Motion Cueing for Stall Recovery Training in Commercial Transport Simulators

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Starting in 2019, airline pilots will be required to perform full stall recovery training in flight simulators. Historically, training simulators weren't required to provide training at conditions outside their normal flight envelope. Post-stall aircraft models are generally required to be implemented to simulate the aircraft response after the stall point. In addition, motion cues need to adequately represent this response to ensure the skills learned in simulator training are directly usable in real flight. This paper provides and overview of six simulator experiments conducted at NASA Ames Research Center to develop a motion cueing strategies for stall recovery training in commercial transport simulators. One of the experiments verified an enhanced motion cueing strategy for stall recovery training on a level-D-certified full flight simulator. This study showed that the enhanced motion results in lower maximum roll angles in the stall maneuver, lower minimum load factors in the recovery, lower numbers of secondary stick shakers in the stall recovery, and a lower maximum airspeed in the recovery. These results indicate that relatively minor enhancements to the motion logic of heritage commercial transport simulators can significantly improve pilot performance in simulated stall recoveries, and potentially improve stall recovery training.

I. Introduction

This paper provides an overview of a comprehensive research project with six simulator experiments which developed a motion cueing strategy for stall recovery training. Today, airline pilots only receive training in recognizing and recovering from an approach to stall, but not in full stall recovery. Starting in 2019, airline pilots will be required to perform full stall recovery training in flight simulators [1]. Historically, training simulators weren't required to provide training at conditions outside their normal flight envelope, such as at angles of attack above the stall warning threshold. Post-stall aircraft models are generally required to be implemented to simulate the aircraft response after the stall point [2–6]. In addition, motion cues need to adequately represent this response to ensure the skills learned in simulator training are directly usable in real flight [7].

Under NASA's Airspace Operations and Safety Program, the Technologies for Airplane State Awareness (TASA) subproject conducts research to support the Commercial Aviation Safety Team (CAST) Safety Enhancement 209 (SE209) to study simulator fidelity improvements for commercial aircraft stall training [7]. Under this SE209 research, several simulator studies with pilots were conducted in the Vertical Motion Simulator (VMS) at NASA Ames Research Center to develop a hexapod motion cueing strategy for stall recovery training in commercial transport simulators [8–11]. This motion cueing strategy prioritizes translational accelerations as a result from rotating around the aircraft's center of gravity over translational accelerations of the center of gravity, allowing for a higher fidelity of the motion cues that directly help a pilot damp the flight path response in a stall recovery, as well as stabilize the progressively less-stable roll dynamics and roll off near stall.

While novel motion algorithms have been proposed in the past, showing promising motion fidelity improvements for upset recovery training, they would require drastic modifications to existing commercial transport simulator motion algorithms and elaborate motion tuning [12, 13]. The motion cueing strategy discussed here only requires very minor modifications to existing motion algorithms. The previous VMS experiments simulated a typical hexapod simulator and showed that pilots control more similar to how they would under full aircraft motion using the new motion cueing strategy; however, these experiments used general aviation pilots in more structured tasks [10, 11]. The usefulness of the proposed motion cueing strategy was verified with eight airline pilots in a level-D-certified full flight simulator using a high-altitude stall recovery task [14].

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The paper is structured as follows. An overview of the research methodology is provided in Section II, after which each experiment is briefly discussed in Section III. A general discussion and some results are provided in Section IV. Conclusions are provided in Fig. V.

II. Methodology

Several methodologies were used to determine the effects of different motion cueing strategies on pilot performance and control behavior in a stall recovery, and the effects on the acquisition of manual control skills:

1) The transfer-of-training paradigm was used to investigate the training and transfer of training of the manual control skills needed to control the aircraft in a stall. This methodology was used in the experiments discussed in Refs. [8] and [10].
2) A cybernetic approach was used to model pilot control behavior and the acquisition of manual control skills during training. This approach was used in the experiments discussed in Refs. [8–11]. As pilots control the aircraft in multiple axes and in time-varying conditions, several additional studies improved the utility of the cybernetic approach under these conditions in support of this research project. These studies are discussed in Refs. [15–17].
3) Motion strategies considered the effect of different motion components at the pilot station separately instead of the total pilot station motion as a whole.

The next sections each describe these methodologies in more detail.

A. Transfer of Training

The transfer-of-training paradigm is considered the most valid means of investigating the training effectiveness of motion. Most studies show no or only limited effects of motion on transfer of training [18]. Most of these studies have several limitations (some inherent to transfer-of-training experiments) that could have reduced the effect of motion.

Two types of transfer-of-training experiments can be distinguished: true-transfer and quasi-transfer experiments. In a true transfer-of-training experiment, training is performed in the simulator with different motion conditions. After training, performance is assessed in the real aircraft. In a quasi-transfer experiment, training is performed in a simulator with no motion or reduced motion fidelity. Then, transfer performance is assessed in the same simulator, but with higher motion fidelity. Many transfer-of-training studies have been performed in the past to investigate how simulator motion influences transfer of training. However, most studies are quasi transfer-of-training experiments, where the motion in the transfer case is often only slightly better than the motion in training.

Furthermore, there is generally not a good understanding and reporting of the motion settings in most transfer-of-training experiments. This makes it impossible to judge the difference in motion between the training and transfer phases, and if a positive transfer of training is to be expected [19]. Finally, mostly outcome related variables are used to assess performance in transfer-of-training studies. However, the same performance can sometimes be achieved using different control strategies involving a different use of perceptual modalities. If a pilot learns to rely on a particular set of limited motion cues in a simulator, an unwanted response could be the result in real flight.

Refs. [8] and [10] also applied the quasi-transfer paradigm, but on the Vertical Motion Simulator (VMS), a simulator with an order-of-magnitude more physical motion than in a typical training simulator [20]. The cybernetic approach was used to determine the effects of motion on pilots' utilization of different perceptual modalities during the training and transfer of training of manual control skills for stall recovery.

B. Cybernetic Approach

The modeling of skill-based pilot control behavior, a so called cybernetic approach, can give more insight into the use of motion cues in a simulator or aircraft [21, 22]. This approach was used in this research project to determine the effects of motion on pilot performance and the training and transfer of training of manual control skills for stall recovery [8–11].

Pilot skill-based behavior is nonlinear and varies over time, however, when keeping task, environmental, operator-centered, and procedural variables constant, can be described by a quasi-linear time-invariant model with a remnant signal that accounts for nonlinear behavior [23]. Many control tasks are inherently multi-loop with feedback from visual, somatosensory, and vestibular cues. The parameters of a multimodal pilot model can give insight into an individual pilot's use of different motion stimuli to produce a control action.

Fig. 1 provides a block diagram of a control task typically used for identification of manual control behavior. In this

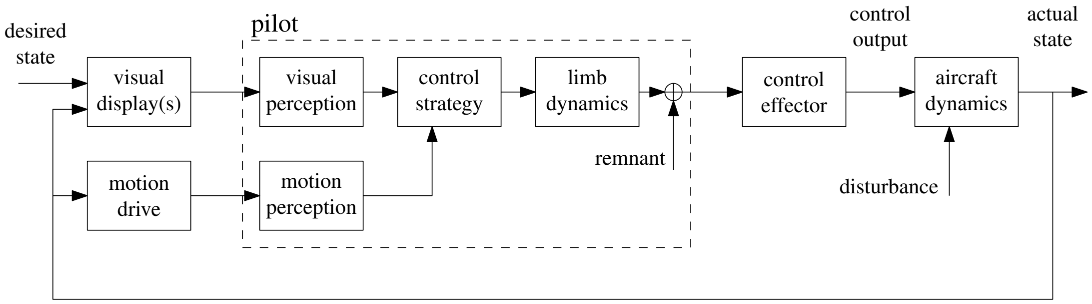


Fig. 1 Closed-loop control task in a simulator.

closed-loop control task, a pilot is using a control effector to control the state of a controlled element, in this case the aircraft dynamics. The actual state or changes in the state of the aircraft can be perceived by the pilot using visual and motion stimuli that are generated by visual displays and the simulator motion drive, respectively. The visual perception process consists of the dynamics of the eye and the transportation and transformation of visual information by the central nervous system and visual cortex. Although motion perception processes are dominated by the perception of linear and rotational accelerations by the vestibular system, other forms of motion perception, for example, using the somatosensory system, also contribute to the total perception of motion.

The perceived visual and motion information is transformed and combined using a certain control strategy (Fig. 1) that is dependent on the controlled dynamics and other task variables. The pilot control output is limited by the combined dynamics of the limb and control effector. A latency is associated with this skill-based control process that is a combination of human signal processing and control delays.

Previous transfer-of-training studies typically used outcome-based variables as a measure of transfer of training. In the block diagram of Fig. 1, these outcome-based variables can be associated with the pilot control output or the actual state of the aircraft. However, these measures do not provide any insight into how pilots adapt their control strategy to the limited cues in a simulator and the development of this control strategy during training. A cybernetic approach allows for the identification of the pilot response from visual and motion stimuli to the control output.

To identify this response function, an external signal, also called a forcing function, needs to be provided that excites the total pilot-vehicle system. This can either be a desired state visualized on a visual display, or a disturbance on the aircraft dynamics (Fig. 1). The forcing function needs to have specific properties in the frequency domain to allow for accurate estimates of the frequency response and pilot model parameters. Often multi-sine signals are used for this purpose. A pilot model can be used to characterize the different elements of the pilot frequency response. Different techniques exist to estimate the pilot model parameters from measurements of visual and motion stimuli and the control output [11, 24–28]. Estimating the parameters of such a pilot model at different instances during training, allows us to investigate a pilot's skill acquisition. By using structured variations in motion settings for different pilot groups during training, we can determine how these different settings influence skill acquisition and transfer of training.

C. Motion Cueing

Fig. 2 provides a schematic overview of the heave motion components at the center of gravity (CG) and pilot station (PS) of an aircraft in a pitch maneuver. During a change in pitch attitude θ, a pilot at the pilot station experiences rotational accelerations $\ddot{\theta}$ and heave accelerations $a_{z_{PS}}$.

In the simulation of aircraft dynamics, forces, moments, and resulting accelerations are typically resolved relative to the CG. Heave accelerations at the PS are a combination of heave accelerations of the CG, $a_{z_{CG}}$, and heave accelerations due to rotations about the CG, $a_{z_{\theta,CG}}$. The CG heave accelerations are a result of variations in lift due to changes in angle of attack. The total heave accelerations at the pilot station are then given by:

$$a_{z_{PS}} = a_{z_{CG}} + a_{z_{\theta,CG}} = a_{z_{CG}} - l_{x_{PS}}\ddot{\theta} \tag{1}$$

with $l_{x_{PS}}$ the longitudinal distance between the center of gravity and the pilot station, with a value of 48 ft for the aircraft simulated in [8–11]. Similarly, a pilot experiences surge accelerations at the pilot station during a pitch maneuver, which are a combination of surge accelerations of the CG due to variations in drag and surge accelerations due to rotations about the CG. The surge accelerations have been omitted from Fig. 2 for brevity, but were also simulated.

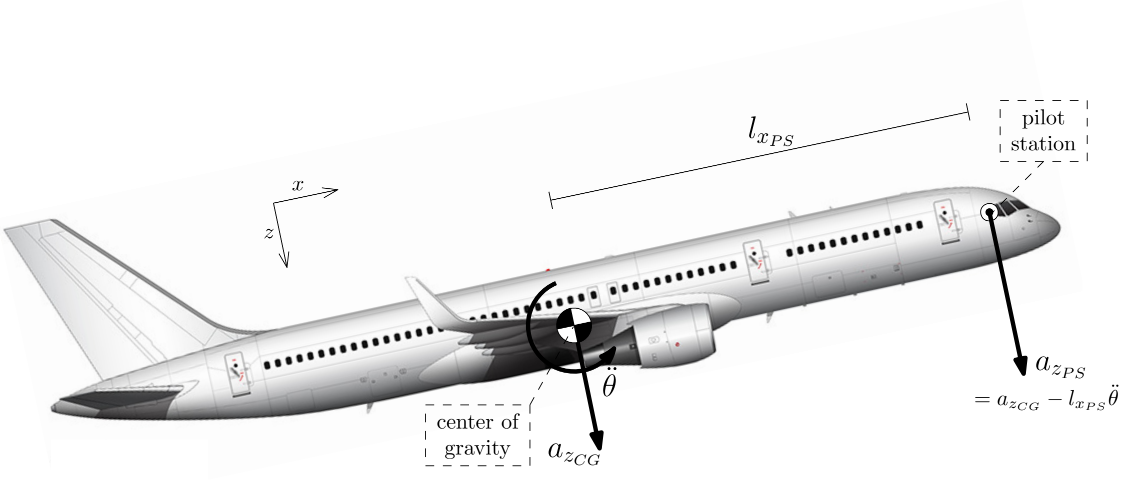


Fig. 2 Aircraft heave motion during a pitch maneuver.

During an aircraft pitch attitude control task, pilots receive additional feedback from the aircraft pitch and heave motion components, allowing them to close extra feedback loops around the controlled aircraft dynamics and increase performance. Both pitch accelerations $\ddot{\theta}$ and pitch heave accelerations with respect to the CG $a_{z_{\theta,CG}}$ are directly correlated with changes in aircraft pitch attitude. However, the CG heave $a_{z_{CG}}$ has a less direct relation to pitch attitude changes due to the slower altitude mode of the aircraft dynamics. A previous study showed that this heave component does not significantly affect pitch control behavior and performance, while it requires the most simulator motion [29]. The study in [9] investigated how different weightings of CG heave and pitch heave with respect to the CG affect pitch control behavior and performance. This motion cueing strategy using different weightings of different motion components was further utilized in [10, 11].

III. Experiments

Six simulator experiment were conducted as part of this research project. An overview of the experiments is provided in Fig. 3. This figure also provides the AIAA paper numbers of the papers discussing these experiments. The sections below provide a brief overview of each experiment.

A. Effects of False Tilt Cues in Roll

A transfer-of-training study was performed in the NASA Ames Vertical Motion Simulator Fig. 4 [8]. The purpose of the study was to investigate the effect of false tilt cues on training and transfer of training of manual roll control skills. Of specific interest were the skills needed to control unstable roll dynamics of a mid-size transport aircraft close to the stall point. Nineteen general aviation pilots trained on a roll control task with one of three motion conditions: no motion, roll motion only, or reduced coordinated roll motion. All pilots transferred to full coordinated roll motion in the transfer session. A multimodal pilot model identification technique was successfully applied to characterize how pilots' use of visual and motion cues changed over the course of training and after transfer. Pilots who trained with uncoordinated roll motion had significantly higher performance during training and after transfer, even though they experienced the false tilt cues. Furthermore, pilot control behavior significantly changed during the two sessions, as indicated by increasing visual and motion gains, and decreasing lead time constants. Pilots training without motion showed higher learning rates after transfer to the full coordinated roll motion case.

B. Effects of Heave Motion Components in Pitch

This study described in [9] had two objectives. The first objective was to investigate if a different weighting of heave motion components decomposed at the center of gravity, allowing for a higher fidelity of individual components, would result in pilot manual pitch control behavior and performance closer to that observed with full aircraft motion.

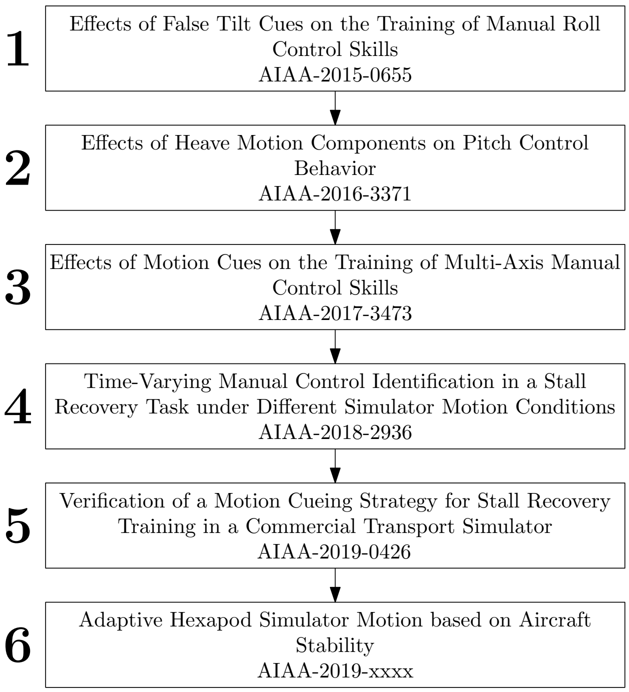


Fig. 3 Overview of simulator experiments.

The second objective was to investigate if decomposing the heave components at the aircraft's instantaneous center of rotation rather than at the center of gravity could result in additional improvements in heave motion fidelity. Twenty-one general aviation pilots performed a pitch attitude control task in an experiment conducted on the Vertical Motion Simulator at NASA Ames under different hexapod motion conditions. The large motion capability of the VMS also allowed for a full aircraft motion condition, which served as a baseline. The controlled dynamics were of a transport category aircraft trimmed close to the stall point. When the ratio of center of gravity pitch heave to center of gravity heave increased in the hexapod motion conditions, pilot manual control behavior and performance became increasingly more similar to what is observed with full aircraft motion. Pilot visual and motion gains significantly increased, while the visual lead time constant decreased. The pilot visual and motion time delays remained approximately constant and decreased, respectively. The neuromuscular damping and frequency both decreased, with their values more similar to what is observed with real aircraft motion when there was an equal weighting of the heave of the center of gravity and heave due to rotations about the center of gravity. In terms of open-loop performance, the disturbance and target crossover frequency increased and decreased, respectively, and their corresponding phase margins remained constant and increased, respectively. The decomposition point of the heave components only had limited effects on pilot manual control behavior and performance.

C. Effects of Motion on the Training of Multi-Axis Manual Control Skills

The study described in [10] investigated the effects of two different hexapod motion configurations on the training and transfer of training of a simultaneous roll and pitch control task. Pilots were divided between two groups which trained either under a baseline hexapod motion condition, with motion typically provided by current training simulators, or an optimized hexapod motion condition, with increased fidelity of the motion cues most relevant for the task. All pilots transferred to the same full-motion condition, representing motion experienced in flight. A cybernetic approach was used that gave insights into the development of pilots' use of visual and motion cues over the course of training and after transfer. Based on the current results, neither of the hexapod motion conditions can unambiguously be chosen as providing the best motion for training and transfer of training of the used multi-axis control task. However, the optimized hexapod motion condition did allow pilots to generate less visual lead, control with higher gains, and have better disturbance-rejection performance at the end of the training session compared to the baseline hexapod motion condition. Significant adaptations in control behavior still occurred in the transfer phase under the full-motion condition

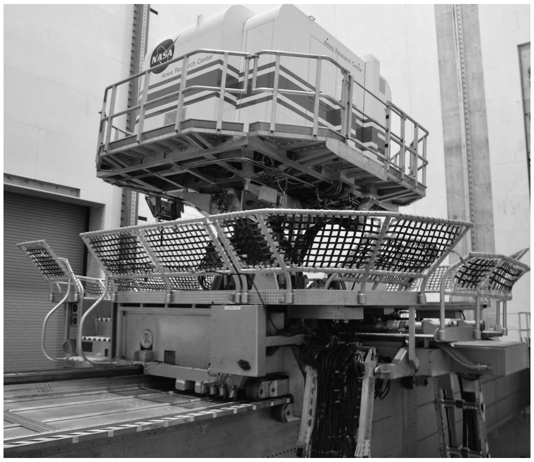


Fig. 4 Vertical Motion Simulator.

for both groups. Pilots behaved less linearly compared to previous single-axis control-task experiments; however, this did not result in smaller motion or learning effects. Motion and learning effects were more pronounced in pitch compared to roll. Finally, valuable lessons were learned that allowed for the improvement of the adopted approach for future transfer-of-training studies.

D. Time-Varying Manual Control Identification in a Stall Recovery Task

This study identified time-varying manual control behavior in a stall recovery task under different simulator motion conditions [11]. An experiment was conducted with seventeen general aviation pilots in the VMS. Pilots had to follow a flight director through four stages of a high-altitude stall task. A time varying identification method was used to quantify how pilot manual control parameters change throughout different stages of the task in both roll and pitch. Four motion configurations were used: no motion, generic hexapod motion, enhanced hexapod motion and full motion. Pilot performance was highest for the enhanced hexapod and full motion configurations in both roll and pitch, and the lowest without motion. In the roll axis, the pilot position gain did not significantly change throughout the stall task, but was the lowest for the condition with no motion. The pilot roll velocity gain was significantly different between motion conditions, the largest difference being found close to the stall point. The enhanced hexapod motion condition had the highest pilot roll velocity gain. In the pitch axis, the pilot position gain was significantly different between time segments but not between motion conditions. The pilot pitch velocity gain was highest for the full motion condition and increased close to the stall point, but did not change significantly for the other motion conditions. Overall, pilot control behavior under enhanced hexapod motion was most similar to that under full aircraft motion. This showed that motion cueing for stall recovery training on hexapod simulators might be improved by using the principles behind the enhanced hexapod motion configuration.

E. Verification in a Commercial Transport Simulator

This study verified the motion cueing strategy for improved pilot stall recovery training in commercial transport simulators [14]. Eight airline transport pilots flew a high-altitude stall recovery task in the NASA B747 level-D-certified full flight simulator (Fig. 5) under three different motion configurations: no motion, baseline motion, and enhanced motion. For each motion condition, pilots performed the task with both baseline aircraft dynamics and aircraft dynamics enhanced with lateral-directional characteristics of the airplane at angle of attack approaching stall. Motion configuration significantly affected: 1) pilot opinions on the helpfulness of motion in performing the task, 2) the maximum roll angle in the stall maneuver, 3) the minimum load factor in the recovery, 4) the number of secondary stick shakers in the stall recovery, and 5) the maximum airspeed in the recovery. The two different aircraft dynamics significantly affected: 1) pilot opinions on the noticeability of the banking roll off near the stall and 2) the maximum roll angle in the stall maneuver. These results indicated that the relatively minor enhancements to the motion logic of heritage commercial transport simulators presented here can significantly improve pilot performance in simulated stall recoveries, and potentially improve stall recovery training.

F. Adaptive Simulator Motion based on Aircraft Stability

An adaptive hexapod motion cueing algorithm based on aircraft stability was developed and evaluated in a heading capture and stall recovery task. An experiment was conducted with nineteen general aviation pilots in the VMS. In every simulation run, pilots had to perform two tasks consecutively: capturing two different headings, followed by a stall initiation and recovery. Both tasks were at high altitude. In the adaptive motion algorithm, gains and break frequencies of the simulator's second order high-pass motion filters were adapted in real time based on the aircraft roll damping coefficient, while making sure the simulator motion remained in the motion space of a typical hexapod training simulator. The motion varied between a generic hexapod motion configuration found in most training simulators and the enhanced hexapod configuration for stall recoveries.

Fig. 5 B747-400 simulator.

IV. Discussion

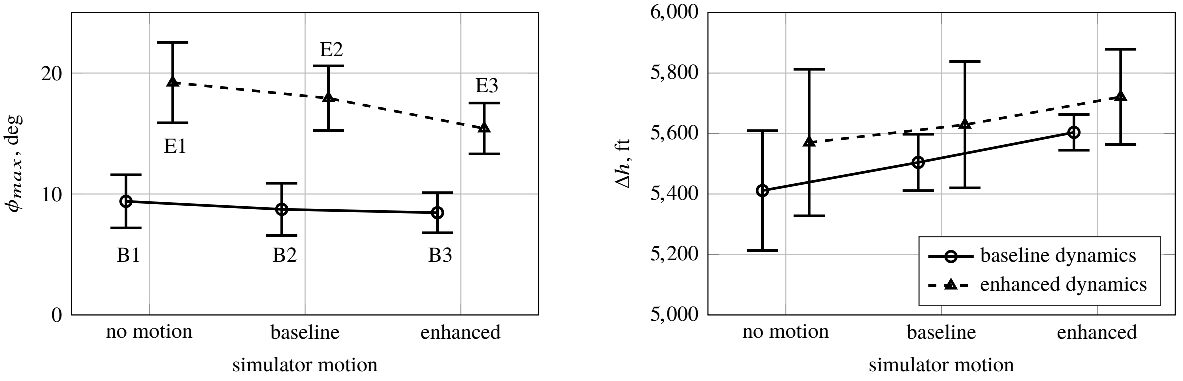
An enhanced motion cueing strategy for stall recovery training in hexapod simulators was developed and evaluated in several studies in the VMS at NASA Ames Research Center [9–11]. These studies showed that pilot control behavior and performance under the enhanced motion developed in this research project was more similar to that under real aircraft motion compared to the baseline motion currently provided by most commercial transport simulators. However, these studies used general aviation pilots in more structured tracking tasks. The effects of the enhanced motion cueing strategy on pilot stall recovery performance were evaluated in a B747 level-D full flight simulator with eight commercial airline pilots [14].

In the level-D full flight simulator evaluation study, the main effects of motion configuration showed that there were statistically significant differences in pilot opinion and performance between the no-motion, baseline-hexapod, and enhanced-hexapod motion configurations. In terms of pilot performance, the maximum roll angle in the stall maneuver and the number of secondary stick shakers in the stall recovery were significantly lower with enhanced motion compared to no motion Fig. 6. Performance under baseline motion was more similar to no motion. These results were also found in previous experiments [30]. This clearly indicates that the enhanced motion allowed pilots to damp the flight path response in a stall recovery, as well as stabilize the progressively less-stable roll dynamics and roll off near stall, more effectively. The minimum load factor and the maximum calibrated airspeed were both significantly higher with better motion fidelity. An overview of the pilot performance results is provided in Fig. 6. More details about the experiment setup and a thorough discussion of the results in Fig. 6 are provided in [14].

Despite the limited number of pilots participating in the experiment and the large variability between pilots, significant effects of motion configuration and aircraft dynamics were found between conditions. Additional effects approached statistical significance. These effects would most likely be significant if the statistical power were increased through additional participants. It should also be noted that the simulator used for the experiment has a motion system with 54-inch legs as opposed to the industry standard of 60 inch. In addition, the aircraft model used did not have a clear stall break and responds relatively sluggish compared to smaller aircraft. The benefits of the enhanced motion could potentially be more profound in simulators of smaller aircraft with 60-inch-legged motion systems.

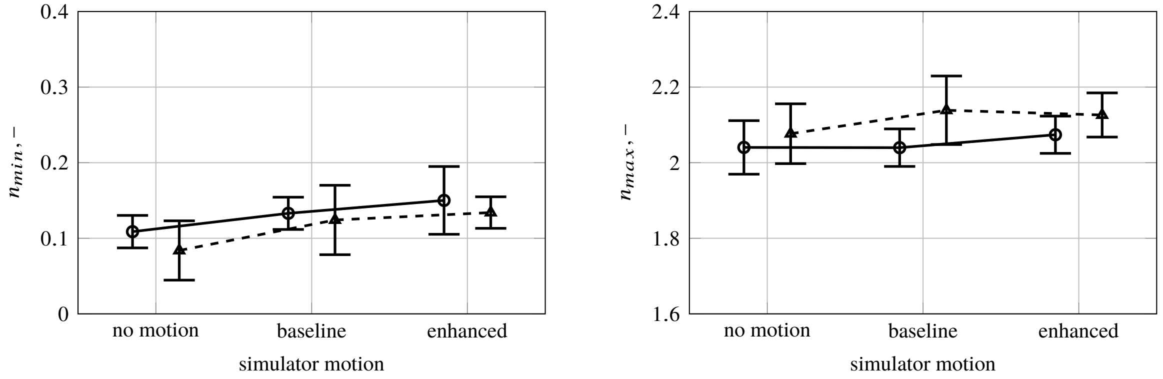
By eliminating the translational accelerations of the center of gravity in the enhanced motion configuration, the fidelity of the remaining motion components at the pilot stations could be increased. However, this also eliminates the sustained g-loads that pilots experience in real stall maneuvers. Because of the limited motion capabilities of hexapod motion platforms (that is, they can generate linear accelerations only for a very brief period), this absence of sustained g-loads was not more pronounced compared to the baseline motion configuration. Presenting pilots with representative g-loads during stall recovery is of great value for stall recovery training [31, 32]. However, this requires centrifuge type simulators or real aircraft, as hexapod simulators are inherently not suitable to produce these sustained accelerations. Furthermore, by eliminating the translational accelerations of the center of gravity, also the sense of deceleration in the approach to the stall could be lost. However, this is highly dependent on the type of stall and pilot performance, and was not noticeable in this B747 simulator experiment.

The results of the level-D simulator verification study indicate that the relative minor enhancements to the motion logic of heritage commercial transport simulators presented here can significantly improve pilot performance in



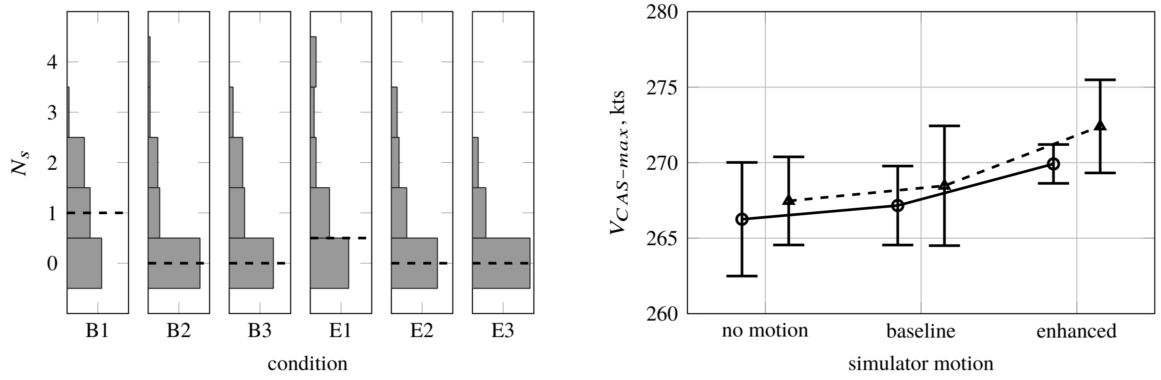
(a) Maximum roll in stall maneuver.

(b) Altitude loss in stall recovery.



(c) Minimum load factor in stall recovery.

(d) Maximum load factor in stall recovery.



(e) Secondary stick shakers in stall recovery.

(f) Maximum airspeed in stall recovery.

Fig. 6 Effects of motion setting and aircraft dynamics on objective measures.

high-altitude stall recoveries performed in simulators. This does not necessarily equate to improved stall recovery training. However, previous transfer-of-training experiments in the VMS using the same enhanced motion cueing strategy did indicate improved training and transfer of training compared to motion provided in current commercial transport simulators. Improvements in pilot performance with the enhanced motion configuration might also be found in other flying tasks where the control of aircraft attitude is important. However, as in many other tasks the translational accelerations of the aircraft center of gravity provide useful information to pilots, such as flaring and landing an aircraft, the proposed motion cueing strategy is not a solution for general simulator operations.

V. Conclusions

In a comprehensive research project six different simulator studies developed and evaluated a motion cueing strategy for stall recovery training in commercial transport simulators. One of the experiments verified this motion cueing strategy in a level-D-certified full flight simulator. It was shown that pilot opinion and performance during the stall maneuver were significantly different under the enhanced motion configuration. The maximum roll angle in the stall maneuver and the number of secondary stick shakers in the stall recovery were significantly lower with enhanced motion compared to no motion. Performance under baseline motion was more similar to no motion. This clearly indicates that the enhanced motion allowed pilots to damp the flight path response in a stall recovery, as well as stabilize the progressively less-stable roll dynamics and roll off near stall, more effectively. The minimum load factor and the maximum calibrated airspeed were both significantly higher with better motion fidelity. These results indicate that the relatively minor enhancements to the motion logic of heritage commercial transport simulators presented here can significantly improve pilot performance in simulated stall recoveries, and potentially improve stall recovery training.

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