Effect of G-cueing on Pilot Performance in Centrifuge-Based Simulation of Unusual Attitude Recovery

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The aim of the collaborative European research project ‘Simulation of UPset Recovery in Aviation’ (SUPRA) is to develop breakthrough simulator technologies for teaching pilots to detect and recover from adverse flight upsets that could lead to unusual attitudes and loss-of-control. In the project, the high-performance research simulator DESDEMONA is utilized, which integrates a flight simulator having a six-degrees-of-freedom motion platform with a sustained acceleration capability up to 3.0g. These characteristics result in improved simulation of motions encountered in upset conditions, compared to conventional fixed base or hexapod simulators. This paper describes a study consisting of two experiments to determine how accurate pilots can judge and reproduce a specific G-level in the DESDEMONA simulator, and respectively, how their control behavior depends on G-forces during unusual attitude recovery. In total seventeen civil pilots, without previous G-maneuvering experience, participated in the study. The results show that pilots without previous G-exposure tend to overestimate G-levels based on their seat-of-the-pants, resulting in performance below the target G-level. With minimum training, their performance instantly improved up to adequate level. However, a retest after six months showed that this improvement did not endure. With respect to aircraft control during recovery from a nose-low unusual attitude, the pilots showed significantly better performance with G-cueing simulation, in terms of deviation from the target G-load, compared to fixed-base simulation in which they tend to ‘over-G’. It can be concluded that G-cueing simulation results in improved upset recovery performance of civil pilots compared to Fixed-base simulation. Hence, simulation of upset recovery with G-cueing may result in more realistic and adequate recovery training.

I. Introduction

In the past decades aviation has become one of the safest ways of transportation due to introduction of additional safety systems, improved training and operations, and new regulations. Whereas most accident rates have strongly decreased, loss of control in-flight (LOC-I) is left as one of the last remaining factors for aircraft accidents. In fact, LOC-I is recognized as the leading cause of fatal accidents in commercial aviation today. In the course of loss of control events, aircraft often enter into unusual attitudes or stalls, also called upsets, developing in loss-of-control. To prevent, or adequately recover from a loss-of-control situation it is essential that pilots timely recognize the condition, initiate recovery action and follow appropriate recovery procedures. However, many commercial pilots have never experienced a LOC-I situation, neither on transport aircraft nor during training on smaller airplanes. Training on a real aircraft is unsafe and prohibitory expensive, while training on small aerobatic aircraft may be not representative for larger aircraft. As a consequence, pilots may not be proficient in dealing with such...
critical events, indicating the need for specific upset recovery training. The FAA-Industry Airplane Upset Recovery Training Aid was an important step to improve theoretical understanding, recognition and recovery from unusual attitudes and stalls, using conventional hexapod simulators for demonstration and training of recovery techniques. However, due to the lack of validated aircraft models outside the normal operating envelope, the training aid remains limited to maneuvers within this envelope. As analysis of LOC-I accidents shows, upset events can take the aircraft outside the normal envelope which justifies investing Research & Development effort into modeling and simulation of these flight regimes. The Seventh European Framework Program project SUPRA – Simulation of Upset Recovery in Aviation – aims at filling this gap by extending dynamic aircraft simulation models beyond the current state-of-the-art and investigating the feasibility of conducting advanced upset recovery simulation on hexapod-type as well as centrifuge-based simulators.

Efficient recovery from commercial transport aircraft upsets may require the crew to load the aircraft up to the so-called limit load of +2.5g (or up to +3.8g depending on design takeoff weight). However, standard flight simulators, featuring a hexapod motion base, are incapable of reproducing sustained G-loads. Therefore an important research question in the SUPRA project concerns the application of the new-generation simulator facility DESDEMONA, as presented in Fig. 1, for the purpose of upset recovery simulation.

In the context of the SUPRA project we are performing motion perception studies in DESDEMONA to develop G-cueing solutions for the purpose of upset recovery simulation. For example, in a previous study we investigated how sensitive pilots are for deviations in the magnitude of the simulated G-load. In the current study we investigated how accurate pilots without previous G-training perceive and reproduce G-loads in the DESDEMONA flight simulator. More specifically, we addressed the following research questions:

1a) How accurate do pilots, without previous G-exposure, judge and reproduce G-loads within a representative range for upset recovery of transport aircraft?

1b) Does the pilots’ performance to reproduce G-levels improve with simple G-training in the simulator, and are the effects of this (minimal) training still noticeable after six months?

2) Does G-cueing improve the pilots’ performance in controlling a recovery from a nose-low unusual attitude, which requires loading the aircraft up to +2.5g?

II. Methods

A. Subjects

In this study one female and sixteen male commercial pilots participated. Their mean age was 23 years, ranging from 20 to 30 years. On average they had 413 flight hours, ranging from 54 to 2650h. Fifteen pilots had just graduated from flight academy with a type-rating for the Boeing 737 NG or Embraer E-190, and had no or little
commercial flight experience. Two other pilots had already cumulated 1210 respectively 2650 flight hours as commercial pilots on the Fokker 70/100, and had just completed Embraer E-190 type-rating. The inclusion criterion for the experiment was that the pilots had negligible (less than five hours) experience with in-flight aerobatics or G-maneuvering. Before the experiment, all subjects signed an informed consent, stating that they participated voluntarily in the experiment. The experiment was conducted with approval of the institutional ethical committee. Participants received a financial reimbursement in return for taking part in the study.

B. Apparatus and Materials

The experiments were performed in the DESDEMONA research simulator. This facility features a full flight simulator with six degrees-of-freedom of motion including a centrifuge axis. The simulator cabin is fully gimbaled 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 155°/s DESDEMONA can simulate sustained G-loads of up to 3.0g. Compared to Dynamic Flight Simulators, DESDEMONA offers lower G-loads, but more degrees-of-freedom of motion, combining onset cueing along its axes (like a hexapod simulator) with sustained acceleration cueing for simulation of sustained G-loads. The simulator’s motion limits are listed in Table 1.

Although the study was oriented to controlling transport aircraft, no such cockpit configuration was available at the time of the experiment. Instead, the cabin was equipped with F-16 flight controls; thrust was controlled with an F-16 throttle, and pitch and roll were controlled with an F-16 (force) side-stick, which is called ‘Hands On Throttle And Stick (HOTAS). Aircraft yaw could be controlled with rudder pedals, while trim was adjusted with the trim-knob on the stick. The sampling frequency of the controls was 60Hz.

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 60Hz. Three projectors (resolution 1024 x 768 pixels) projected the image on a three part flat screen, placed approximately 1.5m from the eye reference point, creating an out-of-the-window field-of-view of 120° horizontally and 32° vertically. Image edge blending and distortion was also computed in the image system. The instrument panel was presented on the centre outside visual screen, while a G-meter was displayed on the head-down LCD screen.

Motion driving algorithms were implemented in MATLAB Simulink ®. The commanded motion was logged in MATLAB ® with 10Hz. Commercial of the shelf flight simulation software was used for the simulation of the aircraft model, instrument panel visualization and outside visuals.

C. Centrifuge Setup and Motion Cueing Algorithm

In a classical centrifuge the pilot is facing the direction of motion, while the free-swinging gondola remains aligned with the specific force, i.e. the gravito-interal force (GIF) vector, while variation in G-load is accomplished by increasing or decreasing the angular rate of the centrifuge. A disadvantage of this configuration is that, due to cross-coupled stimulation, pilots can experience strong and uncomfortable tumbling sensations during acceleration and, in particular, deceleration of the centrifuge which can provoke motion sickness and serious nausea.

For this reason we developed an alternative solution in DESDEMONA, where the cabin is positioned 4.0m from the main centrifuge axis and re-oriented so that the pilot is tilted backward and facing outward in a fixed position, as can be seen in Fig. 2. Although the pilot now is oriented orthogonal to the direction of motion, his body is aligned with the GIF. In this way, the angular motion artifacts occur mainly in the pilot’s roll plane. Besides that, because of the fixed orientation of the cabin during acceleration and deceleration of the centrifuge, the solution prevents from cross-coupled stimulation. We have found that this approach indeed leads to fewer problems with nausea. A consequence of the alternative solution is that the direction of the GIF with respect to the pilot is changing in the pilot’s pitch plane during acceleration and deceleration of the centrifuge. Besides that, some mild side-slip effects are introduced, which are minimized by slightly rotating the cabin.

### Table 1. DESDEMONA simulator motion characteristics

<table>
<thead>
<tr>
<th></th>
<th>Centrifuge axis</th>
<th>Radius track</th>
<th>Heave track</th>
<th>Cabin roll</th>
<th>Cabin yaw</th>
<th>Cabin pitch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>&gt;360°</td>
<td>+/- 4.0 m</td>
<td>+/- 1.0 m</td>
<td>&gt;360°</td>
<td>&gt;360°</td>
<td>&gt;360°</td>
</tr>
<tr>
<td>Velocity</td>
<td>155 °/s</td>
<td>3.2 m/s</td>
<td>2.2 m/s</td>
<td>180 °/s</td>
<td>180 °/s</td>
<td>180 °/s</td>
</tr>
<tr>
<td>Acceleration</td>
<td>45 °/s²</td>
<td>4.9 m/s²</td>
<td>4.9 m/s²</td>
<td>90 °/s²</td>
<td>90 °/s²</td>
<td>90 °/s²</td>
</tr>
</tbody>
</table>
The motion cueing algorithm uses a baseline rotation at a constant G-level (e.g. 1.2g or 1.4g), resulting in a slightly elevated G-level during simulation of 1.0g straight-and-level flight. This technique is commonly applied in centrifuge-based flight simulation to improve the simulator response time. It also minimizes the directional shift of the GIF during acceleration and deceleration of the centrifuge (e.g. acceleration from 1.0g to 2.5g results in a 66.4 degrees directional shift of the GIF, while acceleration from 1.4g to 2.5g only rotates the GIF with 22.0 degrees). The semicircular canals within the vestibular system respond to this constant baseline rotation with a transient response, which fades soon after steady state is reached. Hence, after about twenty seconds, the baseline condition gives the sensation of flying ‘straight and level’ when subjects do not make any head movements. As a consequence of this technique, the actual G-load (i.e. the magnitude of the GIF) does not exactly match the simulated aircraft G-load for levels below the baseline G-load. Furthermore, the actual G-load was clipped at the maximum hardware limit of 3.0g. Figure 3 shows a flow chart of the pilot control input resulting in a simulated G-load as calculated by the aircraft model, the motion driving algorithms, and finally the actual G-load measured in DESDEMONA. In this paper we will refer to the different G-loads as presented in this picture.

**D. Signal Processing**

In off-line analysis, the time history of the specific force was calculated in pilot’s coordinates from the logged linear accelerations in x, y, and z directions. This signal was smoothened with a fourth order Butterworth filter with cutoff frequency 0.11Hz, which is well above the frequency of interest since higher frequencies are not relevant in
determining the general G-profile trend. To prevent from time delays, a non-causal filter (filtfilt zero-phase forward and reverse filtering in Matlab®) has been used. An example of this filtered signal is shown in Fig. 4.

![Figure 4. Part of example time history of a G-learning profile with raw signal (thin line), average of peaks (dashed line), and smoothened signal (thick line).](image)

**E. Design and Procedure**

The entire study was completed in five consecutive work days. Except for the first day, when only one pilot was invited to rehearse and optimize simulator procedures, pilots were invited in pairs; two in the morning, and two in the afternoon. Pilots alternately participated in three simulator trials of about 20-30 min, each dedicated to different experiments; two sessions were related to the experiments addressed in the current paper, while a third session was related to another experiment, which is beyond the scope. By alternating between pilots we reduced simulator down time and also minimized accumulation of motion sickness. Total simulator time for each pilot cumulated to about two hours. The 20-30 min breaks were spent in a different room where pilots could not see the simulator. Seven pilots were able to participate in a retest on their G-performance six months after the initial session. In the next sections research question 1 (1a and 1b) and research question 2 will be treated as two different experiments.

1. **Experiment 1: G-performance**

The first experiment addressed research question 1a): How accurate do pilots without previous G-exposure reproduce G-loads in a centrifuge when they have no feedback on their performance, and how does this improve after training with feedback on their performance. Research question 1b) was addressed by the Re-test after six months. In the experiment, pilots were asked to reproduce two G-levels, 2.0g and 2.5g respectively, in four different tests (Pre-test, Training, Re-test 1, and Re-test 2), as shown in Table 2. The first three tests were performed within their first participation, consisting of a Pre-test without G-meter, a (double) training test with G-meter, and a Re-test 1 immediately after the training test. The fourth test (Re-test 2) was performed six months later, also without G-meter.

For the purpose of this experiment, the simulator was operated from a baseline centrifuge of 1.2g, and no outside visuals were displayed. For all subjects, the order of conditions was fixed, because of the psychological impact; subjects should experience the lower G-level first. Subjects were asked to control the G-load, by pulling the stick, as accurately as possible, and to maintain it for three seconds before releasing the stick. The subjects did not see the simulator move in any way before they went in for the experiment.
2. Experiment 2: Effect of G-cueing on control performance in pull-up maneuver

After the first experiment, we addressed research question 2) in the second experiment; i.e. the effect of G-cueing on pilot control during a pull-up maneuver from a nose-low attitude. Since the aircraft model used for this study did not allow for realistic upset recovery simulation outside the normal envelope, we chose a pull-up maneuver as a simplified analogue for upset recovery from an unusual attitude within the envelope, requiring a G-load of 2.5g. In this experiment we compared the pilots’ performance between a Fixed-base condition and a G-cueing condition, measured in deviation of the controlled G-load from the target G-level. In the Fixed-base condition no simulator motion was present, while in the G-cueing condition DESDEMONA was operated in the centrifuge mode with a baseline G-level of 1.4g. The rationale for choosing a baseline of 1.4g rather than 1.2g was that this creates a larger envelope for simulation of unloading (e.g. at the top of a parabola), by slowing the centrifuge down below baseline level. The subject pilots were kept naïve about the motion conditions, and they did not see the simulator move before the experiment. The dependent variable was the maximum simulated G-load achieved during the recovery from nose-low unusual attitude.

In each condition, the pilots performed three recoveries from a 30° pitch down attitude. They were told to recover with a maximum load factor of 2.5g and minimum altitude loss. Each maneuver was initiated at 180kts, where the pilot controlled the aircraft to a 30° pitch down attitude. The pilots were instructed to keep the airspeed within 320kts and keep the throttles in idle position. After the recovery pilots were told to climb with a pitch angle of 10° until airspeed was 180kts again at which the next maneuver commenced. Due to energy loss during the preceding maneuver, there was a cumulative altitude loss over the three consecutive maneuvers. The flight model and instrument panel were derived from a modern short- to medium-range generic twin-engine narrow-body jet airliner with wings-mounted engines and fuselage mounted tail planes.

F. Motion Sickness and Safety Instructions

A standard procedure in our simulator studies is to regularly have subjects rate their motion sickness symptoms according to the TNO misery scale (MISC)\textsuperscript{11,12}, as listed in Table 3. The stop criterion for the instructor is when the subject reaches a MISC of 7, while the subjects may decide themselves to stop at any moment.

<table>
<thead>
<tr>
<th>Symptom</th>
<th>MISC</th>
</tr>
</thead>
<tbody>
<tr>
<td>No problems</td>
<td>0</td>
</tr>
<tr>
<td>Slight discomfort but no specific symptoms</td>
<td>1</td>
</tr>
<tr>
<td>Dizziness, warm, headache, stomach awareness, sweating, etc</td>
<td>Vague</td>
</tr>
<tr>
<td></td>
<td>Some</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>Severe</td>
</tr>
<tr>
<td>Nausea</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Retching</td>
</tr>
<tr>
<td></td>
<td>9</td>
</tr>
<tr>
<td>Vomiting</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 2. Order of tests on G-performance experiment

<table>
<thead>
<tr>
<th>Test</th>
<th>N</th>
<th>Session</th>
<th>G-feedback</th>
<th>G-level (g)</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Pre-test</td>
<td>13</td>
<td>1</td>
<td>no G-meter</td>
<td>2.0</td>
<td>0 – 10'</td>
</tr>
<tr>
<td>2</td>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Training</td>
<td>13</td>
<td>1</td>
<td>with G-meter</td>
<td>2.0</td>
<td>10 – 20'</td>
</tr>
<tr>
<td>3</td>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td></td>
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<tr>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Re-test 1</td>
<td>13</td>
<td>1</td>
<td>no G-meter</td>
<td>2.0</td>
<td>20 – 30'</td>
</tr>
<tr>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Re-test 2</td>
<td>7</td>
<td>2</td>
<td>no G-meter</td>
<td>2.0</td>
<td>6 months</td>
</tr>
<tr>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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</table>

Table 3. The Misery Scale (MISC), developed and validated at TNO Human Factors
In addition to explaining the possibility of motion sickness to occur, we also briefed the pilots on the potential risk of sustained G-loads for fainting. Even at a moderate G-level of 3.0g, people may suffer from G-induced loss-of-consciousness (G-LOC) when such G-load is sustained for a long time without countermeasures. Therefore we explained to the pilots that when they felt light-headed, or experienced a gray-out, they should ease on the stick. We also practiced a breathing technique (‘straining’) by contraction of the stomach- and leg muscles, while blocking ones breath, so as to prevent the blood from pooling in the lower body part. During the G-sessions we continuously monitored the subjects and frequently asked for their well-being through two-way voice communication.

III. Results

Out of seventeen pilots participating in this study, three subjects were not able to finish the experiment because of nausea accumulating during centrifugation, and one subject was used to try-out different experiment aspects. This resulted in thirteen usable datasets for the experiments.

A. Experiment 1: G-performance

In Fig. 5 an example of a recorded G-profile time history is presented (thin line), together with the smoothened signal (thick line). Peak values (maximum achieved G-levels) were determined from the smoothened profile. This example shows that in the Pre-test, without G-meter, the G-load remained under the desired target levels of 2.0 and 2.5g. In the training with G-meter, both G-loads were reproduced accurately on target. In the Post-test, the achieved G-loads were higher than in the Pre-test but still deviated from the desired target levels.

We substantiated these observations with statistical tests, where effects with $p < 0.05$ were considered significant. First, the pilots’ performance (N=13) in the Pre-test was compared with the first Re-test using a repeated measures ANOVA in a 2x2 design (Test X G-load). There were significant main effects for both Test and G-load, showing a positive effect of training and a positive effect of G-load, respectively (see Fig. 6). There was no significant two-way interaction.

![Figure 5. Example time history of a raw (thin line) and smoothened G-profile (thick line). The thin dotted horizontal lines indicate the target G-levels of 2.0g and 2.5g](image-url)
We tested the deviation between the measured G-loads and the target G-loads using a two-sided t-test. The results showed that, in the Pre-test without a G-meter, the achieved G-load averaged over all pilots (N=13) was significantly less than the target value (see Fig. 6). In the training session with G-meter, the average reproduced G-loads did not significantly differ from the target value. In the first Re-test, the average performance did also not differ from the target value. Hence, these results indicate that untrained pilots significantly pulled less G-load than desired and that immediately after a brief training session with a G-meter they performed at the desired level.

In another repeated measures ANOVA with a 3x2 design (Test X G-load) we compared the performance of seven out of thirteen pilots (N=7) who completed the Pre-test, Re-test 1 (immediately after the training), as well as the Re-test 2 (after six months). The results are shown in Fig. 7.

Figure 6. Average results of thirteen pilots in the Pre-test and Re-test 1 for both G-level conditions (2.0 and 2.5g), vertical bars denote the 0.95 confidence interval

Figure 7. Average results of seven pilots who participated in the Pre-test, Re-test 1, and Re-test 2 (six months after the initial session), for both G-level conditions (2.0 and 2.5g), vertical bars denote the 0.95 confidence interval
There was a main effect for G-load, but the main effect for Test did not reach significance. However, using a Fischer LSD correction for the small number of subjects, a post-hoc comparison showed significant differences between the Pre-test and Re-test 1, and the Pre-test and Re-test 2, respectively, but not between Pre-test and Re-test 2. This indicates that the initial positive effect of training had disappeared after six months.

B. Experiment 2: Effect of G-cueing on control performance in pull-up maneuver

Figure 8 shows example time histories of G-level and altitude for three pull-up maneuvers in the Fixed-base and G-cueing condition, respectively. Note that the actual simulator accelerations (a_{out}) differ from the simulated aircraft model accelerations (a_{a/c}) because of motion filtering, a baseline of 1.4g and clipping at 3.0g. Another difference occurs when (a_{a/c}) is below 1.0g, because it is inherently impossible to have sustained unloading in a ground-based simulator.

The maximum peak values of the aircraft model accelerations (a_{a/c}) were determined from the smoothened signals. A within-subject ANOVA with a 2x3 design (G-condition X Repetition) showed no main effect of Repetition, but did show a significant main effect of G-condition. Figure 9 shows that subjects controlled the maneuvers at higher simulated G-loads in the Fixed-base condition than in the G-cueing condition. According to a two-sided t-test the mean G-load differed significantly from the target level of 2.5g in the Fixed-base condition but not in the G-cueing condition.

The altitude-loss data were tested in an ANOVA withinsubjects 2x3 design (G-condition X Repetition), showing main effects for both G-condition and Repetition, but no two-way interaction. The main effect for Repetition means that, in both the Fixed-base and G-cueing condition, average altitude-loss got smaller with subsequent maneuvers. The main effect for G-cueing means that average altitude-loss per parabola was significantly larger in the G-cueing condition than in the Fixed-base condition. This can be explained by a more conservative recovery technique in the G-cueing condition, resulting in a slower recovery with more altitude-loss, as can be seen...
in Fig. 9. This was confirmed by the significant negative correlation coefficient between maximum performed aircraft model acceleration ($a_{ac}$) and altitude-loss.

IV. Discussion

A. Experiment 1: G-performance

The results of the first experiment showed that pilots with no previous experience in G-maneuvering tend to overestimate G-loads in a centrifuge. Their conservative control behavior resulted in significantly lower G-levels than the target G-level. Similar behavior has been observed in in-flight upset recovery training programs, where commercial pilots with no prior aerobatic experience tended to apply small control inputs\textsuperscript{13}. When such conservative behavior would happen in a real upset situation, this could result in delayed recovery, more altitude-loss and/or excessive speed. Our results show that a simple training session with feedback on performance, by means of a G-meter, instantaneously improved the pilots’ G-performance up to adequate level. However, the results of the re-test after six months (Re-test 2) showed that this positive effect of training did not endure and performance was back to baseline again, i.e. measured G-loads were too low and highly variable. It should be noted that the seven pilots participating in the second re-test did little or no flying in the period between the initial training session and the re-test. According to their own comments they found it hard to remember the sensation of G-load after such long period. It is likely that a positive ‘G-memory’ can be obtained by a longer initial training session or by providing refresher training.

At the time of the experiment the simulator was configured with F-16 controls, in particular a force stick, whereas all pilots had a commercial background and no experience with such controls. Although pilots were asked to practice with the controls before the experiment, it is likely that the controls have increased the variability in control behavior. However, we do not believe that this has affected the main results of the experiment, which were based on stationary responses rather than the dynamics of the responses. Moreover, the control task of the first experiment was simplified by not including an aircraft model or out-the-window visuals. Possible variability in the response was further limited by asking the pilots to maintain the target G-load for three seconds, and by smoothing the signal in the off-line analysis.

B. Experiment 2: Effect of G-cueing on control performance in pull-up maneuver

The results of the second experiment showed that the actual sensation of G-load as produced by centrifugation (G-cueing) enabled the pilots to fly a G-critical maneuver within the maximum allowable G-load, even without G-meter. In the G-cueing condition pilots accurately performed at the target G-level of 2.5g with little variance. In contrast, in the Fixed-base condition pilot control was more variable and the simulated G-load exceeded the desired level. As a consequence, pilots recovered with smaller altitude-loss in the Fixed-base condition.
In itself it may not be surprising that pilots performed inaccurately without any sensation of the G-load. However, the practical implication of this phenomenon is that flight simulators without G-cueing capabilities, such as the common hexapod-type, can elicit unrepresentative upset recovery behavior, with unrealistic small altitude-loss and over stressing of the simulated aircraft.

A factor that may have contributed to the accurate performance in the G-cueing condition is that this experiment followed the first experiment on the same day, where pilots were trained to pull 2.0 and 2.5g with feedback from a G-meter. Hence, pilots could not be considered completely untrained when they controlled the nose low recovery maneuver.

V. Conclusions

In the two experiments we studied the effect of G-cueing on pilot performance in centrifuge-based simulation of unusual attitude recovery. Results showed that commercial pilots, without experience of G-maneuvering, are too conservative in pulling G-loads in a centrifuge-based simulator. By means of a brief training session, their seat-of-the-pants G-performance improved significantly, as measured in deviation of the achieved G-load from the target G-level. However, after six months without refresher training, performance was back to pre-training again.

Furthermore, Fixed-base simulation of recovery from a nose-low unusual attitude evoked inaccurate and unrealistic control behavior. Pilots recovered with less altitude-loss but over stressed the aircraft, while in contrast, centrifuge-based G-cueing resulted in adequate recoveries with smaller variance in G-load and without overstressing the aircraft. It can be concluded that for flying G-critical maneuvers in a simulator, pilots do need G-cueing. Hence, simulation of upset recovery with G-cueing may contribute to more realistic and adequate upset recovery training.

VI. Acknowledgments

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VII. References


