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Simulation System Optimization for Rotorcraft Research on the Vertical Motion Simulator

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To obtain handling qualities ratings similar to flight in a ground based motion simulator, the motion and visual pilot cueing systems should be optimized to provide realistic cues. A handling qualities experiment conducted on the Vertical Motion Simulator using the GenHel UH-60A Black Hawk helicopter math model demonstrated the benefits of an optimized simulation system. The simulator's motion and visual system frequency responses were measured, the aircraft math model was adjusted to account for the simulator motion system delays, and the motion system gains and washouts were tuned for the bob-up, sidestep and hover tasks. The resulting handling quality ratings from the optimized simulation system are better than the simulation system with the standard GenHel math model for all three tasks. The sidestep and bob-up handling qualities ratings for the optimized simulation system are similar to those from actual flight tests.

I. Introduction

Ground-based motion flight simulators are an efficient and cost-effective method for predicting actual aircraft handling qualities when the impact of the simulation system on pilot performance is understood. For ground-based simulation to be effective, the exhibited handling qualities ratings (HQR) must be similar to flight. Obtaining HQRs similar to flight can be challenging due to necessary compromises required for ground-based motion simulation such as motion/visual system transport delays, reduced motion envelope, visual cueing differences, and math model fidelity.

Considerable research has been completed on various aspects of ground-based motion simulation to better understand and mitigate the adverse effects of the simulation system on pilot performance. Knotts and Bailey advocated keeping the added delay from the simulator motion below 50 msec so the pilot does not differ their control strategy from flight.[1] Mitchell et. al., showed that a motion transport of 80 msec would degrade HQRs from Level 1 to Level 2.[2] Sinacori hypothesized,[3] and later Schroeder extended,[4] criteria for defining the quality of simulator motion based on the gain and phase of the motion software filters. Mitchell and Hart suggested minimizing the mismatch between motion and visual delays.[5] Gum and Martin suggested techniques to reduce math model delays to compensate for the motion delays.[6] Chung and Schroeder recommended that the equivalent time

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delay between roll and lateral motion be synchronized for a sidestep task, but if they cannot be, the mismatch should not exceed 40 msec.[7] Chung and Schroeder actually added delay to the math model to synchronize the roll and lateral axis. All the research listed above addresses individual aspects of flight simulation, but does not look at the ground-based simulation system as a whole and compare it to actual flight data. The purpose of the study described here was to apply these previous recommendations and measure the value of doing so with flight versus simulation comparisons.

In 1989-90 two experiments on the Vertical Motion Simulator (VMS) at NASA Ames Research Center assessed the fidelity of a UH-60A Black Hawk helicopter simulation. A bob-up, sidestep, and dash/quick-stop task were performed in the actual aircraft then repeated in the VMS in 1989 and 1990.[8] In May 2012, the bob-up and sidestep tasks were reproduced from the 1989-90 experiments in the VMS using two configurations. The first configuration is similar to the 1989-90 experiment setup and is used as a baseline. In the second configuration, the motion and visual pilot cueing system response is optimized to be similar to flight by removing excess time delay from the math model to compensate for motion system delay. For both configurations the motion software filter gains and washouts were optimized using the modified Sinacori fidelity criteria for each task. HQRs using the Cooper-Harper rating scale, in addition to qualitative data, were collected for actual flight and simulations.

This experiment, named SimOpt, demonstrates the improvement in simulation results when the end-to-end simulation system response is optimized to be similar to flight. This paper describes the SimOpt experiment, the simulation systems optimization, and quantifies the system performance improvements. The HQR results from the actual flight, 1989-90 simulations, and the SimOpt simulations will be presented and compared.

II. Vertical Motion Simulator

A. Description

The Vertical Motion Simulator, with its large motion envelope provides the realistic cueing environment necessary for performing handling quality studies. Schroeder, et. al., concluded that larger simulator motion envelopes provide more accurate HQRs than small motion envelopes when compared to HQRs taken in the actual aircraft for the same tasks.[9] Additionally, pilots gave large motion higher confidence factor ratings and achieved lower touchdown velocities compared to small motion simulators. The VMS motion system, shown in Fig. 1, is an uncoupled, six-degree-of-freedom motion simulator that moves within the confines of a hollow ten-story building.

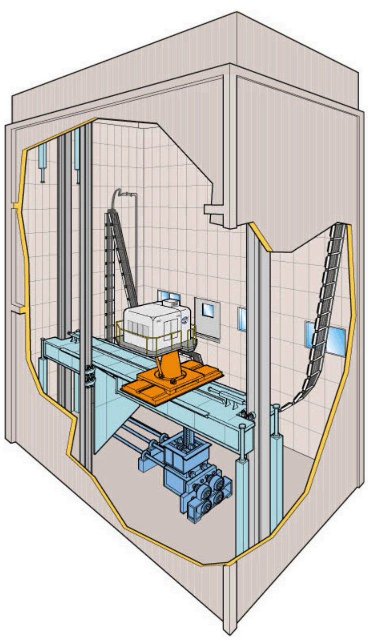


Figure 1. Vertical Motion Simulator.

The VMS motion capabilities are provided in Table 1. Included in the table are two sets of limits: system limits that represent the absolute maximum levels attainable under controlled conditions; and operational limits that represent attainable levels for normal piloted operations.[10]

The VMS has five interchangeable cabs (ICABs) with each having a different out-the-window (OTW) visual field-of-view (FOV) that is representative of a class of aircraft. The ICABs can be customized for an experiment by installing various flight controls, instruments, instrument panels, displays and seats to meet research requirements.

A Rockwell-Collins EPX5000 computer image generator creates the OTW visual scene for up to seven-window collimated displays for the ICAB with the largest FOV. Standard flight instrumentation and other aircraft information, as needed for an experiment, are provided on head-down displays that are generated using separate graphic processors. The OTW and head-down display graphics are created in-house and are usually customized for each experiment.

The high-fidelity flight controls are heavily modified and optimized McFadden hydraulic force-loader systems' with a custom digital-control interface. The custom digital-control interface allows for comprehensive adjustment of the controller's static and dynamic characteristics.[11] Force-loader characteristics may be varied during simulated flight as necessary for studying pilot cueing concepts using inceptors. A variety of aircraft manipulators, ranging from the regular column-and-wheel type to conventional rotorcraft controls and side sticks may be combined with the force-loader systems.

Table 1. VMS motion system performance limits (From Ref. 10).

Degree of Freedom	Displacement		Velocity		Acceleration	
	System Limits	Operational Limits	System Limits	Operational Limits	System Limits	Operational Limits
Longitudinal	±4 ft	±3 ft	±5 ft/sec	±4 ft/sec	±16 ft/sec^2	±10 ft/sec^2
Lateral	±20 ft	±15 ft	±8 ft/sec	±8 ft/sec	±13 ft/sec^2	±13 ft/sec^2
Vertical	±30 ft	±22 ft	±16 ft/sec	±15 ft/sec	±22 ft/sec^2	±22 ft/sec^2
Roll	±0.31 ft	±0.24 rad	±0.9 rad/sec	±0.7 rad/sec	±4 rad/sec^2	±2 rad/sec^2
Pitch	±0.31 ft	±0.24 rad	±0.9 rad/sec	±0.7 rad/sec	±4 rad/sec^2	±2 rad/sec^2
Yaw	±0.42 ft	±0.34 rad	±0.9 rad/sec	±0.8 rad/sec	±4 rad/sec^2	±2 rad/sec^2

B. Motion Description

The cockpit motion cueing algorithms use high-pass (washout) filters and a rotational/translational cross-feed arrangement shown schematically in Fig. 2. The computed pilot station accelerations of the modeled aircraft are second-order high-pass filtered, and attenuated, before commanding the motion drive system. Turn coordination and induced acceleration compensation account for the cross-coupled motion commands and provide the correct cues at the pilot's station. A low-pass filter tilts the simulator to provide steady-state longitudinal and lateral acceleration cueing at low frequency.[12]

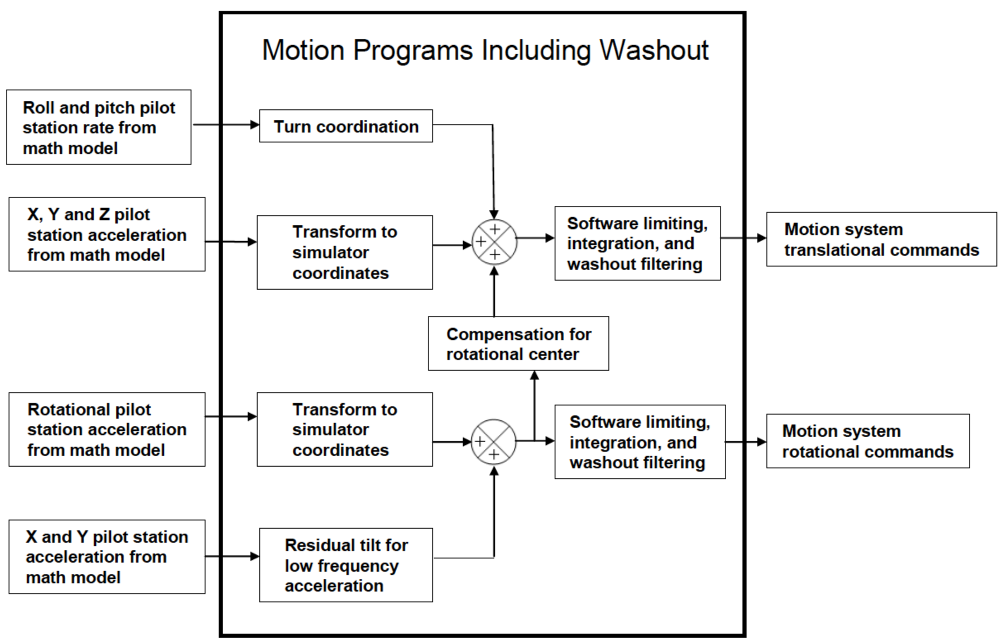


Figure 2. VMS motion algorithm schematic.

The VMS motion system may be adjusted for each simulation task by selecting the motion cueing filter gains and frequencies that provide the most realistic motion cueing within the simulator motion envelope. The motion tuning is a subjective process where the project pilot flies the maneuver and evaluates the motion cuing. A motion-tuning expert then adjusts the filter gains and washouts to satisfy the pilot while staying within the operational motion envelope.

The motion cueing dynamics as defined by the selected gains and washout parameters are then assessed against the modified Sinacori criteria described by Schroeder.[4] An example of the modified Sinacori plot is shown in Fig. 6. The modified Sinacori criteria plots show the gain and phase distortion imposed by motion filters at 1 rad/sec. Actual flight would display zero phase shift and unity gain and therefore would reside in the bottom right hand corner (see Fig. 6). Fixed-base simulators would have a motion gain and phase distortion of zero and would reside on the bottom left hand corner of the Sinacori plot.

Schroeder and Grant recommended the following best practices, which were used to tune the motion system:[13]

- Know your motion gains and washout frequencies in each axis; many simulator users do not know them and are therefore assuming unknown risks.
- Assess your motion cues with existing motion fidelity criteria; if you are in a low region, make sure you are satisfied that cues in that axis are not affecting your results adversely.
- If your motion cues are low fidelity for a particular task, then strongly consider changing the task to one that achieves the evaluation objectives but allows for higher motion fidelity.
- Overplot your math model angular rates and translational accelerations at the pilot's location with what your motion system is providing; make sure you are satisfied with any disparity.
- Try to find a task that allows the pilot to feel the vehicle's true control sensitivity.
- If your task has predominant frequencies, such as a dolphin maneuver over regular hills at a constant speed, adjusting the washout frequency is better than adjusting the gain to keep the motion cue in phase with the visual cue.

C. Transport Delays

Transport delay, for the purposes of this paper, is the time the motion system or visual system takes to respond to rate and acceleration outputs of the UH-60A GenHel math model.

1. Motion System Transport Delays

Prior to this experiment, a frequency response analysis was conducted by independently driving each axis of the VMS with the twelve discrete frequency sine waves as specified by ICAO Doc. 9625[14], including an additional frequency of 4.77 Hz, of varying amplitude (amplitude decreased with frequency to avoid exciting motion limits and structural modes) injected one at a time. From the frequency response plots, the system was observed to behave as a pure time delay and exponential curve fits were computed using the least squares method to determine the equivalent time delay (see Table 2).

In addition, frequency sweeps were used to drive each of the axes through a chirp signal, injected directly into the motion system for each axis at a frequency range of 0.2 – 20 rad/s over two minutes. CIFER[15] was then used to compute the frequency response plots and determine the equivalent time delay for the motion system, validating the response from the discrete sine waves.

2. Visual System Transport Delay

The visual system transport delay was measured at the start of the experiment. A chirp signal was injected into the pitch axis at a frequency range of 0.2 rad/s to 30 rad/s over two minutes. A board with a black upper surface and white lower surface was positioned directly in front of the aircraft in the OTW view. As the aircraft pitched up and down from the chirp signal, the transition from black to white was measured using a photodiode against the OTW projection screen recorded by the Mark 2 Image Dynamic Measurement System (IDMS-2) developed at the VMS.[16]

Table 2. Motion system equivalent time delay.

Axis	Equivalent Time Delay [sec]
Pitch	0.047
Roll	0.068
Yaw	0.048
Longitudinal	0.050
Lateral	0.069
Vertical	0.067
Visual	0.062

The IDMS-2 uses the composite and vertical sync signals from an NTSC (National Television System Committee) or RGB (Red Green Blue) video signal to determine the relative position of a transition from a dark region of video to a bright region. The vertical sync signal references the beginning of a frame of video and is used in the IDMS-2 to reset the counters and detector logic. By comparing the video brightness in each line with a threshold level set by the user, the IDMS-2 counts the number of composite sync pulses since the end of vertical sync to determine the relative position of the dark to bright transition in the video field.[17]

The data collected by IDMS-2 was analyzed using CIFER and the time delay was found to be a constant 62 ms over the frequency range.

III. Objectives and Approach

In 1989 flight tests were performed with a UH-60A Black Hawk helicopter flying bob-up, sidestep, and dash/quickstop tasks at the NASA Ames flight test facility at Crows Landing Naval Auxiliary Air Station. Concurrent with the flight-testing, the same tasks were performed on the VMS using the same four pilots flying the UH-60A GenHel math model. During the 1989 simulation a problem with the data acquisition software resulted in the loss of all performance data leaving only the subjective data. The simulation was repeated in 1990 using three pilots with only two of the pilots that participated in the original experiment.[8]

In the SimOpt experiment, the bob-up and sidestep tasks were repeated on the VMS while maintaining similarity with the 1989 and 1990 simulations. This experiment used two configurations of the UH-60A simulation model. The first configuration was the baseline UH-60A GenHel math model used in the previous simulations. The second configuration was a modified UH-60A GenHel math model with reduced model delays. A hover task was added to this experiment to contrast the more aggressive bob-up and sidestep maneuvers and evaluate the motion cueing in large and small amplitude tasks.

This experiment had the following two objectives:

1. To compare pilot-vehicle performance between the two math model configurations for the bob-up, sidestep and hover maneuvers.
2. To compare pilot-vehicle performance of the bob-up and sidestep maneuvers for both math model configurations to that of the 1989 and 1990 simulations and actual flight.

IV. Experimental Setup

Exact replication of the simulation cueing experiment from the 1989 and 1990 experiments was not possible due to the upgraded visual database, image system, and motion system's dynamic performance. Various VMS subsystems, such as the computer image generator and sound system, have been upgraded. In addition, the motion-base frequency response has been improved since 1990. The ICAB used in the 1990 simulation could not be used for this experiment because it now has a rear projected visual display system and is no longer a collimated system as in 1990.

A. Baseline UH-60A GenHel Math Model

The GenHel math model configured for the UH-60A helicopter is a nonlinear representation of a single main rotor helicopter, accurate for a full range of angles of attack, sideslip, and rotor inflow. It is a blade element model where total rotor forces and moments are calculated by summing the forces from blade elements on each blade, which are determined from aerodynamic, inertial, and gravitational components. Aerodynamic forces are computed from aerodynamic function tables developed from wind tunnel test data.

B. Modified UH-60A GenHel Math Model

Due to the inherent motion system delay of the VMS, the GenHel math model was modified by removing delay in specific areas to provide a more accurate pilot input to motion cue representation of the UH-60A vehicle. Using the math model outputs as the truth set representing the actual flight vehicle, two techniques to reduce the equivalent time delay of the GenHel math model were implemented and tested. The first concentrated on the primary servo (actuator) models, and the second focused on the blade-element model of the main rotor.

The Black Hawk's main rotor primary servos account for approximately 30 msec of equivalent time delay from command to actuation. In GenHel, the primary servos are modeled as second-order systems with a fixed damping ratio (ζ) and natural frequency) (ω_n). The equivalent time delay (t_{eq}), is defined as:

$$t_{eq} = \frac{2\zeta}{\omega_n} \tag{1}$$

Increasing the natural frequency of the system can therefore reduce the equivalent time delay. In this study, the natural frequency was increased to recover approximately 14 msec of equivalent time delay from the primary servo model. An alternate approach would be to remove the primary servo models altogether, thus completely eliminating all servo delay resulting in a more accurate cyclic to motion cue UH-60A simulator model. For the purposes of the current study, however, the modeled natural frequency was increased just enough to produce a significant effect without introducing high-frequency modes or requiring restructuring of the math model code.

In an effort to further reduce the equivalent time delay of the math model, modification to the rotor dynamics module was investigated. The rotor contains complex dynamics, including flapping, lead/lag, and inflow, that take time to develop; they do not reach steady state immediately. These dynamics can be approximated as an equivalent rotor delay, which is approximately 60-80 msec on the Black Hawk. In theory, if the rotor could be made to achieve a new steady-state position instantly when given a control input, the equivalent time delay of the rotor would be eliminated.

The GenHel rotor module was modified to effectively remove the rotor dynamics, thus removing the associated equivalent time delay; this is often referred to as a quasi-steady rotor model.[15] To accomplish this, the GenHel code was modified so that multiple calls were made to the rotor routine on each simulation time step. This rotor "multi-loop" allowed the rotor to settle out before moving on to the next time step, therefore eliminating the equivalent rotor delay.

Table 3 shows the difference in closed-loop equivalent time delay between the baseline GenHel model and both versions of the compensated model: increased actuator natural frequency only, and increased actuator natural frequency plus rotor "multi-looping." In the fully compensated model the pitch and roll axes have the greatest time-delay recovery, with a minimal recovery in the vertical and a negligible difference in the yaw axis. Note the rotor looping technique has adverse effects on the yaw axis possibly due to complex inflow dynamics coupling with the directional axis, resulting in an increase in delay, however the tasks were not focused on the directional axis.

Table 3. Equivalent time delay recovered from model.

Axis	Actuator Only (sec)	Actuator and Rotor Looping (sec)
Pitch	0.016	0.064
Roll	0.013	0.045
Yaw	0.014	0.005
Vertical	0.014	0.016

Fig. 3 and Fig.4 show the on-axis closed loop pitch (q) and roll (p) response overlays with respect to longitudinal cyclic (δ_{lon}) and lateral cyclic (δ_{lat}) pilot inputs of the baseline math model versus the VMS configured with the baseline and modified math models. The additional time delay introduced by the VMS motion systems increases the end-to-end equivalent time delay of the system beyond the baseline math model, as seen by the increased roll-off of the phase curve. Configuring the VMS with the modified math model, however, which has reduced time delay, closely restores the end-to-end equivalent time delay of the system to that of the math model itself. This verifies the need to reduce the equivalent time delay of the model to allow the closed-loop responses of the VMS to better match that of the baseline math model.

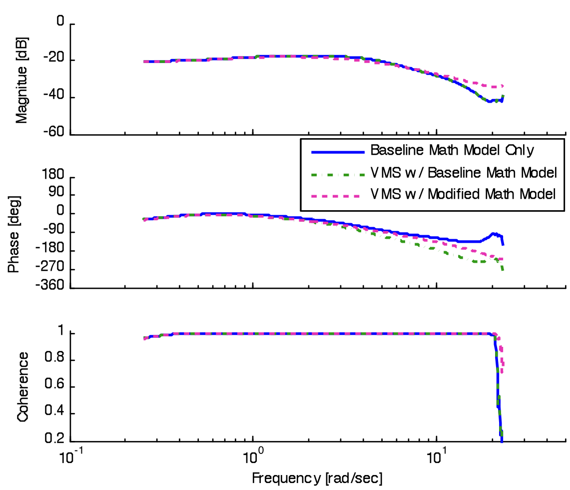


Figure 3. Closed-loop responses, q/ δ_{lon}.

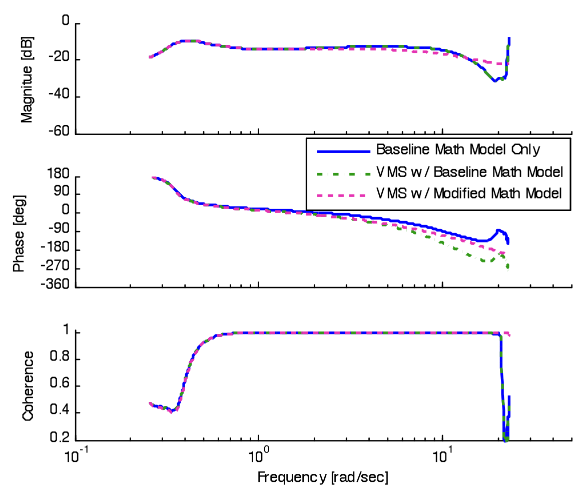


Figure 4. Closed-loop responses, p/ δ_{lat}.

As a companion analysis to the closed-loop frequency response results, the short-term response to control inputs (bandwidth) and phase-delay parameters were calculated. The bandwidth and phase-delay for the pitch and roll axes were calculated based on the methods described in Aeronautical Design Standard (ADS) - 33.[18] The calculated values of the baseline and modified GenHel with the VMS motion are shown co-plotted with results of the baseline math model on the Bandwidth specifications for Pitch and Roll in hover, as presented in Fig. 5. These results verify that the modified math model effectively increases the speed of response due to control inputs as compared to the baseline model, as evident by the increased bandwidth and reduced phase delay. These results reinforce and validate the effectiveness of the math model modifications.

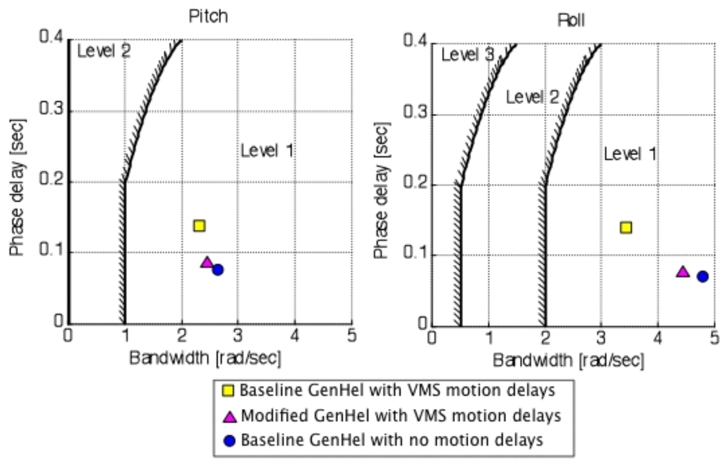


Figure 5. ADS-33 Bandwidth Specifications.

It is important to note, however, that this rotor modification degrades the accuracy of the bare-airframe model in two key ways. Firstly, the rotor dynamics are a real phenomenon and are extensively modeled in the GenHel nonlinear blade-element module. Removing these dynamics from the model essentially degrades the full-nonlinear blade-element model. This effect can be seen in the high frequency portion (15-20 rad/sec) of the magnitude curve in the closed-loop roll response (Fig. 4). Secondly, eliminating the rotor dynamics also affects the off-axis (i.e., roll due to longitudinal control input and pitch due to lateral control input) coupling inherent to the system. This can have adverse effects in tasks in which off-axis responses are significant; however, the current simulation study focused on the on axis closed-loop handling qualities, so the off-axis effects are not expected to have significant affects on the results.

Adverse consequences can also arise when reducing the equivalent time delays unevenly in all axes. Since each motion axis carries a unique time delay, the visual transport delay cannot match all axes. Therefore the axis deemed most critical to the task would be tuned to provide the most accurate end-to-end response in regards to the actual flight vehicle. The visual system transport delay was left unchanged for this experiment. Since the bob-up and sidestep tasks attempt to isolate specific axes, configurations were tuned for each to ensure the primary axis was an accurate representation of the UH-60A rotorcraft.

C. Model Configurations

1. Bob-up Configurations

The baseline configuration is the standard UH-60A GenHel model that was used in the two previous experiments. The modified configuration for the bob-up maneuver reduces the time delay in the actuators only and does not use the rotor looping technique. The rotor looping technique was not used since the bob-up maneuver is primarily a vertical task and there is no benefit in the vertical axis (see Table 4).

2. Sidestep and Hover Configurations

The baseline configuration is the standard UH-60A GenHel model used in the two previous experiments. The modified configuration for the hover and sidestep maneuver utilized both the actuator and rotor looping techniques to reduce the model delay (see Table 4).

Table 4. Equivalent Time Delay of Simulation System for the Bob-up, Sidestep and Hover Maneuvers.

Axis	Baseline GenHel (sec)	Bob-up Maneuver	Sidestep and Hover Maneuvers
		Modified GenHel (Actuators only) (sec)	Modified GenHel (Actuators plus rotor looping) (sec)
Pitch	0.047	0.034	0.002
Roll	0.068	0.052	0.004
Yaw	0.048	0.034	0.032
Longitudinal	0.050	0.050	0.050
Lateral	0.069	0.069	0.069
Vertical	0.067	0.053	0.062

D. Simulator Cockpit

The Rotorcraft Cab (RCab) was used for this experiment, which has three horizontal windows and a chin window (see Fig. 7). The field-of-view for RCab is similar to the cab that was used in the 1990 simulation (see Fig. 8). The cockpit controls and seat shaker were the same as the 1990 experiment including the cyclic and collective force-feel characteristics. The analog gauges from the 1990 simulation were replaced with head down displays.

E. Tasks and Performance Criteria

The bob-up and sidestep maneuver were configured and performed exactly as in the 1989 and 1990 experiments as described in Ref. 8. The OTW visual targets were recreated to the same specifications as in the past two simulations (see Fig. 9 and Fig. 10).

In the 1989 and 1990 simulations the motion gains and washouts were the same for all configurations. In the SimOpt experiment the gains and washouts were optimized for each task. The project pilot flew the tasks prior to the experiment and the motion system gains and washouts were selected and assessed against the modified Sinacori criteria. An example of the modified Sinacori criteria for all axes is shown in Fig. 6 for the SimOpt experiment. The green region illustrates "like flight" fidelity, yellow region would be considered "different from flight", and the red region "objectionably different from flight." The gains and washouts for the three maneuvers are shown in Appendix A.

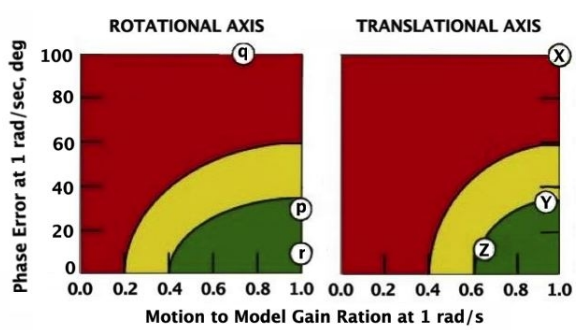


Figure 6. Bob-up Vertical Axis Sinacori Plot.

The hover maneuver was not performed in the past experiments, but it was included here, as it is a well-defined and tested precision low speed handling qualities evaluation task. The hover task was created as defined in the ADS-33 Handling Qualities Requirements for Military Rotorcraft[18] with an additional hover board included in the field of view through the right window to improve longitudinal position cueing that is degraded due to the reduced FOV of the simulator cab as compared to the aircraft. The hover task, requiring closed-loop pilot control in all axes, is less aggressive compared to the other evaluation tasks.

Figure 7. R-Cab cockpit.

The pilots familiarized themselves with each maneuver over a 40-minute period, operating the vehicle under the same configurations as experienced in evaluation runs. Once they were sufficiently familiar with the task they were asked to complete at least two practice runs before flying three evaluation runs and providing an HQR. Performance and HQR data was collected on all evaluation runs. In addition to the performance and HQR data, pilots responded to a questionnaire on certain aspects of the simulator fidelity (see Appendix B).

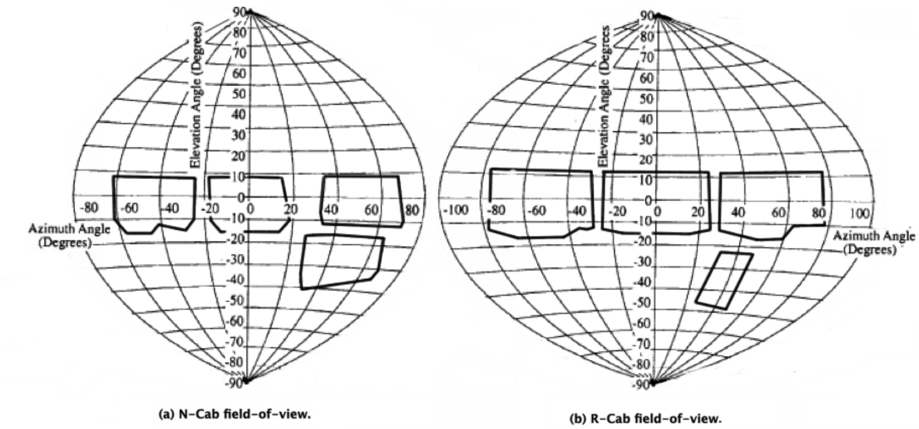


Figure 8. Field-of-view diagrams for N-Cab and R-Cab.

1. Bob-up Maneuver

The bob-up maneuver started from a stabilized hover 106 ft away from the lower hover board shown in Fig. 9. The pilot signaled the start of the task, started a timer, and then rapidly ascended 40 ft to the upper hover board. The pilot then signaled that he was stable, which then stopped the timer. The bob-up and stabilization was to be completed within 10 sec. After stabilization, the top position was held for 5 sec. until a tone sounded. Next, the pilot rapidly bobbed down 40 ft to the lower hover board and signaled that he was stable within 10 sec. The hover position was held for 20 sec after stabilization.

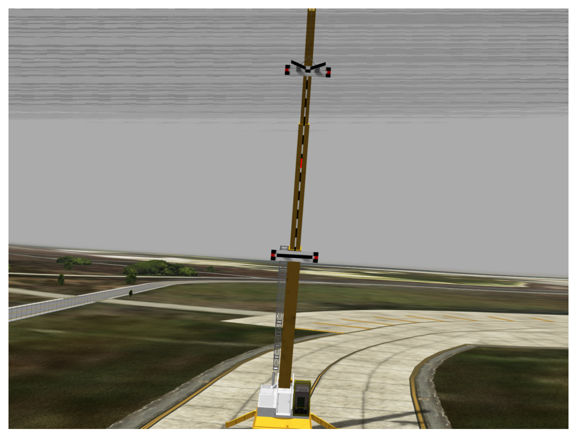


Figure 9. OTW view of bob-up lower hover target.

HQR Performance Standards:

Desired:

1. Complete translation and stabilization within 10 sec and with no objectionable oscillations.
2. Maintain altitude excursions within ±3 ft from hover board center after stabilization.
3. Heading excursions within ±5 deg of desired heading throughout, maneuver.
4. Lateral excursions within hover board width after stabilization.

Adequate:

1. Maintain desired performance taking more than l0 sec to bob up (or down) and stabilize, or
2. Maintain desired performance for most of task except for occasional excursions that exceed, but are followed by return to, desired performance limits.

2. Sidestep Maneuver

The sidestep maneuver was performed starting from a stabilized hover at the left or right hover board as shown in Fig. 10. The pilot signaled the start of the maneuver, started a timer, and then rapidly translated 40 ft. to the other hover board. The pilot then signaled that he was stabilized, which stopped the timer. The sidestep translation and stabilization were to be completed within 7 sec. The stabilized hover was held for 20 sec. The maneuver was then repeated in the opposite direction.

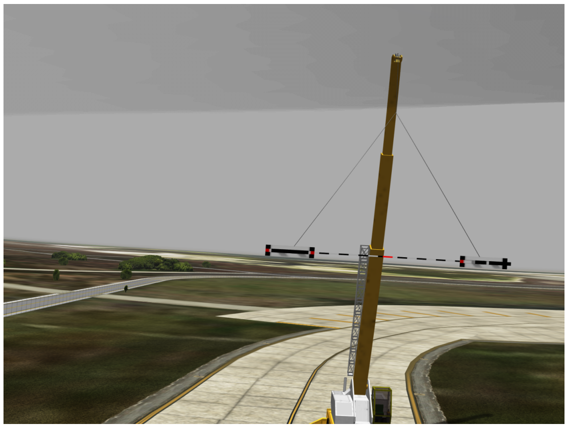


Figure 10. OTW view of sidestep left hover target.

HQR Performance Standards

Desired:
1. Complete translation and stabilization within 7 sec with no objectionable oscillations.
2. Maintain altitude excursions within ±3 ft from hover board centerline throughout the maneuver.
3. Maintain heading excursions within ±5 deg of desired heading throughout the maneuver.
4. Maintain lateral excursions (with reference to the pilot station) within hover board width after stabilization is reached.

Adequate:
1. Maintain the desired performance taking more than 7 sec to translate to right (or left) and then stabilizing, or
2. Maintain desired performance for most of task except for occasional stable excursions, which exceed, but are followed by a return to, desired performance limits.

3. Hover Maneuver

The hover task started at a stabilized hover at an altitude of 33 ft. The pilot initiated the maneuver by accelerating to a ground speed of between 6 and 10 knots while translating at approximately 45 degrees to the relative heading of the rotorcraft. The ground track was such that the rotorcraft should arrive over the target hover point. The pilot signaled that he started his deceleration by starting a timer. The pilot then signaled that he was stabilized at the hover board, stopping the timer (see Fig. 11). The deceleration and stabilization were to be completed within 5 sec. This task was performed with a five-knot rear quarter wind in a good visual environment.

Figure 11. Cockpit view of hover maneuver at hover target.

HQR Performance Standards

Desired:
1. Attain a stabilized hover within 5 seconds of initiation of deceleration.
2. Maintain a stabilized hover for at least 30 seconds.
3. Maintain lateral and longitudinal position within ±3 feet.
4. Maintain altitude within ±2 feet.
5. Maintain heading within ±10 degrees.

Adequate:
1. Attain a stabilized hover within 8 seconds of initiation of deceleration.
2. Maintain a stabilized hover for at least 30 seconds.
3. Maintain lateral and longitudinal position within ±6 feet.
4. Maintain altitude within ±4 feet.
5. Maintain heading within ±10 degrees.

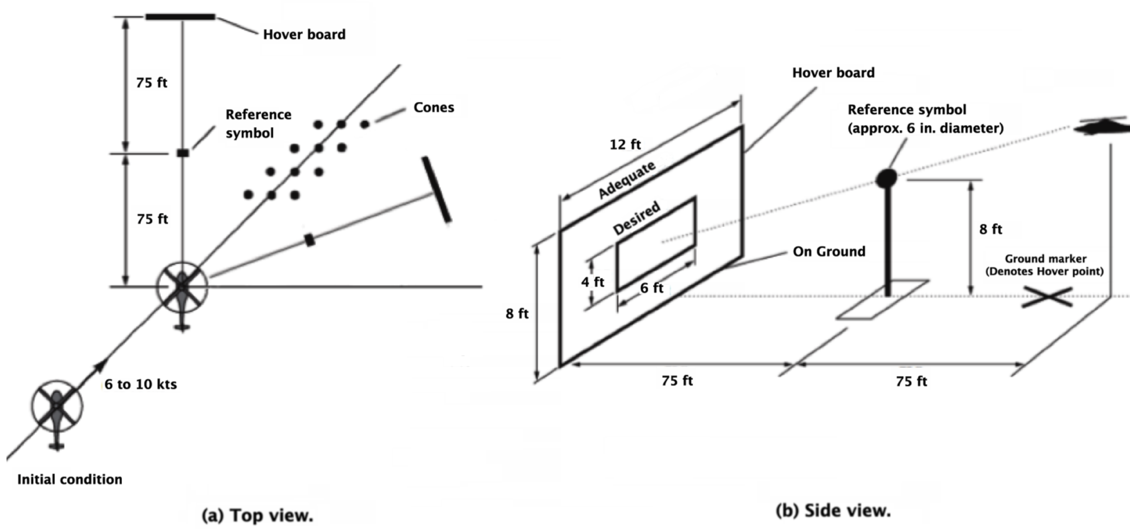


Figure 12. Hover task diagram.

F. Pilots

Four Test Pilots with extensive rotorcraft experience ranging from 1850 to 3500 hours evaluated the configurations.

1. Pilot 1: has 1850 hours of total rotorcraft flight time with 1500 hours of UH-60 time. Pilot 1 is currently an active Army UH-60 pilot.
2. Pilot 2: has 2350 hours of total rotorcraft flight time with 60 hours of UH-60 time. Pilot 2 is currently an active Army OH-58 pilot.
3. Pilot 3: has 3500 hours of rotorcraft time including 200 hour in tiltrotors but with no UH-60 hours. Pilot 3 has not had significant rotorcraft time in 6 years.
4. Pilot 4: has 4000 hours of rotorcraft time with 800 UH-60 hours. Pilot 4 is currently active in rotorcraft.

V. Results

The HQRs, performance data, subjective pilot ratings, and relevant pilot comments are included in this section. The maximum, average and minimum values are shown for each category on Figs. 13 - 21 denoted by the vertical bar showing the range of the minimum and maximum value with the solid square representing the average.

After providing HQRs for each configuration, the pilots were asked to complete a questionnaire (Appendix B). At the end of this questionnaire the pilots were asked to rate various aspects of the simulation from one to five with one being poor and five being excellent. The only categories that should be different between the baseline and modified GenHel configurations were the motion cues and vehicle response characteristics. The other categories should not be affected by the difference in the configurations.

A. Bob-up Maneuver

1. HQRs

The HQRs for the 2012 baseline and modified UH-60 model configurations by all four pilots were the same (see Fig. 13). This was expected since there was only a .014 sec difference in the equivalent time delay between the configurations (see Table 4). The average HQR for both configurations is less than the 1990 simulation but slightly more than the 1989 simulation. The possible reason for the SimOpt experiment HQR improvement over the 1990 experiment is the VMS motion system was tuned specifically for the task, and the motion system performance has been improved over time. The average flight test HQR is less than one rating point better than both SimOpt configurations. The pilots on average were able to achieve Level 1 handling qualities for the SimOpt configurations.

It is difficult to compare flight HQRs with simulation HQRs unless the maneuvers are evaluated back-to-back with the same pilots. The HQRs from the 1989 simulation performed in conjunction with the test flights showed the best correlation. The 1990 simulation that was conducted six months after the flight test shows a significant increase in the average HQR as compared to the 1989 simulation. Atencio[8] states, "It appears as if the flight experience was enhanced with passing time and unfavorable flight characteristics were forgotten." as a possible reason for the worse HQRs. The HQRs from both SimOpt configurations are similar to the 1989 simulation though different pilots participated and there was no concurrent flight test.

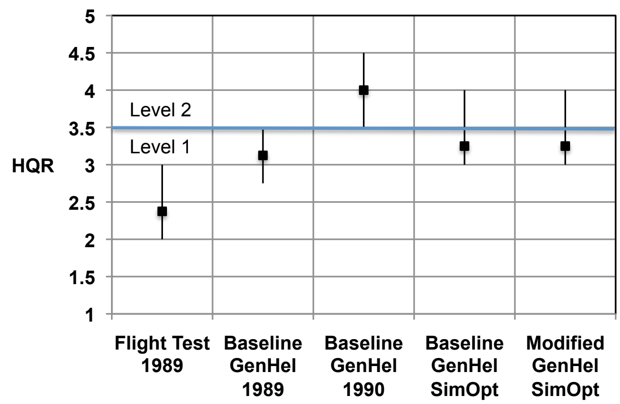


Figure 13. Bob-up maneuver HQRs.

2. Bob-up Performance Data

The pilots easily achieved the desired transit time going from the lower to the upper hover board with several seconds to spare (see Fig. 14). The transit from the upper to the lower hover board was more challenging because it was easier to overshoot the target on the bottom. The pilot would have to time the vertical deceleration carefully so as to not overshoot the target. If the pilot did overshoot the target, the resulting additional time to stabilize would exceed the desired performance requirements. All the pilots found that limiting their aggressiveness during the transit would save time in the stabilization and reduce the overall transit time. The pilots found it easier to time their vertical deceleration and get stabilized faster with the modified GenHel configuration as shown by the smaller range of transit time down values as shown in Fig. 14. This may be attributed to the improved predictability provided by the reduced delay configurations that closely represented the motion and visual cueing dynamics of the actual aircraft.

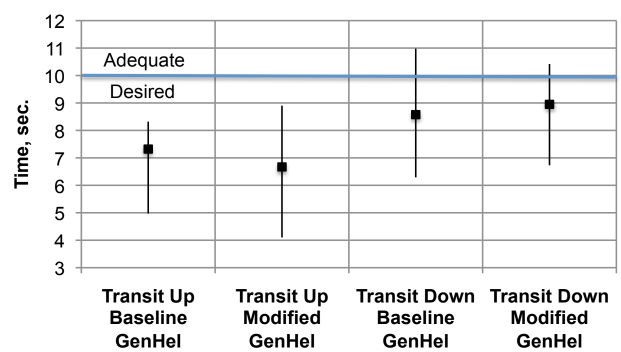


Figure 14. SimOpt Bob-up transit time.

The position error data between the two bob-up configurations are similar, which is to be expected since the modified GenHel model has only a slight advantage in equivalent time delay. Maintaining the altitude within the desired range was the only position error category where any of the pilots exceeded the desired error range (see Fig. 15).

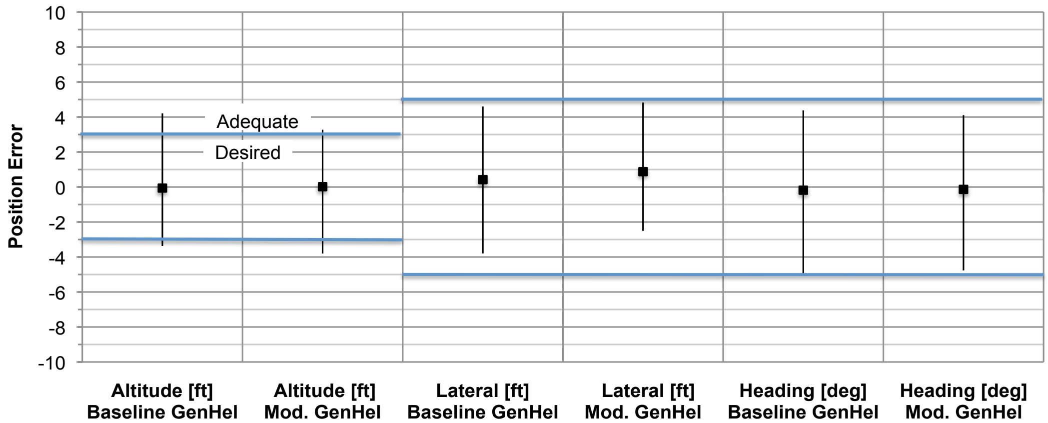


Figure 15. SimOpt Bob-up position error.

The questionnaire results suggested that the modified GenHel configuration was rated slightly better which was expected in both the motion cues and vehicle response characteristics categories. Overall, the two configurations were rated almost the same in all categories (see Table 5).

Table 5. 2012 Bob-up subjective pilot ratings from questionnaire.

Rate the following on a scale from 1 = poor : 5 = excellent	Baseline GenHel	Modified GenHel	% Improvement
motion cues:	4.38	4.50	2.9%
visual cues:	4.12	4.25	3.0%
cyclic:	4.25	4.25	0.0%
collective:	4.50	4.75	5.6%
pedals:	4.75	4.50	-5.3%
vehicle response characteristics:	4.25	4.50	5.9%
task:	4.50	4.50	0.0%

3. SimOpt Bob-up Maneuver Pilot Comments

Overall, the pilots preferred the modified GenHel configuration. Pilot 1 who is a current UH-60 pilot thought he could be more precise with the modified GenHel configuration. Pilot 4 thought both configurations had a tendency to bobble in roll. The following comments were chosen from the questionnaire because they described the pilots perceived differences in the configurations.

Baseline GenHel:

General comments:

Pilot 2 stated, “Deficiencies were slightly worse that the previous configuration (Modified GenHel). This configuration appeared to have more latency in the visuals but did not appear to affect my ability to get desired performance.” Pilot 4 stated, “Transit times seem to take longer in this configuration. This configuration seems similar but a slight difference in vertical axis.”

Questionnaire responses:

Q1. Which axis (roll, pitch, heave) required the most compensation in the task?

All pilots thought the vertical axis required the most compensation except Pilot 4. Pilot 4 thought the roll and yaw required the most compensation due to bobbling. Pilot 4 compared the bobbling in the roll axis to being in a boat.

Q3. Was there any tendency for PIO in any axis in the task?

All pilots accept pilot 4 thought there was no tendency for PIO in any axis. Pilot 4 when asked the question stated, “Yes, in the roll axis. Felt like I was bobbling around. This was totally dependent on the level of aggressiveness.”

Q6. Did the motion cues feel appropriate for the task?

All pilots except felt the motion cues were appropriate for the task. Pilot 2 stated, “They did but felt slightly out phase with the visuals. The visuals lagged slightly but it was perceptible.” Pilot 1 stated, “Yes, the heave axis motion cues felt good. The visual cues looked good outside the window. The cockpit motion cues were appropriate, I felt as if I were climbing or descending. I was pitching a little bit to stop any longitudinal drift and the motion cues felt reasonable. I never felt that I was feeling a motion cue that wasn't appropriate for what the aircraft simulation was doing.”

Q8. Did the basic vehicle response characteristics seem reasonable for this task?

All of the pilots thought the basic vehicle response felt reasonable for the task. Pilot 1, who is a current UH-60 pilot stated, “Yes, I was looking for things like delayed response to control inputs and nothing seemed objectionable. If I put an input in it didn't seem like I was waiting for a long period of time for the aircraft to react. I think it mimics the aircraft fairly closely as far as the control response to the pilot inputs. There is no tendency to PIO. It didn't seem like it was overly sensitive to the small inputs that I was making. For the most part everything felt reasonable.”

Modified GenHel:

General comments:

Pilot 1 stated, “Pilot compensation was required but could achieve a little tighter altitude control in this configuration. On a workload scale, I was working slightly less hard in this configuration than the previous.”

Questionnaire responses:

Q1. Which axis (roll, pitch, heave) required the most compensation in the task?

Pilot 1 and Pilot 4 thought the vertical axes required the most compensation. Pilot 3 thought the yaw axis and Pilot 4 thought the roll and yaw axis required the most compensation.

Q3. Was there any tendency for PIO in any axis in the task?

All pilots accept pilot 4 thought there was no tendency for PIO in any axis. Pilot 4 thought there was a tendency in yaw and roll depending on how much roll was inputted.

Q6. Did the motion cues feel appropriate for the task?

All pilots thought the motion cues felt appropriate.

Q8. Did the basic vehicle response characteristics seem reasonable for this task?

All of the pilots thought the basic vehicle response felt reasonable for the task. Pilot 1, who is a current UH-60 pilot stated, “Yes, I had a hard time resolving which of the two configurations seemed like the actual aircraft. It seemed like I was able to achieve better vertical performance in this configuration but the difference is pretty small. With no winds or turbulence, I would expect the vertical axis to be somewhat stable. I think I could be as precise in the vertical axis of the actual aircraft as this configuration. The two configurations were very close so it was hard to tell other than my performance seemed better with this configuration.”

Q9. Can you describe your control technique for this task?

All of the pilot’s techniques stayed the same between configurations. Pilot 1 stated, “The technique was the same as the other configuration with the only difference being less of a tendency to overshoot the targets with the exception of the second run where I ballooned up past it. I had an easier time my inputs to zero out the vertical rates to stop close to the center. It was a little more difficult in the first configuration. Once I was in the center, I was moving the collective slightly less than the previous configuration to hold it in there. No change in the strategy, just the vertical axis was easier to control.”

B. Sidestep Maneuver

1. HQRs

The sidestep task is primarily a roll/lateral task and the modified GenHel configuration has a 0.045 sec reduction in equivalent time delay which positively impacted the HQRs. The average HQR for the modified GenHel configurations is more than a half point better than the standard GenHel configuration (see Fig. 16). The SimOpt modified GenHel configurations HQRs are similar to those from 1989 and 1990. The SimOpt baseline GenHel configuration has the highest average HQR with a range of values greater than the three other simulation categories.

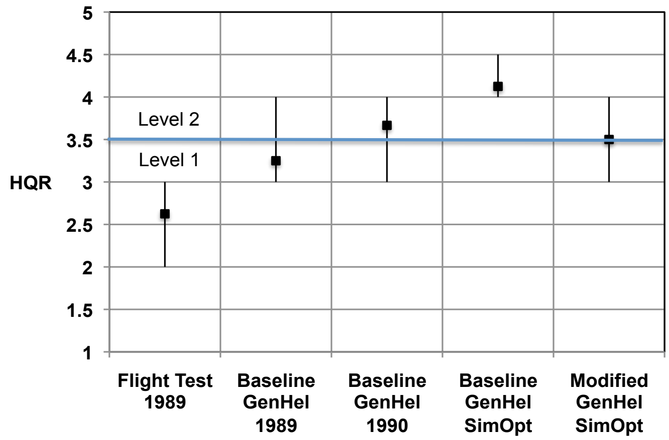


Figure 16. Sidestep maneuver HQRs.

2. Sidestep Performance Data

The pilots found achieving the desired lateral transit time of seven seconds to be challenging. On average the pilots could achieve desired performance but with only a half a second to spare (see Fig. 17). The average transit time for both configurations was about the same, but the range for the modified GenHel configuration was smaller.

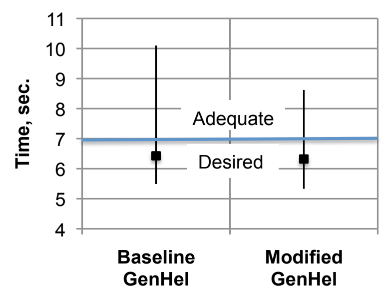


Figure 17. SimOpt sidestep transit time.

The pilots found that they had to time their lateral deceleration carefully or they would overshoot the target. If the pilot did overshoot the target the resulting additional time to stabilize would exceed desired performance. All of the pilots found that limiting their aggressiveness during the transit would save time in the stabilization and reduce the overall transit time. The pilots found it easier to time their lateral deceleration and get stabilized faster with the modified GenHel configuration as shown by the smaller range of downward transit time values as shown in Fig. 17.

The position error data between the two configurations were similar. The lateral position error had the largest excursions outside of the desired region. This can be attributed to the challenging transit time required to achieve desired performance which caused the pilots to accept a less stable hover before calling out stable to stop the timer (see Fig. 18).

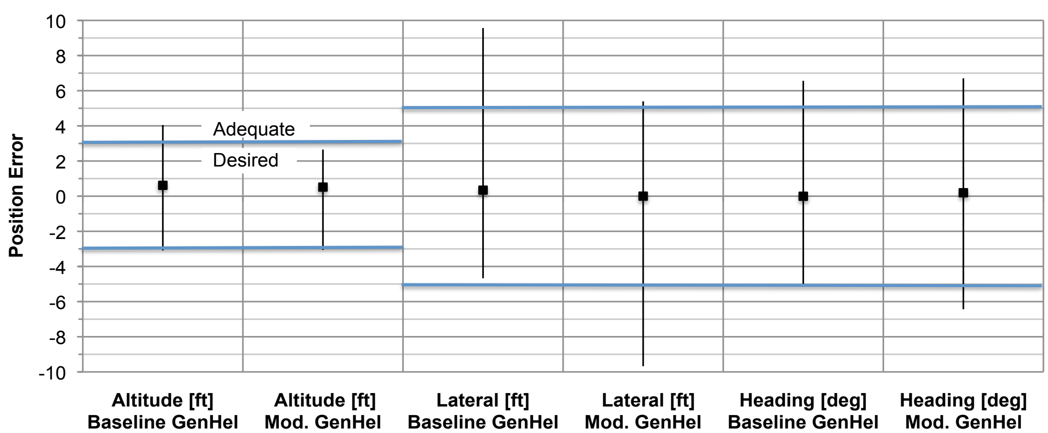


Figure 18. SimOpt sidestep position error.

The modified GenHel configuration was rated 16.1% better in the motion cues category, which can be attributed to the 0.045 sec. reduction in equivalent time delay (see Table 4). The vehicle response characteristics only showed a negligible 3% improvement (see Table 6).

Table 6. Sidestep subjective pilot ratings from questionnaire.

Rate the following on a scale from 1 = poor : 5 = excellent	Baseline GenHel	Modified GenHel	% Improvement
motion cues:	3.88	4.50	16.1%
visual cues:	3.75	4.38	16.7%
cyclic:	4.25	4.25	0.0%
collective:	4.75	4.75	0.0%
pedals:	4.50	4.75	5.6%
vehicle response characteristics:	4.12	4.25	3.0%
task:	4.38	4.25	-2.9%

3. Sidestep Pilot Comments

Overall, the pilots preferred the modified GenHel configuration. Pilot 1, who is a current UH-60 pilot, and Pilot 2, thought they could be more precise with the modified GenHel configuration. Pilot 1 also thought the baseline configuration motion had a slight lag. Pilot 4 thought both configurations had a tendency to bobble in roll. The following comments were chosen from the questionnaire because the described the pilots perceived differences in the configurations.

Baseline GenHel:

General comments:

Pilot 1 stated, "Notice that more aggressive with decel the harder the task. Could never get a good feel for aircraft response with rapid lateral control reversals. A little bit of loss of predictability. In the actual aircraft could be a little bit more aggressive with lateral control input or lateral reversal to be a little bit more precise."

Questionnaire responses:

Q1. Which axis (roll, pitch, heave) required the most compensation in the task?

All pilots thought the roll/lateral axis required the most compensation.

Q3. Was there any tendency for PIO in any axis in the task?

All pilots, except Pilot 4, thought there was no tendency for PIO in any axis. Pilot 4 felt there was a tendency in the roll axis followed by the yaw. Pilot 1 thought there was no tendency for a PIO but did make this comment, "No, just a more sluggish response than what I would expect but there wasn't a tendency to get into a PIO where I felt completely out of phase with the aircraft. Slightly more of a delay than what was expected. There may have been some more artificial delays that made the task require more precision on when to start the decel."

Q6. Did the motion cues feel appropriate for the task?

Pilot 2 and Pilot 3 thought the motion cues felt appropriate for the task. Pilot 1 and Pilot 4 thought motion system sound was objectionable. Pilot 1 stated, "Only time it felt a little odd was rapid lateral reversals, the cues may have lagged a little bit. The motion cues felt a little bit behind the aircraft when making rapid lateral cyclic inputs."

Q8. Did the basic vehicle response characteristics seem reasonable for this task?

All of the pilots except Pilot 1 thought the basic vehicle response felt reasonable for the task. Pilot 1, who is a current UH-60 pilot, thought the lateral axis was slightly slow when making lateral control reversals.

Modified GenHel:

General comments:

Pilot 1 and Pilot 2 thought the Modified configuration allowed them to be more precise.

Pilot 1 stated, "Borderline level 1 level 2. Increased ability to be precise. Increase in pilot compensation wasn't necessary or an increase in the workload but an increase in precision." Pilot 2 commented, "I felt that I could be a lot more precise in that configuration. Still required pilot compensation on when to decelerate and not to be too aggressive in the lateral axis. As long as I did that I was well within the time constraint. I was doing the task faster than the previous configuration. It felt like I had better heading control as well."

Questionnaire responses:

Q1. Which axis (roll, pitch, heave) required the most compensation in the task?

All pilots thought the roll/lateral axis required the most compensation.

Q3. Was there any tendency for PIO in any axis in the task?

All of the pilots except Pilot 4 thought there was no tendency for PIO. Pilot 4 thought the roll axis had a tendency for PIO if too aggressive. Pilot 1 stated," No, it felt that it was easier to achieve a higher level of precision. I felt I could be more precise and more predictable in this configuration."

Q6. Did the motion cues feel appropriate for the task?

All of the pilots thought the motion cues felt appropriate for the task. Pilot 1 stated, "This had the overall feel of being slightly better than the other configuration. I didn't feel like there was any lag in the motion, where I could kind of pick that up on the first configuration. There is an improvement over the first configuration."

Q8. Did the basic vehicle response characteristics seem reasonable for this task?

All of the pilots thought the vehicle response characteristics were reasonable for the task. Pilot 1 added, "They were reasonable. Both configurations seemed to have a heading drift of 2 to 3 degrees before I would have to come into the loop and stop it. I would expect less heading drift on the actual aircraft. The response of the aircraft (simulated) seemed more in tune and seemed to resemble more of how the actual aircraft would respond. It was hard to fly by being aggressive but I could a predictable response out of the aircraft with my inputs a lot easier in this configuration."

C. Hover Maneuver

1. HQRs

The precision hover is a less aggressive maneuver compared to the bob-up and sidestep maneuvers and was not performed in the 1989 and 1990 experiments. The average HQR for the modified GenHel configurations is slightly better than the standard GenHel configuration (see Fig. 19) by 0.38 of a point. All of the pilots except Pilot 3 rated the modified GenHel configuration the same or worse than the standard GenHel configuration. Pilot 3 rated the modified GenHel configuration two points better than the standard GenHel configuration. If Pilot 3's ratings were removed from the modified GenHel average then the two configurations would be rated virtually the same. The hover maneuver was the only task that required longitudinal position keeping as part of the HQR performance and this increased pilot workload as reflected in the HQRs.

2. Hover Performance Data

On average both configurations were in the desired performance region (see Fig. 20). The average time to decelerate and achieve to a stable hover was slightly better for the modified configuration with the maximum time being about a second faster than the baseline GenHel configuration.

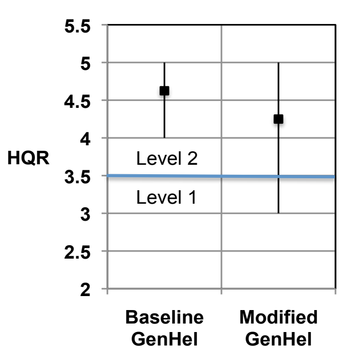


Figure 19. Hover maneuver HQRs.

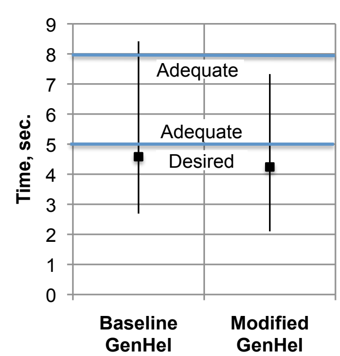


Figure 20. Hover deceleration time.

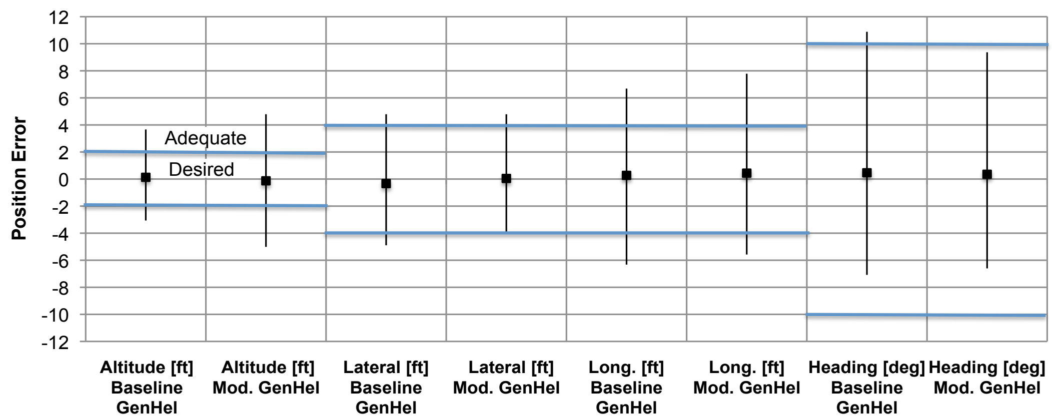


Figure 21. Hover position error.

The position error data between the two configurations were similar (see Fig. 21). The longitudinal position error had the largest excursions outside of the desired region. This can be attributed to the poor FOV in the simulator cab and weak longitudinal cues on the motion axis with the smallest displacement (see Table 1). The FOV is less than 180 degrees so the pilot cannot look perpendicular to his heading. The hover board, visible in the right window (see Fig. 11), was at a 60-degree angle, which was not ideal for a longitudinal cue. Also, the seam between the right and center window was distracting and could also block the cones on the ground depending on the vehicle heading. A power spectral density analysis was conducted on the longitudinal pilot stick inputs, comparing the workload of the hover task (longitudinally dependent task) to the sidestep task (longitudinally independent task). The analysis shows that the increased pilot workload caused by the longitudinal axis position keeping adversely affected the maximum excursions for the hover task (see Appendix C).

Even though the HQRs were better for the modified GenHel configuration, the subjective motion cues and vehicle response characteristics were slightly worse. The modified GenHel configuration resulted in an 8.6% decrease in the motion cues category over the baseline configuration while the vehicle response characteristics resulted in a 6.7% decrease with respect to the baseline configuration (see Table 7).

Table 7. Hover subjective pilot ratings from questionnaire.

Rate the following on a scale from 1 = poor : 5 = excellent	Baseline GenHel	Modified GenHel	% Improvement
motion cues:	4.38	4.00	-8.6%
visual cues:	3.62	3.88	6.9%
cyclic:	4.38	4.38	0.0%
collective:	4.62	4.50	-2.7%
pedals:	4.12	4.12	0.0%
vehicle response characteristics:	3.75	3.50	-6.7%
task:	4.12	4.25	3.0%

D. Hover Pilot Comments

There is no clear preference between the configurations based on the pilots' comments. The reduced FOV and weak longitudinal cueing increased the pilot workload. Pilot 1 and Pilot 4 thought the pitch/longitudinal axis did not feel reasonable for the modified GenHel configuration. Additionally, Pilot 1 thought the vehicle responsiveness in the longitudinal axis was sluggish for the standard GenHel configuration.

Baseline GenHel:

General comments:

All of the pilots felt that the field of view was inadequate for the task. The seam between the cockpit windows was blocking the hover target during the translation to the hover board.

Pilot 2 stated, “Work load was less, but the ability to get desired performance didn't seem like it was that much better.”

Questionnaire responses:
Q1. Which axis (roll, pitch, heave) required the most compensation in the task?
All pilots except Pilot 4 thought the pitch/longitudinal axis required the most compensation. Pilot 4 thought the roll/lateral axis followed by the pitch axis.
Q3. Was there any tendency for PIO in any axis in the task?
All of the pilots except Pilot 2 thought there was tendency to PIO in the pitch/longitudinal axis. Pilot 4 stated, “It looked like in the pitch axis that it was PIOing quite a bit. You couldn't be very aggressive with it either.” Pilot 1 stated, “Yes, longitudinal axis. I can't control long enough to get desired performance.”
Q5. Did the control of the vehicle longitudinal position pose any problems?
All of the pilots felt the longitudinal axis posed a problem to their performance and drove up their workload. Pilot 4 stated that the weak longitudinal cue was the cause of the problem.
Q6. Did the motion cues feel appropriate for the task?
All of the pilots thought the motions cues felt appropriate and Pilot 2 thought the motion cues felt better than the Modified GenHel configuration.
Q8. Did the basic vehicle response characteristics seem reasonable for this task?
All of the pilots except Pilot 1 thought the basic vehicle response characteristics felt reasonable for the task. Pilot 1 thought the pitch response was too slow.

Modified GenHel:
General comments:
All of the pilots felt that the field of view was inadequate for the task. The seam between the cockpit windows was blocking the hover target during the translation to the hover board.
Pilot 1 stated, “Fairly consistent, slow on the stable call and my heading was drifting just slightly out of 5 degrees, but the workload is fairly consistent.”

Questionnaire responses:
Q1. Which axis (roll, pitch, heave) required the most compensation in the task?
All the pilots thought the pitch/longitudinal axis required the most compensation. Pilot 2 and Pilot 4 thought the next hardest axis to control was the yaw.
Q3. Was there any tendency for PIO in any axis in the task?
All of the pilots thought there was tendency to PIO in the pitch/longitudinal axis. Pilot 1, Pilot 2 and Pilot 3 thought there was only a small tendency for PIO but was easily controllable.
Q5. Did the control of the vehicle longitudinal position pose any problems?
All of the pilots felt the longitudinal axis posed a problem to their performance and drove up their workload. Pilot 4 stated that the weak longitudinal cue was the cause of the problem.
Q6. Did the motion cues feel appropriate for the task?
Pilots 2, Pilot 3 and Pilot 4 thought the motion cues felt appropriate for the task. Pilot 1 commented, “The only one that felt kind of strange was in the longitudinal axis in which the pitch rates felt more aggressive than what I would have anticipated. The other axis felt fine, the pitch axis, felt a little too aggressive for the motion.
Q8. Did the basic vehicle response characteristics seem reasonable for this task?
Pilot 2 and Pilot 3 felt the basic vehicle response characteristics felt reasonable for the task. Pilot 1 and Pilot 4 thought the pitch axis did not feel reasonable but with conflicting concerns. Pilot 1 commented, “I felt I had to make fairly large inputs on the longitudinal axis to get a reasonable response. The initial response would end up being an overcorrection and I would have to fight that and stay in the loop with a very tight control on the control axis for awhile and it felt a little bit different than what I expected.” Pilot 2 stated, “For the most part, the pitch movements in the end when you put in the aggressive pitch movement seemed to be a little extreme.”

VI. Discussion

This experiment demonstrates the improvements in simulation results when the motion and visual pilot cueing system response is optimized to be similar to flight. The modified GenHel model was clearly the better performing configuration, based on HQRs and pilot comments for the bob-up and sidestep tasks. It is unclear which configuration was better in the hover task. The inadequate FOV and weak longitudinal visual cues increased pilot workload and made the hover task challenging to the pilot and more difficult to discern which configuration was better. In future experiments that plan to use a similar hover task, the FOV should be at least 180 deg. or the task should be modified to provide adequate longitudinal cues.

Directly comparing simulation and actual flight HQRs can be problematic unless the flight tests are performed concurrently with simulations as discovered by Atencio[8] in 1989 and 1990. The SimOpt HQRs compare favorably to the 1989 and 1990 HQRs and would probably have been rated better if run concurrently with flight tests.

Removing excess delay from an existing aircraft math model can be challenging, as was the case for the GenHel model. The rotor looping technique reduced the equivalent time delays unevenly in all axes. Since each motion axis carries a unique time delay, the visual transport delay cannot match all axes and was therefore left unchanged. It may have been beneficial to try and sync the visual and motion time delay in the dominant axis of the task. Chung and Schroeder recommends that the time delay between the visual and roll motion and roll and lateral motion be less than 40ms with the motion not leading the visuals when performing a sidestep task.[7]

When developing a new math model, with the knowledge that it will be used on a motion flight simulator, it would be beneficial to implement easily modifiable aircraft delays in all axes. This would facilitate the optimization of the simulation system to compensate for the inherent motion system delays which would result in a higher fidelity simulation.

VII. Conclusion

A handling qualities experiment was performed on the Vertical Motion Simulator using two configurations of the GenHel math model configured for a UH-60A Black Hawk helicopter. The baseline configuration was the standard GenHel model used in two previous experiments in 1989 and 1990. The second configuration of the GenHel model was modified to remove excess delay to help compensate for the time delay inherent in the motion system. Bob-up, sidestep and hover tasks were conducted using both configurations. The bob-up and sidestep tasks were performed in the 1989 and 1990 simulation experiments, and an actual flight test was performed concurrently with the 1989 simulation. The motion system was tuned specifically for each task in the paper's experiment, but only one set of motion gains and washouts were used for all tasks in the 1989 and 1990 experiments.

The 1990 simulation was conducted six months after the flight test and was significantly worse in the average HQRs as compared to the 1989 simulation and flight test. The principal investigator for the 1989 and 1990 experiment states, "It appears as if the flight experience was enhanced with passing time and unfavorable flight characteristics were forgotten"[8] as a possible reason for the worse HQRs. The SimOpt experiment did not have the benefit of a concurrent flight test but the HQRs compare favorably to the 1989 simulation and flight test.

A summary of the results is as follows:

- The frequency responses of the VMS motion and visual systems were measured.
- Eliminating the roll axis equivalent time delay of the motion system, by reducing the model delay in the roll axis by 0.045 sec. in the modified GenHel configuration improved the HQR rating in a sidestep task by more than half a point when compared to the baseline GenHel configuration.
- The HQRs of the sidestep task for the modified GenHel configuration were comparable to the 1989 simulation experiment and flight test.
- The HQRs of the bob-up task for both the modified and baseline GenHel configurations compared favorably to the 1989 simulation experiment and flight test.
- The results of the hover tasks were inconclusive between the baseline and modified GenHel configurations due to problems with field-of-view and simulation task setup.

Appendix A
Motion Gains and Washouts

Axis	1989 - 1990 Experiments		SimOpt 2012					
	All Tasks		**Bob Up**		**Sidestep**		**Precision Hover**	
	Gain	Washout	Gain	Washout	Gain	Washout	Gain	Washout
Pitch	0.5	0.7	0.737	1.08	0.991	0.417	0.974	0.31
Roll	0.3	0.7	0.996	0.296	0.642	0.358	0.75	0.289
Yaw	0.5	0.5	0.993	0.1	1	0.1	0.998	0.1
Longitudinal	0.4	1.5	0.976	1.37	0.993	1.52	0.915	2
Lateral	0.8	0.6	0.927	0.332	0.74	0.264	0.697	0.22
Vertical	0.8	0.3	0.648	0.119	0.933	0.337	1	0.1

Appendix B

SimOpt Pilot Questionnaire

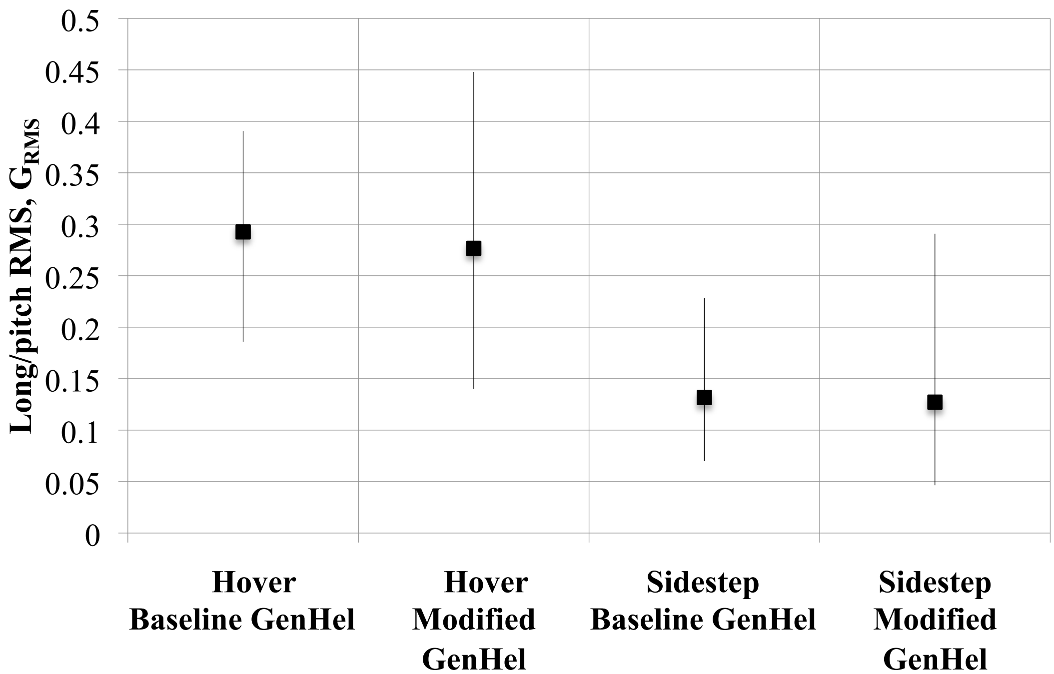
Pilot: Date: Time:
Run No.: Task:
HQR:

Questions:

1. Which axis (roll, pitch, heave) required the most compensation in the task?
2. Did you have cyclic force trim on or off during the task?
3. Was there any tendency for PIO in any axis in the task?
4. What was the limiting factor(s) in the aggressiveness with which you were able to perform the task?
5. Did the control of the vehicle longitudinal position pose any problems?
6. Did the motion cues feel appropriate for the task?
7. Were the controller characteristics reasonable in this task, e.g., force-feel characteristics?
8. Did the basic vehicle response characteristics seem reasonable for this task?
9. Can you describe your control technique for this task?
10. Rate the following on a scale from 1 = poor to 5 = excellent
    motion cues:
    visual cues:
    controllers: cyclic: collective: pedals:
    vehicle response characteristics:
    task:

Appendix C

Average Longitudinal Stick RMS for Sidestep and Precision Hover tasks



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