for upset recovery training that can be applied on a short term, and are acceptable and deployable for the flight simulator industry, operators and aviation authorities. Hence, the simulator work space should be optimize d in a way that can be readily implemented in conventional Level-D full flight simulators, while leaving integrity of the current architecture intact.

Conventional or classical motion driving algorithms consist of a combination of high (HP) and low pass (LP) filters (Figure 1 15). Rotational rates (?) of the airplane are scaled (gain parameter K) and subsequently high pass filtered, so that only the high frequency component is generated in the simulator. This is referred to as onset cueing. It thus uses the sensitivity of the vestibular semi-circular canals in the high frequency domain. The same method is used to simulate linear accelerations: specific forces (n) are filtered through a high pass filter for generating the high frequency force corresponding to the inertial acceleration. The low-pass filtered part represents sustained acceleration. Because this is associated with relatively large simulator displacements, this part is usually generated by tilting the simulator cab, i.e. input to the -channel. By doing this, the gravity vector is used to simulate sustained linear acceleration due to self-motion. This method is referred to as tilt-coordination and works well when an adequate visual is provided and the cabin tilt is not too fast (usually a rate limit of 3°/sec is applied).

Based on analysis of time histories derived from in-flight tests performed by GFRI, the typical aircraft motions were identified that occur during different upset recoveries. It was concluded that current motion cueing filters fall short on the following aspects:

- The high angular rates (especially roll) occurring during upsets are not adequately reproduced and are a major source for false cues.
- Lateral and longitudinal specific forces (nx, ny) are not represented adequately, mainly due to phase distortions and/or amplitude reduction

- Loading and unloading cues (nz) are insufficient, since only high-frequency, onset cues are provided.
- Actuator stroke is not used optimally with the current filter settings.

1.3.3.1.1 Motion cueing solutions at TsAGI

TsAGI operates the PSPK-102 simulator (Figure 1 17) featuring a two-seat flight deck typical of a transport aircraft. The visual system consists of a collimated CGI system with 80° (horizontal) x 30° (vertical) field of view with a resolution of 1280x1024. The simulator is equipped with two column/wheels, pedals, side-sticks (left and right) and the throttle station located in between the pilots' stations. All control inceptors are loaded by an electrical loading system of MOOG (ECoL-8000), allowing for changing of feel system characteristics.

An important element in TsaGI's motion cueing research was based on the observation that under large g-loads pilots are less sensitive to other (angular) motion cues. Obviously, a centrifuge-type simulator automatically reproduces this effect. However, a hexapod simulator is unable to generate sustained g-loads. Hence, TsAGI decided to mimic the reduced perception of angular motion by implementing an adaptive weight coefficient into the angular motion paths, reducing the angular rates in accordance to the following expression: where p0=1.0 rad/s (for roll motion) is an averaged angular motion threshold value at nz =1. This expression was derived from experiments performed previously and during SUPRA, both in simulators and in actual flight.

Figure 1 18. Boundaries of false sensations arising during low-frequency longitudinal acceleration simulation.

Another focus of motion cueing research at TsAGI was on minimizing false cues, like false rotational sensations during the simulation of linear accelerations by tilt coordination. As is shown in Figure 1 18, tilt velocity should not exceed 2.5 °/sec, and false specific forces caused by angular accelerations should not exceed 0.01g. Thus, the frequency of the low-pass filter in the longitudinal and lateral accelerations paths of the SUPRA software was chosen as high as possible, i.e. a break frequency of LP=1.4 rad/s.

In a classical washout filter design, frequencies of high-pass and low-pass filters are selected equal in order to avoid large cockpit displacements and/or false cues and phase distortions. The resulting phase distortion in simulator motion is dependent on the frequency spectrum of the aircraft horizontal accelerations, where it is possible that crucial frequencies are not ideally reproduced. In upset situations the crucial frequencies of lateral accelerations are within 1-2 rad/s, resulting in noticeable phase distortions in classical simulator motion (Figure 19, red line). This situation was improved by replacing the classical low-pass filter structure with a complementary filter containing the middle frequencies that typically occur in upsets (Figure 19, green line).

Figure 1-19. Frequency response of lateral specific force reproduced with the classical (red) and modified (green) filters.

The combination of both the NLR workspace optimized and TsAGI perception optimized cueing provided the best balance between improved stall upset motion cueing and minimizing false cues which is a major requirement for hexapod training simulators. Figure 1-20 shows the improvement of motion fidelity according to the Sinacori criteria , computed as the phase distortion and gain of the washout filter at a frequency of 1 rad/s. It should be noted that these criteria have been validated for a helicopter maneuver, and different boundaries may be valid for upset maneuvers in transport aircraft, the plot does illustrates a general improvement of hexapod (lateral) upset cueing compared to conventional (classical) motion cueing.

1. classical algorithms
2. optimized algorithms with enhanced gains (enlarged motion space only)
3. optimized algorithms with the new low-frequency filter (with the middle range frequencies) and enhanced gains

Figure 1-20. Gain and phase distortion of three hexapod motion filters for lateral specific force, plotted against the Sinacori motion fidelity boundaries.

1.3.3.1.2 Motion cueing solutions at NLR

The NLR operates the Generic Research Aircraft Cockpit Environment (GRACE), a modular reconfigurable transport aircraft simulator, representative for today's FFS used for airline pilot training. The simulator motion platform is an electrical hexapod system. For the purpose of SUPRA, the cockpit was configured with a Boeing 737NG cockpit configuration consistent with the SUPRA cockpits at DESDEMONA and TsAGI. Also, a visualization tool was developed to display the upset manoeuvre dynamics and pilot performance on the operator control panel. An additional display presented the motion platform performance and motion filter outputs, allowing for real-time judgment of the quality of replicating the aircraft motions.

The underlying concept for the NLR motion cueing developments was to optimize the simulator work space depending on the phase of the upset recovery scenario . Since the onset of the SUPRA upset scenarios was pre-determined, the motions of the aircraft and simulator were also pre-determined. The five identified phases of the scenario are illustrated in Figure 1 21.

Figure 1 21. SUPRA visualisation tool at NLR providing upset recovery techniques feedback (left) and NLR GRACE research simulator (right).

Figure 1 22. Different phases of the upset scenario (stall).

The normal flight phase was simulated by the classical motion drive algorithm. During the approach to upset or stall phase, improved buffet motion cueing was considered the primary motion effect. In the upset phase, the motion drive algorithm was adjusted to prioritize the primary cue that is required dependent on the aircraft motion in the selected upset scenario, limiting the motion cueing in a single or coupled pair axis. To this end, a single and (Workspace) optimized set of motion filter parameters (i.e. gains, damping and cut-off frequencies) was established. This included the minimization of lateral acceleration phase distortions in the upset or stall entry based on results from the TsAGI experiments. Figure 1 22 shows an example of the better match between simulator and aircraft roll motion obtained by this optimization (but note that a match needs not be perfect for pilots to perceive the simulator motion as perfect). For the simulation of the recovery phase, NLR implemented the perception module from TsAGI that simulates the reduced sensitivity to angular motions under sustained g-loads. In the normal flight after recovery, the filter was changed back into the classic motion driving algorithm.

Figure 1 23. Aircraft and simulator lateral motion during roll-off of stall obtained at NLR for the classical motion cueing (left) and the (Workspace) optimized motion cueing (right).

1.3.3.1.3 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 the following new requirements for stall buffet simulation:

- Onset angle of attack +/- 0.03 g
- Variation in amplitude as a function of AoA

The frequency variation has been identified as a less critical cue. The SUPRA Stall Buffet Module implemented these new key characteristics, and used a frequency variation representative of a large transport aircraft. The SUPRA stall buffet module drives an uses both the aircraft AoA and onset angle of attack as its input.

The several motion cueing elements (i.e. NLR work space optimization module; TsAGI's perception module for reduced sensitivity to angular cues under g-loads; and improved buffet module which was developed by DMU at DESDEMONA) were being coordinated by a so-called fader module which forms the heart of the SUPRA motion cueing add-on developed by NLR (Figure 1 23). This module comprises an algorithm that smoothly switches between both the perception and workspace optimized modules based on the SUPRA aircraft model produced g-loads during the execution of an upset or stall recovery maneuver.

Figure 1 24. NLR Fader module to coordinate the gain scheduling.

1.3.3.2 DESDEMONA motion cueing

This DESDEMONA facility features a full flight simulator with six degrees-of-freedom of motion including a centrifuge axis (Figure 1 2, right). The simulator cabin is fully gimballed and can rotate infinitely about all axes, while it can move vertically along a heave axis (±1m) and horizontally along a linear arm (±4m). The linear arm itself can rotate about its central yaw-axis to generate centripetal forces. With a maximum arm length of 4m and a maximum angular speed of 159°/s DESDEMONA can simulate sustained g-loads of up to 3.3g, adequate for upset recovery of transport aircraft. Motion driving algorithms were implemented in MATLAB Simulink®, running at 200Hz. The commanded motion was logged in MATLAB® at 50Hz.

1.3.3.2.1 G-cueing

Efficient recovery from commercial transport aircraft upsets may require the crew to load the aircraft up to the limit load of +2.5g. This sustained loading provides a strong motion cue that cannot be reproduced in hexapod simulators. SUPRA experiments showed that there is a clear effect of g-load on pilot control behaviour; pilots tend to over-g the aircraft when the g-cue is absent while they do not with g-cueing. Moreover, the presence of the actual g-load affects recovery behaviour from an upset, and pilots without previous g-experience are not able to accurately judge the g-load based on the seat of the pants , .

A disadvantage of centrifugation is that it generates false cues; the centrifuge has to accelerate and decelerate, which might be noticed by the pilot (Figure 1 24). To prevent this Coriolis cross coupling false cue, a new way of g-cueing was developed within SUPRA, where the cabin is kept in a fixed orientation, with the pilot facing inward. Although cross coupling is now prevented, this solution comes at the price of misalignment of the specific force vector in the pitch plane. Experimental findings, however, showed that this misalignment is rather small and not found disturbing by pilots.

Figure 1 25. Alternative cabin orientation (right) used in SUPRA as compared to conventional centrifuges (left).

Another important aspect of the g-cueing research within SUPRA concerned the fading in and out of the centrifuge. Commonly, centrifuge devices spin at a certain baseline g-level (often between 1.2 to 1.4g) before pulling higher g's, which their response rate. The increased g-level now becomes the new simulated 1g level. This constant loading of the pilot has the disadvantage that the omnipresent yaw rotation is felt by pilot when the slightest head movement is made. To cope with these disadvantages, a transition to the centrifuge mode was developed which only is active during the recovery phase when the airplane is loaded. In the preceding phases of approach to stall and the stall itself aircraft motion was simulated using onset cueing (Figure 1 25).

Figure 1 26. Filter scheduling used at DESDEMONA to combine onset and centrifuge cueing.

Here, the Desdemona motion cueing is comparable to a conventional hexapod simulator, i.e. merely simulating onset cues, albeit with larger excursions than standard hexapod systems. At the onset of aircraft buffet a transition phase was initiated where the centrifuge spins up slowly, in order to be at the required baseline level at the moment the pilot starts loading the aircraft. The transition benefits from some masking by the buffet motion. In the g-cueing regime the simulated normal load acting on the pilot, ranging from 1 to 2.5g, is mapped upon normal load generated by the simulator, ranging from 1.3 to 2.5g. The subsequent unloading of the aircraft back to a normal load of 1g would require a deceleration of the centrifuge back to stand still. Because this can cause disorientation (the pilot feels a yaw rotation in the opposite direction), it was decided to decrease the g-load at a lower rate than would be specified by the aerodynamic model. This spin out is therefore no longer part of the simulation, but an inevitable consequence of using the centrifuge.

1.3.3.2.2 Direct pitch tilt

A disadvantage of the conventional hexapod simulator is its inability to provide sustained g-cues for loading and unloading. To mitigate this problem a new cueing solution was developed at DESDEMONA based on the mechanism of tilt coordination: The algorithm converts the vertical acceleration from the aircraft model as input into cockpit pitch tilt, proportional to the load factor. The direct pitch cueing algorithm was evaluated in the evaluation phase of SUPRA both by

DESDEMONA and TsAGI, and the results showed that the majority of pilots (64%) preferred this solution over classical hexapod cueing (Figure 1 26). It seems unlikely that the small change in the magnitude of the normal load vector is causing the feeling of unloading. Rather, it was assumed that the longitudinal component causes the percept by inducing a feeling of released back pressure and increased pressure of the seatbelt on the upper part of the body, which is consistent with actual unloading. In a similar fashion, backward tilt can provide a sensation of loading, since the pilot is being pushed into the chair with the pressure on the seatbelt releasing.

Figure 1 27. Direct pitch to simulate unloading and loading (left) and pie chart showing pilots' preference (right).

In summary, the motion cueing developments in DESDEMONA focused on 3 elements:

1. Mitigation of false cues (Coriolis cross coupling) during centrifugation by limiting the amount of cabin reorientation.
2. Integration of onset cueing and centrifuge cueing, to start up the centrifuge only when it is needed for recovery.
3. Pitch tilt for loading/unloading.

1.3.4 SUPRA Motion perception model

In parallel to the motion cueing developments within SUPRA, another work package aimed to improve understanding of the pilots' perception of self-motion, i.e. aircraft or simulator motion. On the one hand this work package involved carrying out experiments to collect new psychophysical data (some of which already have been touched upon in the description of motion cueing activities in the above section 1.3.3). On the other hand, the motion perception work involved improving motion perception modeling. This modeling work will be summarized in this section.

The SUPRA motion perception model used the TNO model as a starting point upon which to build. The TNO model contains a set of mathematical transfer functions describing the dynamics of the human motion sensors (the visual and vestibular system) and their interactions. It has been implemented as a Simulink program. The model's input is six degrees of (self) motion, and the 3-D orientation, and the model's output is the predicted perception of self-motion and orientation. The main limitation of the model is that it does not include perception thresholds. Consequently, the model always gives a non-zero output for a non-zero input, while it is well-known that certain (aircraft) motions remain unnoticed (corresponding to a zero output?). Hence, within SUPRA the TNO model was extended by implementing a non-linear Weber-Fechner block?, based on a model developed by TsAGI, which accounts for the fact that a (motion) stimulus is only perceived when it exceeds a certain threshold value. It also describes the effect that whether or not a difference between two stimuli is perceived depends on the ratio between the magnitudes, a concept known as just noticeable difference (JND). This non-linear block is given by: where i is the axis (x, y or z) , is a small (10-9) value to ensure the operand of the logarithm is never zero, S0 is the absolute threshold and k is the normalization factor from the experimentally-obtained axis-specific Weber fraction. One of the most significant and powerful changes that this model provides is that its output is given in perceptual units, rather than real-world kinematic units. The output therefore, cannot be related to kinematic signals, for example velocity must be considered as perception of velocity not a quantity in degrees per second. This means that comparisons must be done with similar values. Analyses that can be done include: comparison to zero (is something perceived or not?), and magnitude comparison (is it larger or smaller?).

1.3.4.1 Model validation

The new motion perception model was validated by analysis of several time histories of simulated aircraft and commanded simulator motion obtained during the SUPRA evaluations at NLR and DESDEMONA, including subjective pilot responses. Each trial was run twice through the perception model, once with the motion of the aircraft model and once with the commanded motion of the simulator.

Figure 1 27 shows an example of the model-predicted perception of the subjective vertical? or SV (i.e. perceived aircraft attitude) for the transition from unloading to loading in the g-cueing mode of DESDEMONA. The shaded area shows the discrepancy between the perceived SV in the aircraft and in the simulator. The upper plot is the result of a model run with the visual input taken from the aircraft model's motion, representing the out-of-the-window (OTW) display. However, considering the fact that during this pitch upset the OTW did not show useful information about the aircraft's attitude all the time, since the nose is pitch up or down too much to see the Earth horizon, the model was run once more with the simulator cabin interior as reference for vertical. The result of this model simulation is shown in the lower plot. This shows less fluctuation of the perceived mismatch in pitch, which explains the effectiveness of the direct pitch trick as described in section 1.3.3.2.2. It is noted that the perception model also provides the perceived aircraft motion for the other degrees of freedom, but it is beyond the scope of this summary to discuss this in more detail.

FigFigure 1 28. Time history of discrepancy between the perceived subjective vertical in the aircraft and DESDEMONA, depending on the visual input. See text for explanation.

In summary, the SUPRA motion perception model integrates the deterministic TNO model with the perception threshold model of TsAGI, and correctly predicts a number of perception aspects of SUPRA simulator trials. When the z (and x) components are much smaller in the simulator than the aircraft, it is perceived, as well as the rotation of the centrifuge appearing as a false cue.

1.3.5 Evaluation of SUPRA concept

In the final phase of SUPRA, a total of 12 expert test pilots (42-61 years; between 7,200-22,000 flight hours) with actual experience in stall conditions, participated in validating the SUPRA aerodynamic model and motion cueing solutions. They were asked to evaluate the aircraft model's usability for upset simulation and if it is representative of the aircraft class behaviour within and outside the normal flight envelope. The model was developed to be representative of a commercial airliner in conventional configuration, under-wing mounted engines and a fuselage mounted horizontal tail with a maximum take-off weight of approximately 100 tons (Figure 1 29). After the aerodynamic model evaluation, pilots were asked to evaluate the different motion cueing solutions in terms of required motion cues, on the one hand, and false cues, on the other hand. The evaluations were coordinated between the research institutes (TNO, NLR, TsAGI).

1.3.5.1 Aerodynamic model evaluation

Before the evaluation, pilots were familiarized with the cockpit and the SUPRA aerodynamic model with the simulator operating in the fixed-base mode. Subsequently, the key aerodynamic behaviour during normal flight was evaluated, including three unusual attitudes recoveries (nose-high, wings level recovery; nose-high, bank recovery; nose-low high-bank recovery. For the evaluation of stall behaviour the simulator was operating in conventional cueing (NLR and TsAGI hexapod platforms) or onset cueing mode (Desdemona). The evaluation involved both approach-to-stall and developed stall scenarios. Stall scenarios either were; symmetric without roll instability; symmetric with mild roll instability; asymmetric with mild wing drop; or asymmetric with a large and aggressive wing drop.

Rating A - Aeromodel B - Key Motion Cues C - False Cues

1. 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. 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. 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. 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

Table 2. Rating scales for acceptability of aerodynamic model (A), and key motion cues (B) and false motion cues (C).

Pilots rated the airplane behaviour for a set of pre-defined characteristics. In addition to these detailed characteristics, they also gave ratings for the overall aerodynamic performance of the model inside and outside the normal flight envelope. In general, the aerodynamic model was rated as highly representative, especially for stall behaviour.

After assessing the normal handling, the pilots performed several manoeuvres exploring the edge of the envelope and beyond. This included both approach to stall and developed stalls (symmetric or pitch-up stalls and asymmetric or wing stalls). The simulator was operating in Conventional+ mode (Desdemona) or conventional hexapod (GRACE/PSPK-102) in this part of the evaluation. Again the pilots judged whether the aerodynamic characteristics were representative for the specified aircraft type or not and gave the acceptability rating for stall behaviour (see Table 4.1, column A). A detailed list of the manoeuvres and the scoring items can be found in Deliverable D-6.1. For all manoeuvres the pilots also indicated whether they found them relevant for training or not.

1.3.5.2 Motion cueing assessment

The motion cueing assessment was carried out in the same way on all three simulators, and consisted of four stall scenarios; stable roll symmetric stall, instable roll symmetric stall, mild instable roll asymmetric stall, and intense instable roll asymmetric stall. In the Desdemona trials, each stall case was flown in the three different motion configurations in a fixed order (Buffet motion only Onset Cueing Centrifuge). In the NLR simulator trials also three different configurations were flown (Buffet motion only Classic Workspace / Perception Optimized).

The pilots were asked to assess the motion cues with relation to the aircraft motion that was indicated in the simulator. They rated the strength of the motion cues in the key motion axes as well as the inaccuracies or false cues, identifying whether these would represent a disturbance for a training environment.

he subjective assessment of the experimental test pilots indicated that the modifications to the motion cueing algorithms were an improvement to current motion cueing on hexapod simulators. Initially, the experiment at NLR concentrated on the evaluation of a workspace optimized algorithm, the TsAGI experiment concentrated on a perception optimized algorithm. At a later phase in the SUPRA experiment programme, the NLR and TsAGI motion cueing solutions were integrated and evaluated at both the NLR and TsAGI simulators.

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

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

1.3.5.3 Evaluation results of SUPRA aircraft model

In general, the aerodynamic model was rated as being quite accurate, especially for stall behaviour (see Figure 1 29). For the normal flight behaviour seven out of ten pilots rated an acceptability of 2, three rated 1. For stall behaviour, seven pilots rated a score of 1, and three others gave a score of 2 (representative with minimal or minor pilot adaptation, respectively). This means that all pilots found the SUPRA aerodynamic model acceptable for pilot training. In particular pilots commented that the large roll-off manoeuvres were realistic and not part of current simulator models, and that also the buffet is very realistic.

Figure 1 30. Summary of acceptability ratings of the aerodynamic model in normal flight and during stalls.

1.3.5.4 Evaluation results of hexapod motion

Figure 1 30 shows the median pilot ratings of the motion fidelity of the different hexapod cueing solutions tested at both NLR and TsAGI. The tested motion filter solutions include the classical, workspace and integrated workspace- and perception-optimized cueing (indicated as Perception optimised cueing). On both the NLR and TsAGI hexapod platforms motion cues were consistently rated as too weak for classical motion, but ratings improved with the SUPRA workspace/perception optimized cueing. The classical cueing showed a wide variation of acceptability (including unacceptable?) among pilots, while the perception-optimized cueing resulted in the acceptable range up to ratings of 1. Both the classical and the workspace-optimized cueing were rated as acceptable for symmetrical and asymmetrical stall manoeuvres. However, the workspace-optimized cueing generated some unacceptable false cues in the asymmetrical stall cases, since this cueing solution was operating close to the mechanical limitations of the simulator. The perception-optimized cueing clearly produced the least false cues in all extreme stall manoeuvres. This is due to the attenuation of cues by this cueing solution in the loading phase due to g-effect, resulting in less mechanical platform constraints. On both hexapod platforms the expert pilots consistently preferred the SUPRA motion cueing over the conventional motion cueing algorithms. In particular, it was demonstrated that the perceived hexapod motion cueing during the highly dynamic entry phase of the (stall) upset, for example the aircraft wing drop and roll-off, was reproduced in a hexapod simulator closely to what can be expected in the real aircraft.

Figure 1 31. Motion fidelity ratings (left) of key motion cues (middle) and false cues (right) at GRACE simulator.

As the percentages in Figure 1 31 show, the optimized cueing solutions (Workspace and Perception) were preferred over the classical cueing. No negative effect was observed when upset or stall maneuvers were flown on motion compared to fixed base. This suggests that motion can be applied for Upset Prevention and Recovery Training (UPRT) on conventional hexapod simulators.

Figure 1 32. Preferred motion configuration for symmetric and asymmetric stall cases (GRACE/PSPK-102).

1.3.5.5 Evaluation results of DESDEMONA motion

Regarding the motion fidelity of DESDEMONA, Buffet only was consistently rated as too weak. The Onset Cueing on the Desdemona yielded a slight improvement in ratings but a large spread can be observed, especially during the unloading phase of the upset; g-cueing seemed to reproduce key motion cues at appropriate magnitude (Figure 1 32). The pilots noted that the large roll-off manoeuvres felt realistic, which was considered an advantage over current hexapod simulators. Like in the hexapod simulators, the enhanced buffet cueing at the onset of aerodynamic stall was rated highly realistic. The centrifuge-based g-cueing reproduced the key motion cues of appropriate magnitude, with a median rating of 1 equivalent to the real airplane, as shown in Figure 1 32 (middle). However, this comes at a price: for symmetrical stall scenarios g-cueing the median false cue rating was a 3 (non-acceptable) due to the conflicting motion generated by centrifugation (Figure 1 32, right). Remarkably, the median false cue rating improved from 3 to 1 (no perceivable false cues) for asymmetric stall scenarios. In these scenarios the highly dynamic cueing environment seems to mask some of the false cues caused by spin-up and spin-down of the centrifuge. In addition, these cues were mainly in the pilot?s lateral plane which is more congruent to the lateral aircraft motion during the stall. As a result, g-cueing was selected as the preferred cueing option for asymmetric stalls by 90% of the pilots (8 out of 9 pilots), as shown in Figure 1 33.

Figure 1 33. Expert pilot ratings (left) of key motion cues (middle) and false cues (right) in DESDEMONA.

Figure 1 34. Preferred motion configuration for symmetrical stall cases and asymmetrical case.

1.3.6 Conclusion

It can be concluded that SUPRA successfully extended a generic aerodynamic model to capture the key aerodynamic behaviour of transport category aircraft at high incidence flight. The enhancement of the aerodynamic model, combined with modifications to the motion cueing on both hexapod- and centrifuge-type simulators provide a state-of-the-art platform for upset recovery training. Based on the judgments of highly experienced test pilots it was shown that current hexapod motion can be improved without introducing new unacceptable false cues, so as to provide realistic feedback about the lateral and directional dynamics occurring at the initial part of the upset and stall entry. When available, centrifuge-based motion cueing was considered the preferred solution to simulate the full range of motion of upset recovery. Hence, a centrifuge-type simulator seems to have potential to familiarize airline pilots with the physical demands during upset recovery in a transport cockpit environment, and demonstrate the effects on their spatial orientation, situational awareness and control behavior. Continuation of recurrent upset training can then be conducted on an enhanced full flight simulator where the role of recovery procedures as part of multi-crew operations in a full traffic environment can be introduced.

Potential Impact:

Aircraft safety has been greatly enhanced by technical improvements and new training concepts during the last decades. European accident improvement rates are lower than in the rest of the world. Accident rates fluctuate around 0.05 fatal accidents per 100.000 flights, resulting in a persistent absolute number of accidents. In the last decade the annual average of fatal accidents in fixed wing aircraft in public transport operations was 60 world-wide, and six in Europe . With the increase of air traffic no significant reduction in absolute numbers of accidents is foreseen. In terms of passenger-kilometres, traffic at the airports at EU Member States increased five-fold since 1970. The forecasted two- or three fold increase of air traffic by 2020 implies that the number of accidents and related costs will increase substantially over the years. Aviation accidents in general lead to direct and also indirect (social) costs, which have to be borne by society, as they are not completely covered by the aviation sector itself. According to an analysis by the US Department of Transportation the recommended value of a statistical life (VSL) is 3.6 million Euros ($5.8 millions) . This analysis highlights the higher impact that accidents have for society, and emphasize the importance of increasing safety levels. The aim of SUPRA was to improve aviation safety by increasing the pilots ability to recognize and recover from unexpected upset recovery situations. Considering the increased VSL, there will be a positive return on investment of the research.

In the offing of SUPRA, international initiatives have investigated the need for additional investment in Aviation Safety, i.e.: European Aviation Safety Agency (EASA), European Commercial Aviation Safety Team (ECAST) and others. In this effort, a wide range of communities going from regulators (EASA, FAA, Eurocontrol, UK CAA, IFA, DGAC, CAA-NL), operators (IATA, AEA, BA, BMI, Brussels Airlines, ATA-USA), manufacturers (Airbus, Boeing, Dassault Aviation, Fokker Services, Embraer) to professional organisations (AEI and ECA), identified loss of control in-flight (LOC-I) among the top five safety issues. LOC-I is a cause of aviation accidents, accounting for most of the fatalities worldwide. The most recent Boeing safety review listed LOC-I as the most common category of fatal accidents in the period 2002-2011, accounting for 18 accidents (1493 fatalities) world-wide . The Russian Interstate Aviation Committee (IAC) initiated the founding of a Russian Centre for Upset and Stall Training with its main to counter the contribution of upset and stall in flight accidents.

The initiatives mentioned above indicate the necessity of investigating the causes and solutions that need to be in place to minimize this type of events. The SUPRA project developed a solution by means of replicating such events in a representative environment and suggest changes to current flight simulators to improve pilot performance during this critical events. This also fits in with the vision of IATA that there is a need for enhanced simulator training in order to reduce the accident rate (IATA Safety Report, 2007, Montreal).

SUPRA also complies with the objectives stated in the 7th Framework Programme of the EC, in Areas 7.1.3.3 Aircraft Safety and 7.1.3.4 Operational Safety:

1. To reduce the accident rate by 80%;
2. To achieve a substantial improvement in the elimination of and recovery from human error.

The results of SUPRA showed that the capabilities of existing training simulators can be enhanced by extending the aerodynamic aircraft models, and optimizing the reproduction of motion cues. The SUPRA technologies should be further developed into an effective medium to improve pilot flight handling skills to re-establish stable control of the aircraft after upsets. This will lead to a significant reduction of LOC-I accident rates, which contribute to 10-20% of all fatal accidents in public air transport. In addition, the SUPRA concept also provides a valuable test-bed for research and development of, for example, new cockpit technologies (avionics), and automatic recovery support. This does not only reinforce their competitiveness, but also contributes to an improved capability for avoiding and recovering from human errors.

The SUPRA developments were closely coordinated with the industry research and development that is being carried out by the Royal Aeronautical Society International Committee for Aviation Training in Extended Envelopes (ICATEE) working group. This group is made up of a wide cross-section of aviation industry expertise to investigate and make recommendations for upset prevention and recovery training. The ICATEE group has been investigating the requirements of simulators to support upset prevention and recovery training, in which the SUPRA research has played an important role. The extension to the aerodynamic envelope that has been developed and tested in SUPRA would support the core elements of the ICATEE recommended training. In addition, the motion cueing research that has been carried out in SUPRA is being used to inform the recommendations for simulator research and development from the ICATEE group.

The recent law that has been passed by the United States congress requires full stall training to be included in Part 121 flight operations . As a result of this law, the United States Federal Aviation Administration has issued an Advisory Circular that recommends training for approach-to-stall and stall scenarios on flight simulator training devices . The FAA describes the potential limitations of current FSTD aerodynamic models, and highlights the recommendation for additional validation of the FSTD for training of full stalls. The SUPRA work has contributed to the ongoing research into the updates to simulator standards internationally for the support of stall training. While the regulatory work is currently ongoing in the United States, the European Aviation Safety Agency is closely involved in the international working groups such as ICATEE and the ICAO/FAA joint Loss of Control Avoidance and Recovery Training (LOCART) group which is expected to provide training rulemaking recommendations. The SUPRA developments are available to support the future research and development for the aviation industry in response to the developing regulations.

1.4.2 Dissemination activities

Throughout the project considerable effort has been made to coordinate the work with past and on-going related efforts. Especially in the field of extended envelope modelling SUPRA engaged with key NASA and Boeing experts who were part of the U.S. Extended Upset Recovery Simulation (EURS) project about a decade ago. Further, SUPRA ensured future applicability of the R&D performed by direct involvement in the Royal Aeronautical Society's ICATEE (International Committee on Aviation Training in Extended Envelopes), a group currently developing guidelines for improved upset training and facilities which are being proposed to ICAO for inclusion in future regulatory material. At the end of the project, an international symposium on the SUPRA results was organized which was attended by about 80 stakeholders, including airplane manufacturers, operators and aviation authorities.

The progress of SUPRA was presented on multiple conferences, lobby events, and networking occasions, such as:

- Three meetings with Research and Licensing Department at EASA (Cologne): the European Aviation Safety Agency was tracking the progress of SUPRA throughout the project, as one of the primary stakeholders the SUPRA project provided in depth briefings to EASA, on-site in Cologne, Germany;

- EC RTD Aerodays, Madrid, 2011: the project was showcased with a technical presentation as well as the press conference.

- EC Innovation Days, Brussels, December 2011: the project was presented at a stand at the exhibition.

- ICATEE meetings and telephone conferences: the project continuously coordinated with the International Committee on Aviation Training in Extended Envelopes.

- ICAO LOCART group: The LOCART group was initiated late 2012 to collect and bundle all LOC related activities worldwide and translate their output into ICAO rulemaking, SUPRA provided an in-depth briefing to the group in late 2012.

- Start Alliance Safety Conference 2012, main results of the project were presented to the safety officer of the airline alliance early 2012, the project could rely on help from the external expert group for that task.

- Numerous scientific conferences (AIAA, CEAS, EAAP, EUCASS, ICAS, etc.)

- EU project workshops (i.e. ADDSAFE EU/IEEE Final Workshop)

- Articles in newspaper and magazines (e.g. Dutch Telegraaf, De Ingenieur)

- Television (Euronews, national broadcast news)

- Company news releases (e.g. via public website, internal journals, annual report)

A detailed list of the dissemination activities is provided in section Use and Dissemination of Foreground.

List of Websites:

The project website http://www.supra.aero was published three months after the start of the project. It consists of a public part for dissemination of general project information, and also has a private password-protected part with a document sharing system which is used by the consortium to exchange documents. In addition, another private part is used to share information with the SUPRA Expert group. The website was developed with support of the Dutch company FP-tools (http://www.fp-tools.eu/home.htm).