OPTIMIZING MOTION CUEING FOR RESEARCH FLIGHT SIMULATION

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OVERVIEW

Research flight simulation conducted with the A330/340 Full-Flight-Simulator located at Technical University Berlin exceeds the typical flight envelope of airline pilot training. For such simulator studies a motion cueing algorithm optimized for the research task should provide improved motion reproduction. As one of the potential applications the specific motion system requirements of wake vortex encounter simulation are analyzed. An optimized setting of the motion cueing algorithm is derived and implemented into the simulator motion system. To conclude, results of a piloted test campaign are presented, in which the effect of simulator motion on perceived severity of wake vortex encounters and pilot reaction were studied by comparing results for a motion cueing setup as used for pilot training, a setup optimized for wake vortex encounter simulation and wake encounters conducted without simulator motion.

NOMENCLATURE

ar	Angular rate
CAPT	Captain
C/G	Center of gravity
FBW	Fly-by-wire
F/O	First officer
H	Transfer function (Laplace domain)
KIAS	Knots indicated airspeed
MAC	Mean aerodynamic chord
MCA	Motion cueing algorithm
MOT	Total motion system
MSL	Mean sea level
P	Motion platform
p	Roll axis
sf	Specific force
X	Signal magnitude
y	Lateral axis
z	Vertical axis
ΔL	Vortex-induced rolling moment

1. INTRODUCTION

With the Level-D certified flight simulator at TU Berlin, equipped with a 6 degree-of-freedom hexapod motion platform, the facilities available to the Flight Mechanics and Flight Control group are especially well suited for pilot-in-the-loop studies with focus on human motion perception. A methodical approach and the tools needed to adapt the simulator motion system to the specific requirements of a research flight simulation had to be developed and validated. Using the example of wake vortex encounter simulation, this paper outlines the process of analyzing test specific motion requirements, optimizing motion parameters for the research application and finally the conduct of piloted simulator tests to evaluate the effect of modifications to the motion cueing algorithm.

As discussed in [2], [3] and [4], aircraft motion is perceived by a variety of human sensory channels such as the visual, vestibular, proprioceptive, tactile and auditory system. In ground-based flight simulation an outside visual system, a sound system and a moving simulator base can provide motion cues to the pilot's sensors. While a simulator motion cabin stimulates several sensory channels, it is primarily designed for vestibular cueing. The human vestibular system comprises 3-axis linear acceleration and 3 angular motion sensors. The system is not capable of determining the direction of earth gravity, i.e. gravitational acceleration cannot be distinguished from accelerations effected by external forces acting on the body. On the frequency range relevant to piloting an aircraft the angular motion sensors are acting as angular rate sensors. Thus, a 6 degree-of-freedom simulator motion platform should reproduce linear accelerations and angular rates.

As the motion envelope of the simulated aircraft is much larger than the one of the simulator cabin, a full reproduction of aircraft motion is not possible. Aircraft motion obtained by solving the equations of motion has to be attenuated to fit within the capabilities of the simulator motion platform. The necessary transformation, performed by the motion cueing algorithm, has to be realized in a way to resemble real flight motion perception as closely as possible.

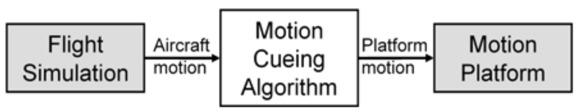

FIG 1. The motion cueing algorithm translates aircraft motion into motion platform commands

Motion cueing algorithm design and tuning is influenced by motion base and simulated aircraft characteristics as well as by the maneuvers to be simulated. As research maneuvers can differ largely from the ones typically flown during pilot training, it is conceivable that a motion cueing algorithm tuned specifically for the research task can improve motion reproduction over a standard training setup.

2. MOTION REQUIREMENTS DURING WAKE VORTEX ENCOUNTER SIMULATION

Research specific motion requirements were studied for the example of wake vortex encounter. Data from 183 piloted wake vortex encounters during cruise, carried out at the A330 Full-Flight-Simulator at TU Berlin, were analyzed. To evaluate motion requirements, magnitude spectra of linear accelerations and angular rates have been calculated. Averaged spectra are shown in FIG 2.

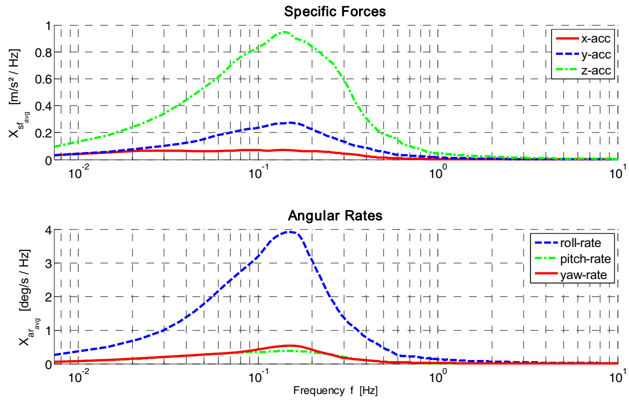

FIG 2. Averaged magnitude spectra of analyzed cruise wake vortex encounters

As can be seen, vertical acceleration and roll rate are the primary motion cues; lateral cockpit acceleration can be regarded a secondary motion cue. Owed to the large distance between center of gravity and pilot location (26.43m), the relatively small pitch and yaw rates can be found as vertical and lateral cockpit accelerations. In FIG 14 (see Appendix) the magnitude spectra of primary and secondary motion cues are plotted along with the motion platform excursion, velocity and acceleration limits for harmonic excitation at the respective frequencies. It shows that vertical cockpit accelerations clearly exceed the vertical envelope of the motion platform. Consequently, attenuation of aircraft acceleration will have to be higher than in all other axes.

FIG 2 and FIG 14 also show peak frequencies of about 0.15Hz in all axes. If possible the motion system optimized for wake vortex encounter simulation should reach unity magnitude and low absolute phase angles in this region.

3. MODIFICATION OF THE MOTION CUEING ALGORITHM

3.1. General Structure of the Algorithm

FIG 3 shows the principal structure of a classical motion cueing algorithm as implemented in the motion system of the flight simulator at TU Berlin. It comprises two high-pass channels for linear accelerations and angular rates and a low-pass cross-feed from linear to angular channel to reproduce sustained lateral and longitudinal accelerations by tilting the simulator cabin.

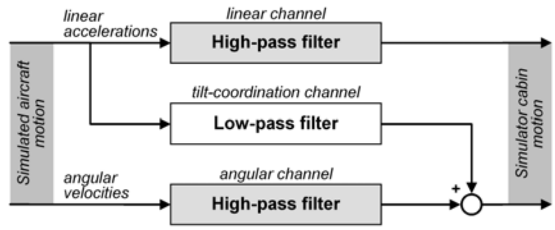

FIG 3. Generic structure of a classical motion cueing algorithm

The tilt-coordination channel also features a cabin tilt rate limiter to avoid false pitch and roll rate cueing when low-frequency longitudinal and lateral accelerations shall be reproduced. High-pass linear (3rd order) and angular (1st order) filters also employ online filter gain adaptation. As function of quadratic cost functions gains are reduced when envelope limitations are approached, thus enabling selective attenuation of large magnitude inputs.

3.2. Modification of Filter Parameters

It was decided to retain the structure of the motion cueing algorithm as implemented by the simulator manufacturer. Altering of motion system characteristics should be realized by modifying filter parameters such as breaking frequency, damping, gain and weighting factors in the individual cost functions.

Main goal was to reach high recovery of cockpit accelerations and angular rates around 0.15Hz, the peak magnitude frequency in spectra FIG 2 and FIG 14. Emphasis was to be put on primary and secondary cues, i.e. vertical acceleration, roll rate and lateral acceleration. However, taking into account physical platform constraints it is clear that capabilities in vertical axis are limited.

Assuming linear behavior, the dynamics of the motion system in Laplace domain H_{MOT} can be written as

$$(1) \qquad H_{MOT}(s) = \frac{X_{simcabin}(s)}{X_{aircraft}(s)}$$

The index *simcabin* denotes linear accelerations and angular rates measured in the simulator cabin and the index *aircraft* refers to simulated aircraft quantities. The total motion system dynamics consist of the transfer behavior of motion cueing algorithm H_{MCA} and the motion platform, including its position control loops H_P.

$$(2) \qquad H_{MOT} = H_{MCA} \cdot H_P$$

As discussed in [1], motion platform characteristics H_P have been determined experimentally using the methods described in [5]. Based on this data the total motion system behavior H_{MOT} can be calculated for arbitrary motion cueing algorithm transfer functions H_{MCA}.

Software for calculation and visualization of total motion system transfer function was developed and validated against experimental data (see [1]). Using this tool the motion filter transfer functions were modified to better suit the needs of wake vortex encounter simulation. FIG 4, FIG 15 and FIG 16 show computed total system transfer functions for standard and modified motion filter parameters for the primary and secondary cueing axes.

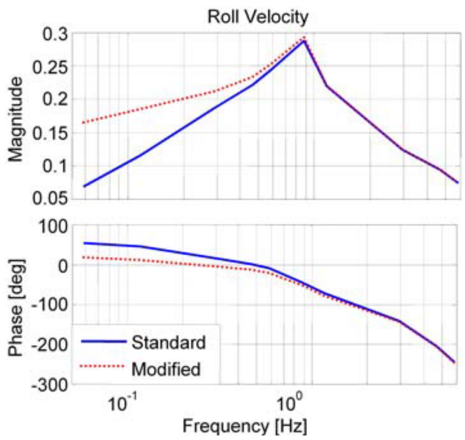

FIG 4. Computed standard and modified motion system dynamics in roll axis

FIG 4 shows that transfer function magnitude in roll axis was increased by about 50% at 0.15Hz. As depicted in FIG 15 and FIG 16 magnitude at this frequency could be increased by about 100% in lateral and by 200% in vertical axis. However, due to the missing of a low-pass channel, as it is present in lateral axis, vertical acceleration magnitude in modified filter setup only reaches a value of about 0.1 around 0.15Hz. Modification of motion filter parameters also effected smaller absolute phase angles.

4. PILOTED EVALUATION TESTS

4.1. Test Description

To evaluate the effect of motion and different motion filter setups on pilot reaction during wake vortex encounters and on pilot rating of encounter severity and importance of certain parameters for perceiving the upset a small-scale piloted simulator test campaign was carried out at the Full-Flight-Simulator at TU Berlin.

FIG 5. A330/340 Full-Flight-Simulator at TU Berlin

The A330/A340 simulator, as shown in FIG 5, features a hydraulic, hexapod type motion base and a 40x150 collimated visual system. For the test campaign hard- and software was configured in A330-300 / PW4000 configuration with wake vortex simulation extension.

To ensure repeatability of encounter tests, time-based wake vortex perturbations have been used, i.e. vortex induced forces and moments recorded during vortex encounters flown in a previous simulator test campaign are played-back and added to the base aircraft quantities before solving the equations of motion. The scenarios of the recorded encounters are listed in TAB 1.

Encounter Case No.	Vortex Strength [m²/s]	Vortex Azimuth [deg]
2	365	10
4	365	0
7	565	15
8	365	15
9	365	25
10	365	-5

TAB 1. Scenarios of recorded vortex encounters

Encounters were flown in normal law, manual flight (no auto-pilot or auto-thrust), without flight director, in the following configuration:

- Flaps 3, gear up
- Zero Fuel Weight 130 t, 15 t fuel on board
- Gross weight C/G 35% MAC

At the start of a test set, consisting of the encounters in TAB 1 in forward or reverse order, the aircraft was trimmed at

- Altitude: 2,700 ft MSL
- Speed: 150 KIAS
- Flight path angle: 0 deg (level flight).

The Pilot was to maintain trimmed altitude, speed and heading to within

- Altitude: +/- 50 ft
- Speed: +/- 2 kts
- Heading: +/- 2 deg.

For every test set the motion system and/or visual system configuration was changed. The following motion system configurations were used

- *No*: No motion
- *Std*: Standard training setup, buffets enabled
- *HP*: Standard training setup with low-pass tilt-coordination in lateral and longitudinal direction disabled, buffets enabled
- *Mod*: Setup modified for wake vortex encounter, buffets enabled.

Switching to *Mod* motion configuration required manual modification of filter parameters and verification by a second engineer. To avoid repeated interruptions of the test series the tests in this motion configuration were carried out en-bloc at the end of the sequence. TAB 2 gives an overview over the test runs.

Test Set	Encounter Sequence	Motion Conf.	Visual Conf.
1	2-4-7-8-9-10	No	Day
2	10-9-8-7-4-2	Std	Day
3	2-4-7-8-9-10	HP	Day
4	10-9-8-7-4-2	HP	No
5	2-4-7-8-9-10	Std	No
10 min Break			
6	10-9-8-7-4-2	No	No
7	2-4-7-8-9-10	Mod	No
8	2-4-7-8-9-10	Mod	Day
9	10-9-8-7-4-2	Mod	No

TAB 2. Test sequencing

In the stabilization period after each encounter the pilot was asked to rate overall encounter severity, on a scale from 1 to 6, and importance of the parameters

- Roll rate,
- Bank angle,
- Yaw rate,
- Vertical load factor,
- Vertical speed,
- Pitch angle,
- Altitude deviation,
- Speed deviation

for perceiving the upset, on a scale from 0 to 3. Rating criteria are attached to this report as TAB 4 and TAB 5. Pilots were also encouraged to provide additional comments. In addition to subjective ratings pilot control inputs, flight parameters and air data was recorded.

Four different airline pilots with experience on Airbus Fly-by-Wire aircraft took part in the study, each flying an identical series of encounters. The pilots controlled the aircraft from the seat they occupy during normal airline operations. TAB 3 provides detailed information on the pilots.

Pilot	A	B	C	D
Year of birth	1962	1967	1976	1960
Rank	F/O	F/O	F/O	CAPT
Ratings (current)	A330/ 340, F-50, MD-80, F-70/ 100	A330/ 340, A320	A320, BE300/ 1900, PA42, C208, Do328 Jet	MD11, Ju-52, A310, A320, B737, C90
Total hours	8,500	5,600	6,000	18,000
PIC hours	0	0	3,000	8,000
FBW hours	5,000	5,300	300	3,500
Relevant activities	---	---	Aero-batics	---

TAB 3. Pilot information, all pilots Air Transport Pilot-licensed

Before the start of the test series a 30 min briefing was held during which the task, the test process and the rating criteria were explained to the pilot. They were not briefed on the nature of the upset, number and scheduling of the encounter scenarios or the planned changes of the cueing environment. Before starting the test series the pilots were given 5 min of free flight time to familiarize with the simulator. Subsequently they were asked to fly 2 wake vortex encounters to exercise the use of the rating scales.

4.2. Data Analysis

Analysis of recorded data and subjective pilot ratings focused on roll axis. Overall severity and importance ratings underwent a statistical analysis to identify dependencies between motion system setup and received ratings. Analysis included calculation of histograms, averages and standard deviations for all tests grouped by motion and visual configuration.

The recorded test data was used to study the impact of motion system setup on pilot reaction. To characterize pilot reaction a reaction time Δt was defined as the time delay between reaching an absolute vortex induced rolling moment of $\Delta L = 1E6$ Nm and 33% of the maximum counter-acting side-stick roll input during the encounter (see FIG 6). An absolute rolling moment criterion was chosen since the aircraft was operated in normal law, i.e. the upset only becomes visible to the pilot once perturbation magnitude reaches a level, which can not be compensated by EFCS feedback commands any more.

A data analysis script for extraction of reaction time from recorded test data and statistical analysis was implemented. Box plot visualization was chosen, i.e. median and upper/lower quartiles of reaction times were plotted for all tests grouped by motion/visual combination, encounter scenario and pilot. Encounter case 4 was precluded from statistical analysis. The encounter has a very slow characteristic so that stick response can not be clearly associated with the vortex induced rolling moment.

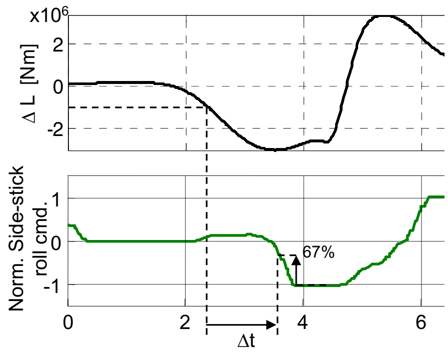

FIG 6. Definition of pilot reaction time in roll axis

The collected data did not allow determination of pilot variation, as every test condition was only flown once by every pilot, except for the modified motion/no visual combination, which was flown twice by each pilot (see TAB 2).

4.3. Test Results

4.3.1. Recorded Data

FIG 7 shows typical pilot responses to the same upset scenario for various motion system configurations (no outside visual). The pilots are using very different control techniques. While Pilots A and C are closing the loop very actively, reaching high stick deflections with temporary saturation, Pilots B and D are performing the task with significantly lower gain. Nevertheless, a connection between motion system configuration and pilot reaction can be suspected.

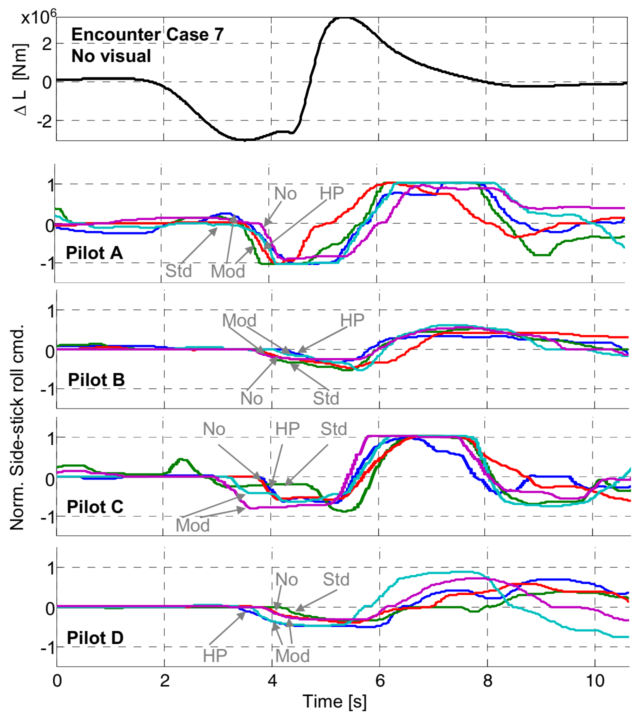

FIG 7. Pilot control inputs for different pilots and motion system configurations

Pilot reaction times, as defined above, were calculated for all encounters. In FIG 8 results for encounters without outside visual are presented grouped by motion system configuration. FIG 9 gives the results for encounters with day visual.

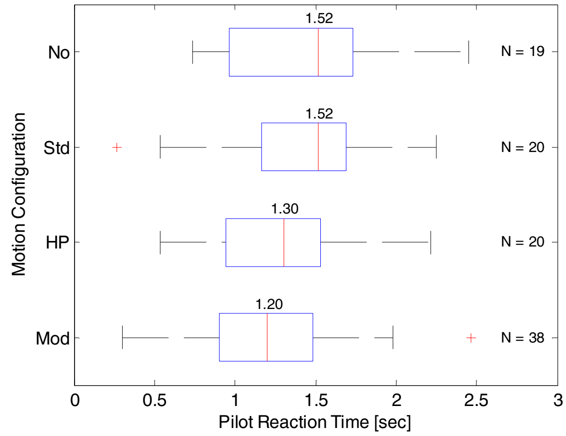

FIG 8[1]. Pilot reaction times by motion configuration, no outside visual

It can be seen that median reaction times decrease by approximately 0.3sec and range of variation decreases significantly when outside visual information is available to the pilot.

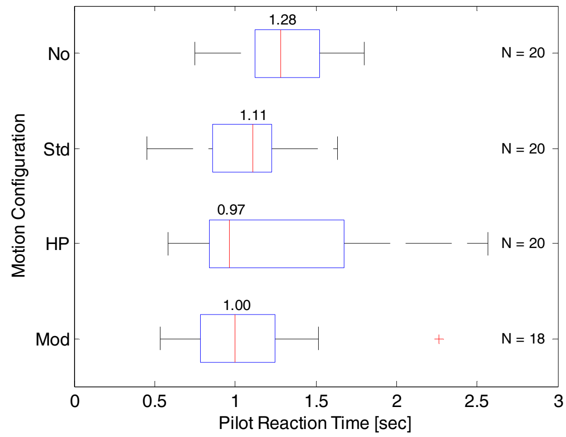

FIG 9. Pilot reaction times by motion configuration, day visual

Independent of the visual system configuration a trend of increasing pilot reaction time from modified, over standard to no motion cueing can be observed. Reaction time in standard configuration is about 0.3sec (no visual) / 0.1sec (day visual) greater than with modified motion setup. No motion encounters exhibit similar (no visual) / 0.2sec greater median reaction times than encounters with standard motion cueing setup.

Considerable variation of pilot reaction times for a given motion / visual system combination is visible in FIG 8 and

[1] Labeled vertical marker inside box denotes median, box extends from lower to upper quartile, dashed lines show range of remaining data within 1.5 x interquartile range, outliers shown as "+"

FIG 9. As significant impact of encounter characteristic on reaction times and a wide variation between pilots was presumed these influences had to be examined as well.

FIG 10 and FIG 17 confirm a clear influence of encounter characteristic on reaction time. Median reaction times vary over a range of 0.7sec (no visual) / 0.3sec (day visual). Encounter case 8, being a high-frequency upset, results in longest reaction times and widest variation, while encounter case 10, being of rather low-frequency, results in shortest reaction times.

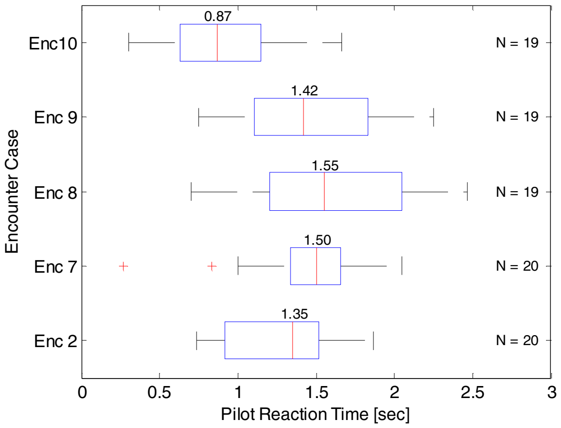

FIG 10. Pilot reaction times by encounter scenario, no outside visual

FIG 11 and FIG 18 indicate a clear difference of control technique between the pilots. As can also be suspected by the exemplary time histories shown in FIG 7, pilots A and C are reaching smaller reaction times than pilots D and B, who are performing the control task with a lower gain. For tests without outside visual a spread of about 0.7 sec can be observed; for tests with day visual the spread of median reaction time between the pilots is reduced to about 0.55 sec.

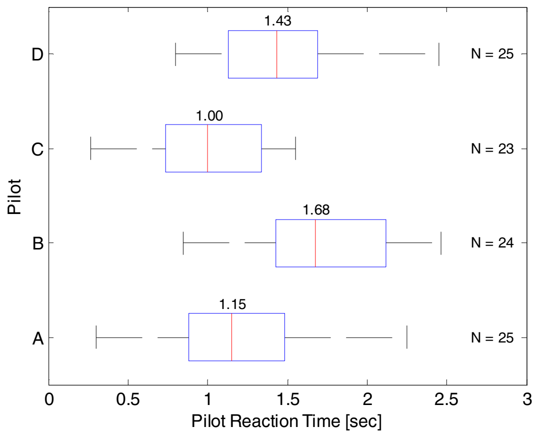

FIG 11. Pilot reaction times by pilot, no outside visual

4.3.2. Pilot Ratings

FIG 12 and FIG 19 show increased severity ratings for encounters with standard motion setup over encounters without motion. Severity ratings further increase when encounters are flown in modified motion system configuration. This trend is found regardless of whether outside visual information is provided to the pilot or not.

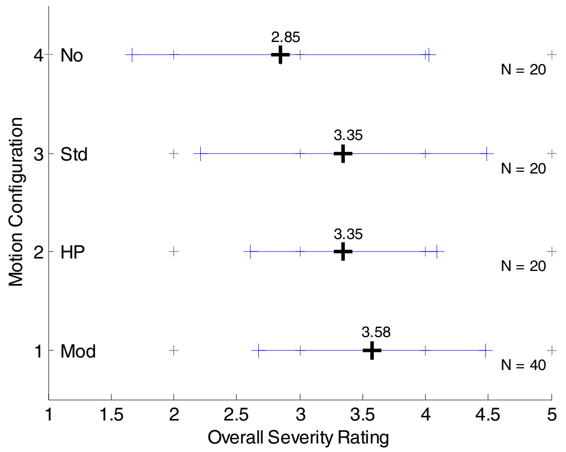

FIG 12[2]. Overall severity ratings by motion configuration, no outside visual

Comparing FIG 12 and FIG 19 it can also be found that overall severity ratings are slightly higher without outside visual, if motion cues are provided.

Analysis of roll rate importance ratings reveals increased roll rate importance if encounters are flown with modified motion setup, as can be seen in FIG 13 and FIG 20 for tests without and day outside visual respectively.

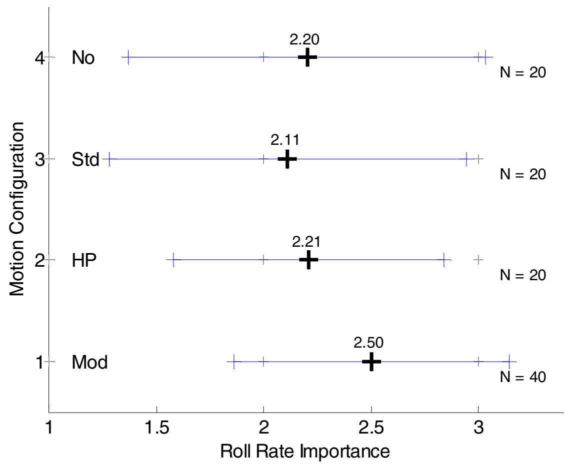

FIG 13. Roll rate importance ratings by motion configuration, no outside visual

[2] Center "+"-marker indicates average, line shows range of standard deviation

5. CONCLUSION AND OUTLOOK

Analysis of pilot reaction time in roll axis, overall severity ratings and roll rate importance ratings suggests that availability of motion cues as well as the characteristics of the motion cueing algorithm influence pilot perception and response during simulated wake vortex encounters. Encounters were perceived more severe and quicker pilot reaction was observed when using a motion system setup optimized for wake encounter simulation rather than the standard training setup. Encounter simulations conducted without cabin motion received lowest severity ratings and showed slowest pilot response.

A follow-on, larger-scale test campaign should be conducted to substantiate the findings of this study and complement the test data. To allow for isolated analysis of pilot variation, a sufficient number of encounters should be simulated in identical motion / visual configuration and encounter scenario.

If the trends presented in this paper can be confirmed, an in-flight simulator campaign should be conducted. With the in-flight simulator tuned to A330-300 dynamics, the pilot has to be exposed to the upset scenarios used in the ground-based campaign. Pilot response and subjective ratings from in-flight simulation could then serve as baseline for comparison with ground-based results to ascertain whether a motion cueing algorithm optimized for wake vortex encounter simulation can improve agreement between simulator and flight test results for this research application.

ACKNOWLEDGEMENT

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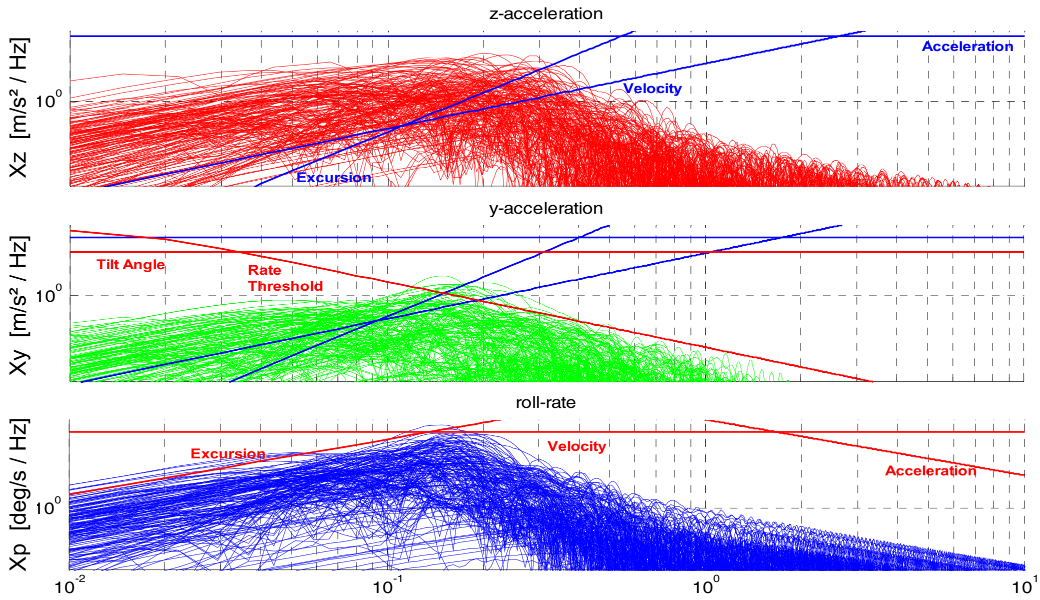

FIG 14. Magnitude Spectra of primary and secondary motion cues during wake vortex encounters

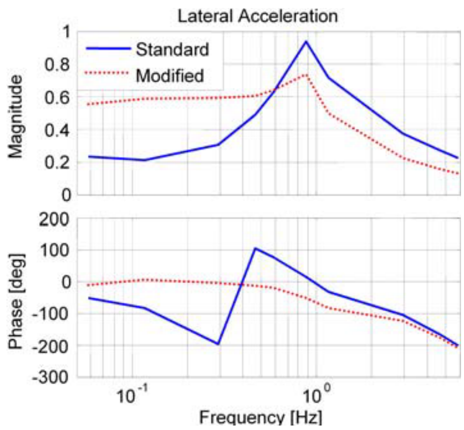

FIG 15. Computed standard and modified motion system dynamics in lateral axis

Disturbance	Effort	Rating
None	None	*1*
Slight	Minimal corrective action required	*2*
Moderate; annoying for passengers and on-board service	Noticeable corrective action required	*3*
Significant; problems for on-board service, minor injuries possible	Considerable but not exceptional corrective action required	*4*
Severe; critical flight state (attitude, rate, acceleration), injuries likely to occur	Corrective action clearly exceeding the limits of normal operation is required for airplane recovery	*5*
Temporary loss of control; serious or fatal injuries can occur	Full or nearly full deflections are reached	*6*

TAB 4. Rating criteria: Overall Severity Rating

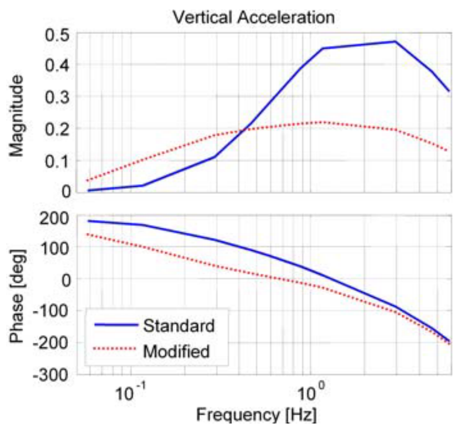

FIG 16. Computed standard and modified motion system dynamics in vertical axis

Description	Verbal rating	Numerical rating
Parameter was not observed during the upset	Not observed	*0*
Parameter was observed, but was not important	Not important	*1*
Parameter was observed and was important	Important	*2*
Parameter was highly important and dominated pilot perception of the upset	Highly important	*3*

TAB 5. Rating criteria: Parameter Importance Rating

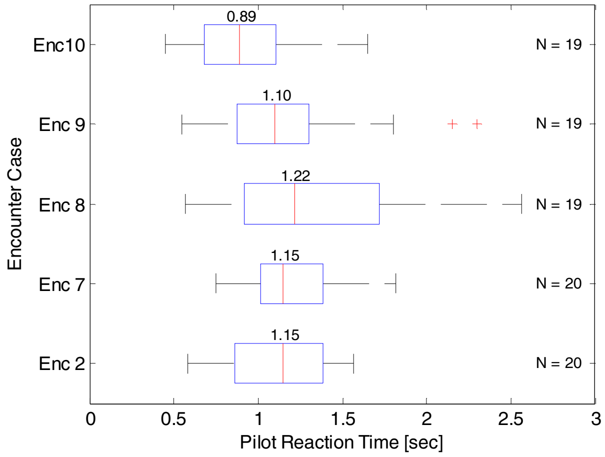

FIG 17. Pilot reaction times by encounter scenario, day visual

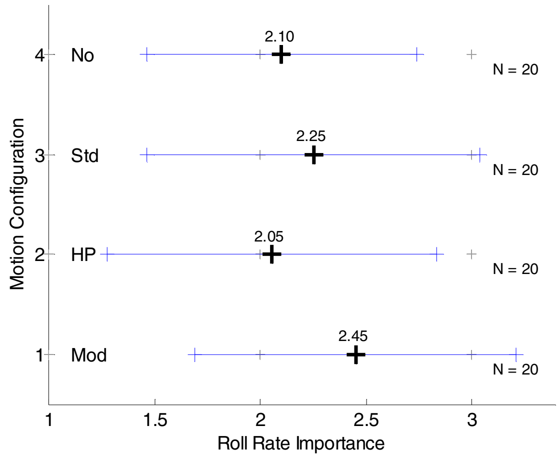

FIG 20. Roll rate importance ratings by motion configuration, day visual

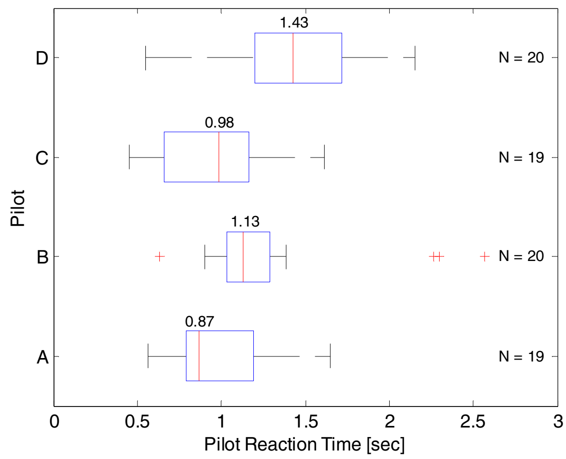

FIG 18. Pilot reaction times by pilot, day visual

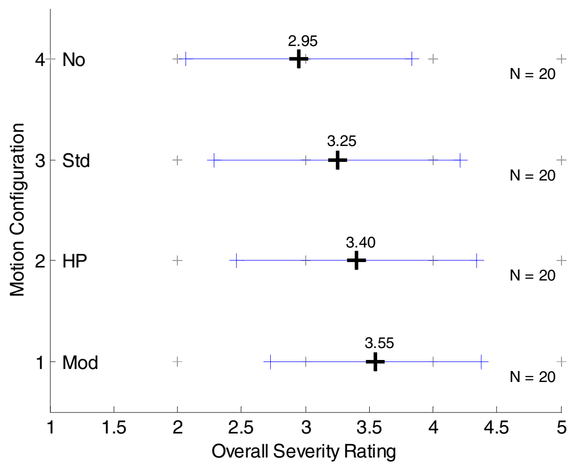

FIG 19. Overall severity ratings by motion configuration, day visual