Evaluation of Motion Tuning Methods on the Vertical Motion Simulator

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ABSTRACT

An experiment at NASA Ames' Vertical Motion Simulator (VMS) evaluated three motion tuning methods using the GenHel UH-60A Black Hawk math model. For each of the three motion tuning methods, adjustments were made to the gain and washout frequency of the high pass filter designed to attenuate the math model accelerations before commanding the simulation motion platform. Two of the tuning methods were established techniques, using a motion-tuning expert to modify the gain and frequency values to satisfy a project pilot while flying the task. The third method is a quantitative approach that minimized the difference between the aircraft math model commanded acceleration and the acceleration outputted by the motion filter. Four test pilots performed the Aeronautical Design Standard (ADS)-33 Hover, Lateral Reposition, and Vertical Maneuvers for each of the three motion-tuning methods, providing Handling Quality Ratings (HQRs) after each. Comparing the simulation results of the three methods, the subjective motion tuning method was found to deliver better HQRs as compared to the quantitative method. The larger washout frequencies used in the quantitative motion-tuning method were found objectionable based on pilot comments.

INTRODUCTION

What is the best way to adjust the motion gains of a ground based simulator? The limited displacement or motion envelope of ground based motion flight simulators require the attenuation of the acceleration commands generated by the aircraft math model. The acceleration attenuation is typically achieved using a high pass filter. The filter parameters, gain and washout, need to be chosen to enable realistic motion cues so the pilot will fly the simulator in the same manner as the actual aircraft. A subjective motion tuning method where a motion-tuning expert iteratively adjusts the motion filter parameters until the motion feels representative of the aircraft to an experienced pilot tends to be the most common method. An effective objective motion tuning method is desirable but has yet to be developed for complicated flying tasks.

There have been many efforts to improve upon the subjective method. Sinacori[1] hypothesized, and later Schroeder[2] extended, criteria for defining the quality of simulator motion based on the gain and phase of the motion software filters. The criteria were defined by motion fidelity regions on a gain verses phase error plot for the motion filters. Schroeder adjusted the regions on the gain verses phase error plot and labeled them as "Like Flight", "Different from Flight", and "Objectively Different from Flight" (see Figure 1). These regions can be used by a motion-tuning expert to assess the fidelity of the motion but may not provide optimal values for the motion filters. The optimal set of gains would enable the pilot to fly the simulation as he would the aircraft.

There have been attempts to develop quantitative motion-tuning methods using pilot models. Pilot model based motion-tuning is attractive to operators of hexapod ground motion simulators because it can filter out aircraft motion that is not an important pilot control cue and thus reduce the required motion envelope of the simulator. In 1979 Hosman[3] compared vestibular differences of a rudimentary pilot model in a simulator and aircraft to optimize the motion filter settings for a simulation consisting of roll, pitch, and heave motion cues. Sivan[4] performed a similar experiment as Hosman, taking the mean square difference of the physiological vestibular outputs to optimize a two degree-of-freedom simulator. More recently, Delft University of Technology completed a five-year project to assess flight simulator fidelity through a pilot model based, cybernetic approach[5]. The pilot model based motion tuning has shown promise in simple control tasks however further development is necessary to handle a broader range of flight scenarios.

The first SimOpt experiment investigated techniques in adjusting the math model delay to provide accurate pilot input to motion cue representation[6]. SimOpt2 continues investigating motion fidelity through different motion-tuning techniques and was conducted on the Vertical Motion Simulator (VMS) located at NASA Ames Research Center. The SimOpt2 experiment tested three motion-tuning methods using Aeronautical Design Standard-33[7] (ADS-33) Hover, Lateral Reposition, and Vertical Maneuvers while flying the GenHel[8] UH-60A Black Hawk helicopter math model. Two of the motion tuning methods were subjective and used the "feels representative" approach and the third motion-tuning method used a simple quantitative approach that minimized the error between the aircraft math model

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and the motion filter accelerations to determine the motion filter parameters. Handling Quality Ratings using the Cooper-Harper rating scale[9], in addition to quantitative data, were collected. This paper describes the SimOpt2 experiment, the motion tuning methods, and compares the HQR results and performance data.

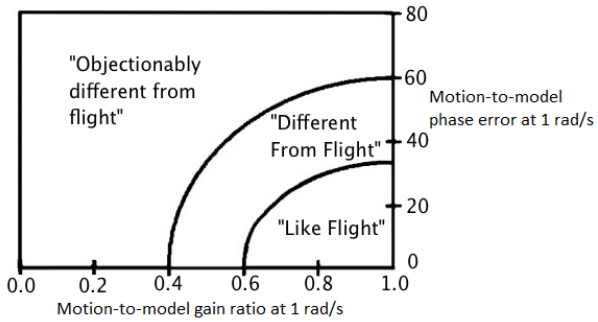

Figure 1. Modified Sinacori Criteria

VERTICAL MOTION SIMULATOR

Description

The Vertical Motion Simulator, with its large motion envelope, provides the realistic cueing environment necessary for performing handling qualities studies. The VMS motion system, shown in Figure 2, is an uncoupled, six-degree-of-freedom motion simulator that moves within the confines of a hollow ten-story building. Schroeder, et al. concluded that larger simulator motion envelopes provide closer HQRs to flight than small motion envelopes for the same tasks[10]. Additionally, pilots gave large motion higher confidence factor ratings and achieved lower touchdown velocities compared to small motion simulators.

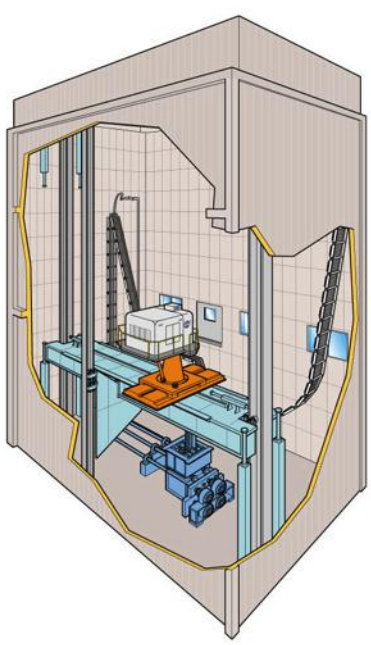

Figure 2. Vertical Motion Simulator.

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 attainable levels under controlled conditions; and operational limits, that represent attainable levels for normal piloted operations.

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. 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.

Motion Description

The cockpit motion cueing algorithms use high-pass (washout) filters and a rotational/translational cross-feed arrangement shown schematically in Figure 3. The pilot station accelerations, calculated from the aircraft model specific forces, are second-order high-pass filtered and attenuated, before commanding the motion drive system. The high-pass filter is shown in Equation 1, where K is the motion gain, ωn is the washout frequency, and ζ is the damping ratio that has a constant value of 0.707[11].

Equation 1.

$$\frac{\textit{Motion Drive System}}{\textit{Pilot Station Acceleration}} = \frac{K \cdot S^2}{S^2 + 2\zeta S + \cdot \omega_n{}^2}$$

Turn coordination, which adds translational acceleration to produce a coordinated turn, and compensation for the rotational center of the simulator account for the cross-coupled motion commands. An algorithm with a low-pass filter tilts the simulator to provide steady-state longitudinal and lateral acceleration cueing at low frequency.

Table 1. VMS motion system performance limits

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 rad	±0.24 rad	±0.9 rad/sec	±0.7 rad/sec	±4 rad/sec^2	±2 rad/sec^2
Pitch	±0.31 rad	±0.24 rad	±0.9 rad/sec	±0.7 rad/sec	±4 rad/sec^2	±2 rad/sec^2
Yaw	±0.42 rad	±0.34 rad	±0.9 rad/sec	±0.8 rad/sec	±4 rad/sec^2	±2 rad/sec^2

OBJECTIVE AND APPROACH

The objective of the SimOpt2 experiment was to develop and validate an objective motion-tuning method by comparing three different motion-tuning methods in the VMS through pilot-vehicle performance. Four test pilots performed the ADS-33 Hover, Lateral Reposition and Vertical maneuvers using the GenHel UH-60A Black Hawk helicopter math model.

EXPERIMENTAL SETUP

Motion Tuning Methods

Three motion-tuning methods were investigated in SimOpt2 to determine their relative effectiveness. Two of the motion –tuning methods are established subjective approaches that have been used at the VMS while the third is an objective approach.

Subjective Method 1

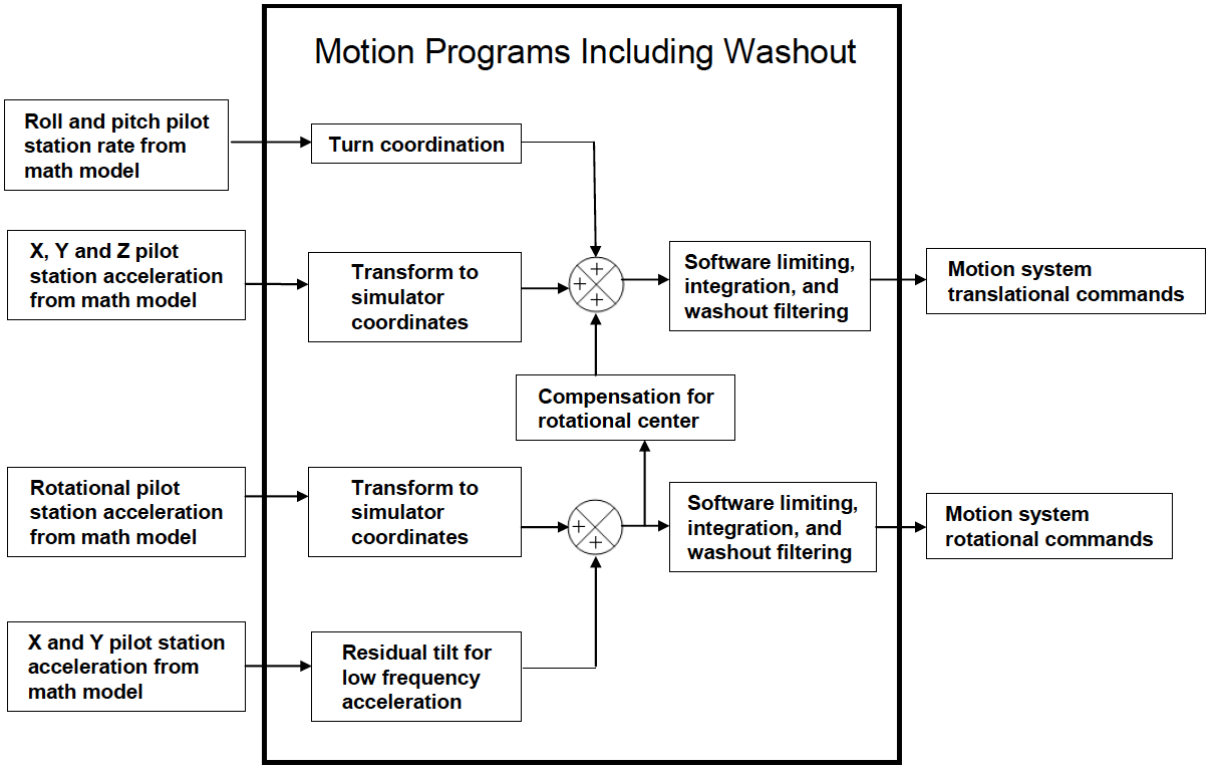

Figure 3. VMS motion algorithm schematic

The VMS motion system is typically tuned for each task by selecting the motion cueing filter gain and washout frequency in each axis. The motion tuning is a subjective process where the project pilot flies the maneuver and evaluates the motion cuing. The motion-tuning expert then adjusts the filter gains and washouts to satisfy the pilot while staying within the operational limits of the VMS.

Subjective Method 2

The motion gains selected for Subjective 2 were the smallest in each axis as determined by the Subjective 1 method. Conversely, the washout frequencies selected were the largest in each axis as determined using the Subjective 1 tuning method. Using the lowest gain and largest washout in each axis guarantees that this motion-tuning method will stay within the operational limit of the VMS for all tasks. This method was chosen because most hexapod training simulators are not tuned for an individual task.

Quantitative Method

Since the VMS uses constant motion filter settings and the motion envelope is much larger than a standard hexapod motion base it, was hypothesized that a simple quantitative motion tuning method could be effective. The Quantitative method used in this experiment requires the project pilot to fly the prescribed task without motion while the aircraft math model acceleration data is recorded. The recorded aircraft accelerations are input into a VMS motion filter model and the average root mean square (RMS) error between the aircraft math model and motion filter output over the entire run is minimized by adjusting the gain and washouts. In addition, the software limits within the motion model were changed to provide a buffer for pilots with different flight techniques. The acceleration gains and washouts pairs for each axis with the lowest average RMS error that remained within the modified VMS operational limits were selected. The project pilot then re-flies the task with motion, configured with new motion parameters, and the process is repeated to refine the acceleration gain and washout pair. The method calculated the motion filter settings one axis at a time starting with the critical axis, while the remaining five axes maintained constant motion filter settings.

Baseline UH-60A GenHel Math Model

The GenHel[7] 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.

Task Description

Hover Maneuver

The first task flown was the ADS-33 Hover maneuver as seen in Figure 4, where the maneuver starts from a stabilized hover at 20 ft. The pilot then translates at a 45-degree angle toward a specific hover position, targeting a ground speed between 6 and 10 kts. The pilot signals the start of deceleration and has 5 seconds to signal the capture of the hover position. The pilot must then hold the hover position for 30 seconds.

Figure 4. Cockpit view of Hover maneuver and Vertical maneuver lower board

The HQR performance criteria for the Hover maneuver were defined as:

Desired Performance:
1. Attain stabilized hover within 5 sec.
2. Maintain altitude excursions within ± 2 ft from hover board.
3. Maintain heading excursions within ± 5° of desired heading.
4. Maintain lateral and longitudinal excursions within ± 3 ft.
5. Maintain hover for 30 sec

Adequate Performance:
1. Attain stabilized hover within 8 sec.
2. Maintain altitude excursions within ± 4 ft from hover board.
3. Maintain heading excursions within ± 10° of desired heading.
4. Maintain lateral and longitudinal excursions within ± 6 ft.
5. Maintain hover for 30 sec.

Lateral Reposition Maneuver

The next task flown was the ADS-33 Lateral Reposition maneuver as seen in Figures 5 and 6 where the maneuver starts from a stabilized hover at 35 ft. The pilot signals the start of the task and translates 400 ft to the right within 18

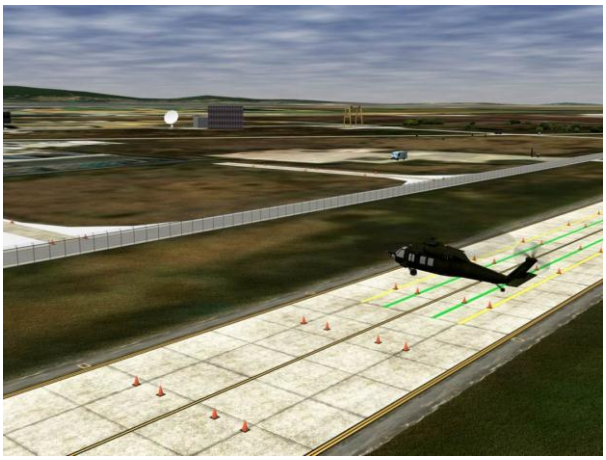

Figure 5. Gods eye view of Lateral Reposition maneuver

seconds. The pilot calls stable at the right hover position and maintains a stabilized hover for 5 seconds.

The HQR performance criteria for the Lateral Reposition maneuver were defined as:

Desired Performance:
1. Complete translation and stabilization within 18 sec. and with no objectionable oscillations.
2. Altitude excursions within ±10 ft from initial altitude.
3. Heading excursions within ± 10° of desired heading throughout maneuver.
4. Lateral and longitudinal excursions with 10 ft of the hover positions after stabilization.

Adequate Performance:
1. Maintain desired performance taking more than 22 sec to complete transition and stabilize.
2. Altitude excursions within ±15 ft from initial altitude.
3. Heading excursions within ± 15° of desired heading throughout maneuver.
4. Lateral and longitudinal excursions with 20 ft of the hover positions after stabilization.

Vertical Maneuver

The last task flown was ADS-33 Vertical maneuver as seen in Figure 4, where the maneuver starts from a stabilized hover at the lower hover board. The pilot signals the start of the task and rapidly ascends 25 feet to the upper hover board. The pilot holds that position for two seconds then descends to the lower hover board. At the lower hover board the pilot signals when stable and maintains that position for 5 seconds. The HQR performance criteria for the Vertical maneuver were defined as:

Desired Performance:
1. Complete translation and stabilization within 13 sec. and with no objectionable oscillations.
2. Altitude excursions within ±3 ft from hover board center after stabilization.
3. Heading excursions within ± 5° of desired heading throughout maneuver.
4. Lateral and longitudinal excursions with 3 ft of the hover board width after stabilization.

Adequate Performance:
1. Maintain desired performance taking more than 18 sec to complete transition and stabilize.
2. Altitude excursions within ±6 ft from hover board center after stabilization.
3. Heading excursions within ± 10° of desired heading throughout maneuver.
4. Lateral and longitudinal excursions with 6 ft of the hover board width after stabilization.

Experimental Procedures

Four test pilots ranging from 2000 to 4000 hours in rotorcraft flight experience flew three motion-tuning methods for three ADS-33 tasks (see Table 2). The four pilots were asked to familiarize themselves with each

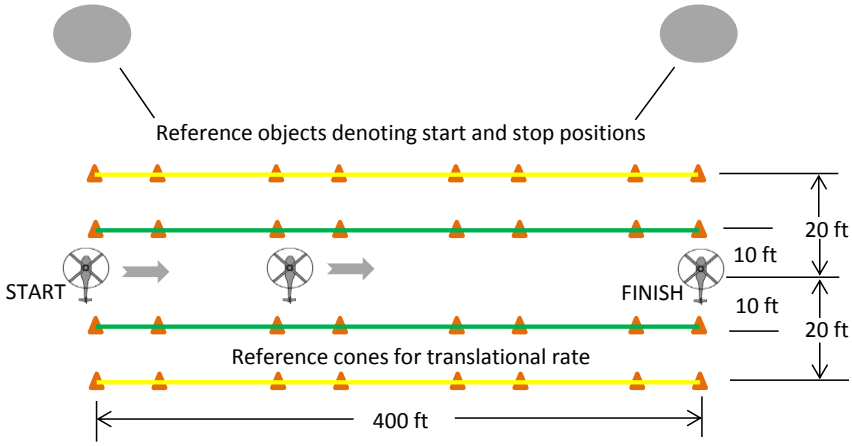

Figure 6. Course for Lateral Reposition maneuver

Table 2. Test Matrix with respect to the Critical Axis

Task	Config.	Acc. Gain	Washout Freq
Hover (Roll Axis)	Quantitative	1.0	.55
	Subjective 1	.70	.30
	Subjective 2	.40	.55
Lateral Reposition (Roll Axis)	Quantitative	.85	.70
	Subjective 1	.40	.55
	Subjective 2	.40	.55
Vertical (Vert Axis)	Quantitative	1.00	.05
	Subjective 1	1.00	.10
	Subjective 2	1.00	.10

maneuver for each motion-tuning method. Once they were sufficiently familiar with the task they were asked to complete at least two practice runs with each motion-tuning method before flying three evaluation runs and providing an HQR. Performance data were collected on all evaluation runs and HQRs were given at the end of the evaluation runs. In addition to the performance and HQR data, pilots responded to a questionnaire (see Appendix A). All motion-tuning method parameters were concealed from the pilots, and the order of the tasks and corresponding methods were chosen randomly for each pilot. The entire test matrix can be seen in Appendix B.

RESULTS

The HQRs and performance data are included in this section. Each pilot HQR is illustrated as a black box while an inverted red triangle displays the average rating for each category (see Figures 7-9).

After providing HQRs for each tuning method, the pilots were asked to complete a questionnaire (Appendix A). The questionnaire inquired the pilots about task performance, pilot demands, and the critical sub-phase for each task. Acceleration plots for each task and motion-tuning method, comparing the math model to motion filter outputs can be found in Appendix C. All acceleration plots in Appendix C were produced from a proficient run, declared by the pilot, and all plots were from a single test pilot.

Hover Maneuver

HQRs are plotted and compared for each motion tuning method for the hover maneuver seen in Figure 7. The quantitative motion tuning method was rated as Level 2 handling qualities while the average HQR values differed by over two ratings. The Subjective 1 and 2 motion-tuning methods both achieved a Level 1 HQR, differing by one half of a rating. Only a single test pilot rated one of the subjective methods as a Level 2 HQR.

One possible explanation why the Quantitative method received Level 2 handling qualities, as compared to the Level 1 ratings given to the subjective methods could be attributed to the roll/lateral, and the pitch/longitudinal motion parameters. Since the roll/lateral, and pitch/longitudinal axes are cross-coupled to ensure coordinated flight, a compromise must be found between the two axes. The Quantitative method calculated a large rotational acceleration gain, which requires most of the translational travel to be used for turn coordination (see Figure 3) at the expense of pure lateral and longitudinal axis acceleration.

One test pilot with over 2000 hours in rotorcraft flight experience (1800 of those hours in the Black Hawk) commented, "I'm limited in aggressiveness in order to meet performance criteria, as I increase in aggressiveness the visual cues do not match the motion cues." Another pilot commented, "It's difficult to meet the adequate performance criteria, the motion tends to get out of sync with the visuals and seems to build up over time."

As a result of increasing the rotational acceleration gain to 1.0 the washout value was also increased to stay within the VMS operational limits. By increasing the washout value, the phase error increases between the math model acceleration and the motion filter output. In addition, the larger washout frequency causes the motion system to be more aggressive in returning to the center position to accept new motion commands, which can result in a false motion cue. To compensate for the false motion cue, the pilots reduced their aggressiveness to keep synchronization between the motion and visual cues.

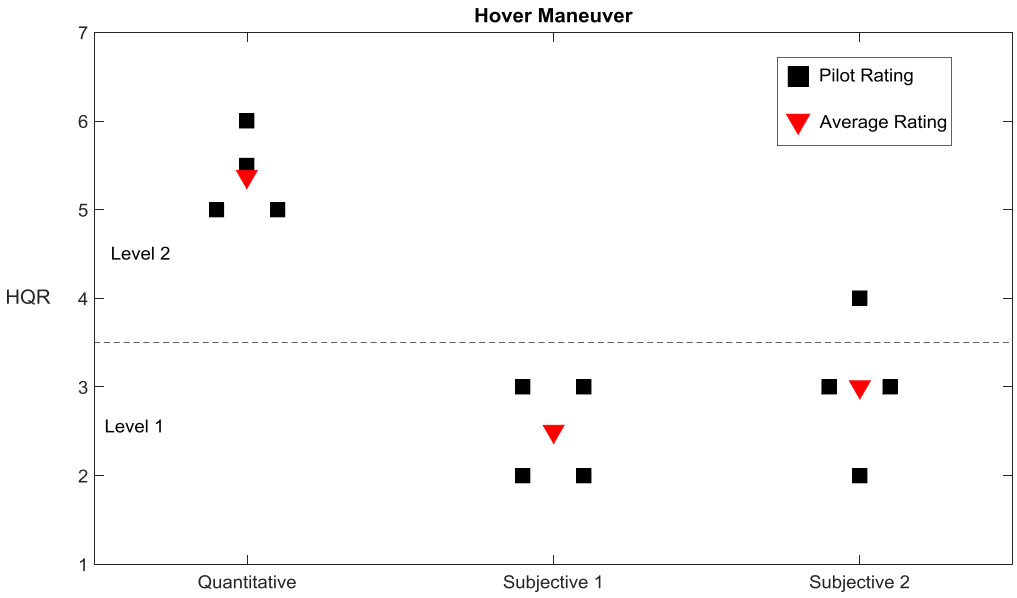

Figure 7. HQR for all three motion-tuning methods for the Hover Maneuver

Figure 8 shows the hover target maintenance from the same pilot for the two extreme methods based on the HQR results, the Subjective 1 and Quantitative methods. The magenta and black dotted lines represent a proficient run for each method with the performance representative of all the pilots. The green box defines the desired performance criteria and the yellow box defines the adequate performance criteria. The lack of aggressiveness led to poorer lateral and longitudinal position maintenance as shown by the black dotted line, the Quantitative method, when compared to the magenta line, the Subjective 1 method.

Lateral Reposition Maneuver

The HQRs are plotted and compared for each motion tuning method for the Lateral Reposition maneuver in Figure 9. The Quantitative and Subjective method 2 both resulted in Level 2 handling qualities while the average HQR values differ by less than one half. Only the Subjective 1 method resulted in

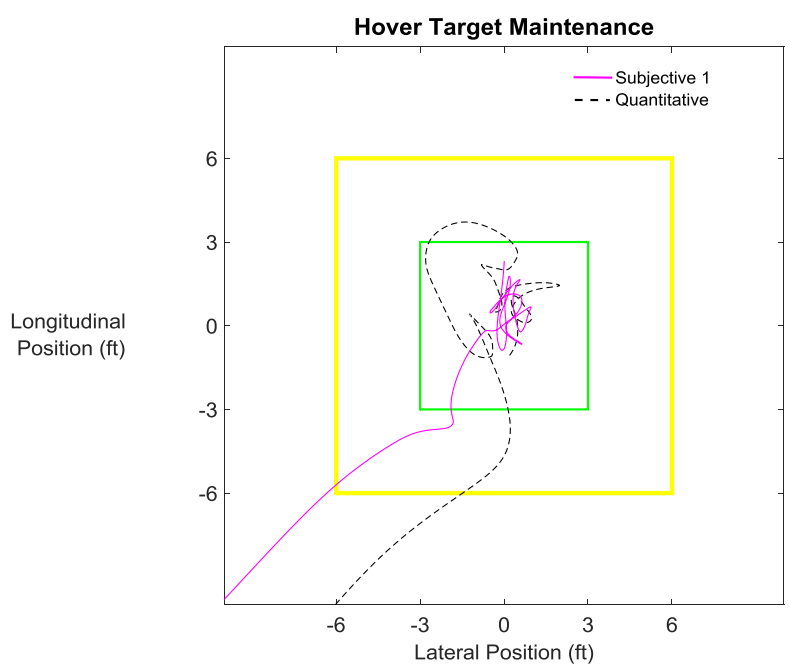

Figure 8. Hover maneuver vehicle track for the Subjective 1 and Quantitative methods

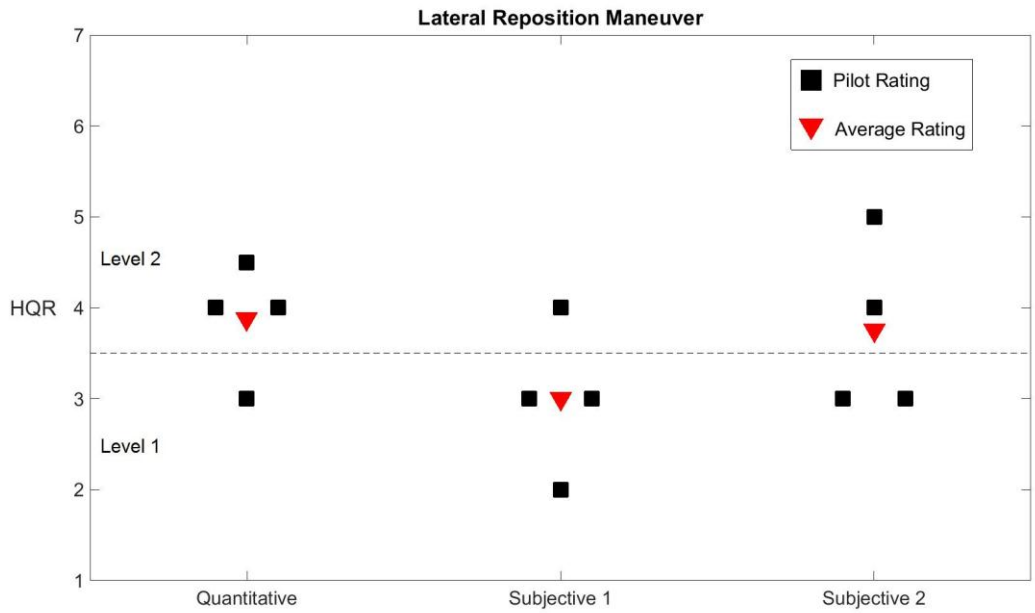

Figure 9. HQR for all three motion-tuning methods for the Lateral Reposition Maneuver

a Level 1 handling qualities with an average HQR of 3.

As in the Hover maneuver, the Quantitative method calculated large roll and pitch acceleration gains, which requires most of the translational travel to be used in turn coordination (see Fig. 3). The large pitch and roll gains limit the pure lateral and longitudinal axis acceleration.

Again, the pilots commented on how a reduction of technique aggressiveness, amplitude and rate of the pilot controls, was necessary to ensure the motion and visual cues remained synchronized. One pilot commented, "Not quite as aggressive as with the actual helicopter but could still achieve desired performance criteria."

Figure 10 shows the lateral and longitudinal vehicle position for the Lateral Reposition task from the same pilot for the two extreme methods based on the HQR results, the Subjective 1 and Quantitative methods. The magenta and black dotted lines represent a proficient run for each method with the performance representative of all the pilots. The green box defines the desired performance criteria and the

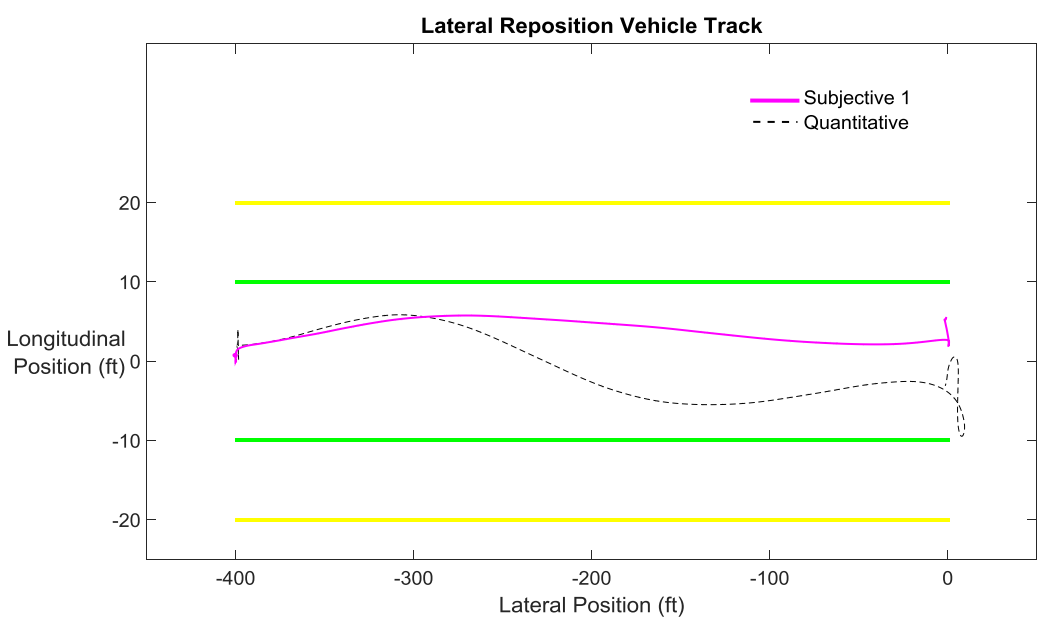

Figure 10. Lateral Reposition vehicle track for the Subjective 1 and Quantitative methods

yellow box defines the adequate performance criteria. Due to the increase in the roll washout value, in the Quantitative condition, pilots had to reduce their technique aggressiveness when compared to the Subjective method 1. The longitudinal and lateral position maintenance tended to suffer but performance remained within the desired criteria limits.

Vertical Maneuver

The HQRs are plotted for each motion tuning method for the vertical maneuver as seen in Figure 11. All simulated motion-tuning methods were completed with four test pilots for the vertical maneuver task.

The VMS can be tuned to operate with a vertical motion gain of one and a washout frequency near zero, which is equivalent to "one-to-one" motion, when the selected task is performed within the motion system operational limits. Although the motion filter parameters for each method were nearly identical in the vertical axis, resulting in near one-to-one motion characteristics, a clear distinction between the Quantitative and Subjective 1 tuning method can be seen.

All four pilots rated the Quantitative method with an HQR of four, which are Level 2 handling qualities. The average HQR for the Subjective method 2 straddled the Level 1 and Level 2 boundary with an average rating of 3.5 while the Subjective method 1 achieved Level 1 handling qualities with an average of three.

It was interesting to note that the Quantitative HQRs were all rated four, even though the vertical motion settings were near identical to the other two methods. After the experiment, it was discovered that from bumping into the vertical position limits during the tasks the pilots were receiving false vertical motion cues. The slight reduction in washout value, which was tuned to the low gain project pilot, resulted in every experiment pilot encountering vertical axis operational limits. Due to these objectionable false cues, all pilots gave the quantitative method higher HQRs than the nearly identical subjective tuning methods.

DISCUSSION AND FUTURE WORK

The Subjective 1 motion tuning method consistently received better HQRs on average than the other methods but is not necessarily the only optimal way to tune a motion system. The only reliable way to demonstrate that one motion tuning method is superior to another is to compare the simulation performance to flight, preferably with the same pilots in the same time frame.

Based on pilot comments the quantitative approach used in this experiment still needs improvement. Currently, the Quantitative method calculates gains and washouts one axis at a time. For this experiment the roll and pitch axis were evaluated before the lateral and longitudinal axes, which seemed appropriate for rotorcraft. If the order had been reversed then the motion filter parameters would have been significantly different. Future work will look at calculating the motion filter gains and washouts simultaneously. In addition, based on the specific task and the comments of the pilots, it may be necessary to invoke a washout threshold to

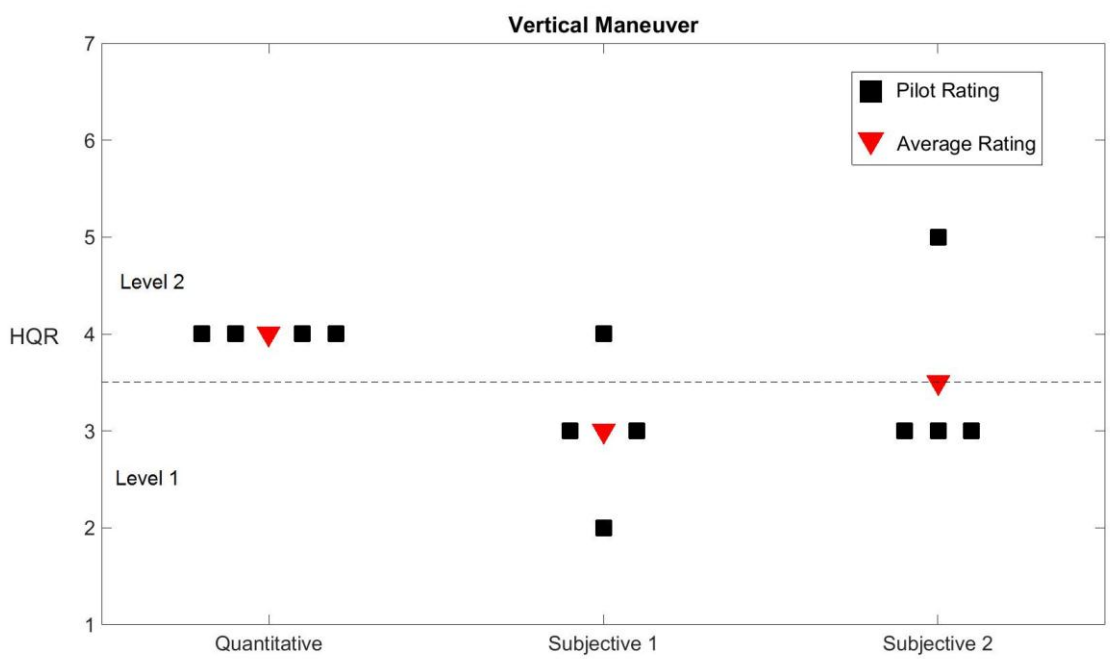

Figure 11. HQR for all three motion-tuning methods for the Vertical Maneuver

minimize pilot technique adaptation from the aircraft to the simulator.

CONCLUSIONS

An experiment at the NASA Ames Vertical Motion Simulator (VMS) evaluated three motion tuning methods using the GenHel UH-60A Black Hawk math model. Two of the motion-tuning methods were subjective and relied on pilot feedback to determine the motion filter parameters. The third motion-tuning method used a simple quantitative approach that minimized the error between the aircraft math model and the motion filter accelerations to determine the motion filter parameters.

Four test pilots evaluated the ADS-33 Hover, Lateral Reposition, and Vertical Maneuvers using the three different motion tuning methods. The Cooper Harper Handling Qualities Rating (HQR) was collected along with performance data. The subjective motion-tuning methods consistently received better HQRs with respect to the Quantitative method for the ADS-33 Hover and Lateral Reposition maneuvers. In addition, pilots commented that they reduced their aggressiveness with the quantitative tuned motion to keep the visuals and motion synchronized due to the larger washout frequencies.

On the Vertical Maneuver, The subjective motion-tuning methods received better HQRs with respect to the Quantitative method even though the motion filter parameters in the vertical axis were nearly identical. This discrepancy was attributed to the lower washout frequency in the quantitative method. The lower washout frequency allowed the pilots to reach the VMS vertical operational limits, which caused false motion cues.

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APPENDIX A

PILOT QUESTIONNAIRE

Task Performance

1. Describe ability to meet DESIRED / ADEQUATE performance standards.

2. Describe aggressiveness / precision with which task is performed.

3. If trying for DESIRED performance resulted in unacceptable oscillations, did decreasing your goal to ADEQUATE performance alleviate the problem?

Demands on the Pilot

4. Describe overall control strategy in performing the task (cues used, scan, etc.).

5. Describe any control compensation you had to make to account for deficiencies in the aircraft.

6. Describe any modifications you had to make to what you would consider "normal" control technique in order to make the aircraft behave the way you wanted.

MISC.

7. Please comment on anything else that may have influenced you.

Assign HANDLING QUALITIES RATING for overall task.

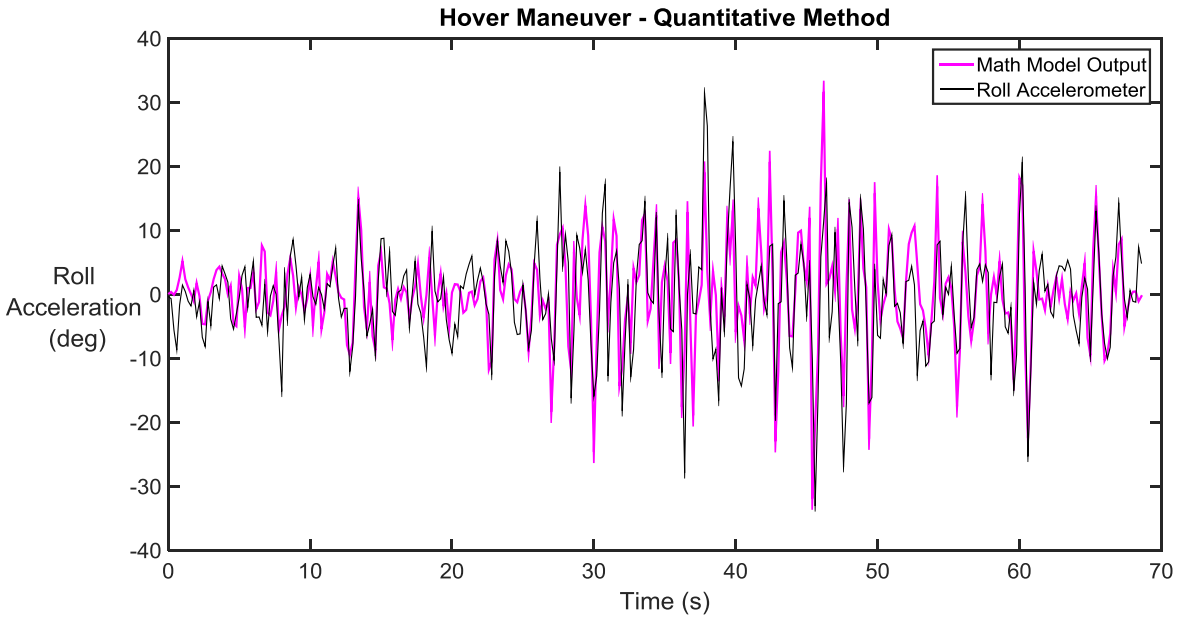
8. Using the Cooper-Harper rating scale, please highlight your decision-making process and adjectives that are best suited in the context of the task. If assigned HQR is Level 2, briefly summarize any deficiencies that make this configuration unsuitable for normal accomplishment of this task, i.e., justify why the procuring activity should reject this configuration as a means to accomplish this task.

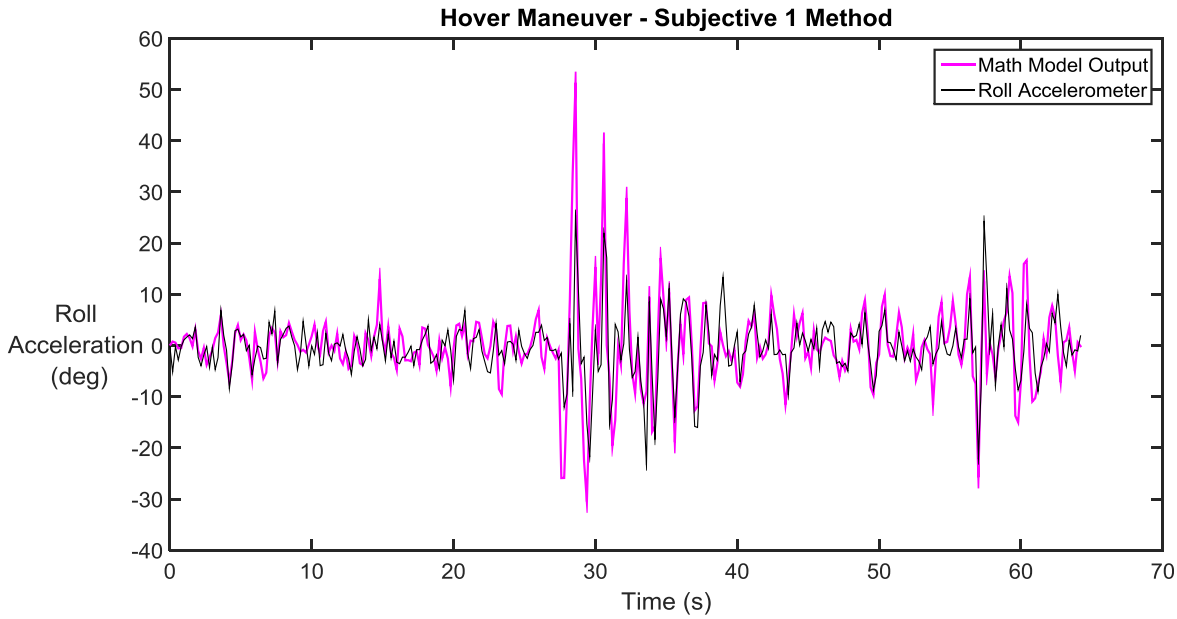
9. What was the critical sub-phase of the task (e.g., entry, steady-state, exit) or major determining factor in the overall Handling Quality Rating (HQR).

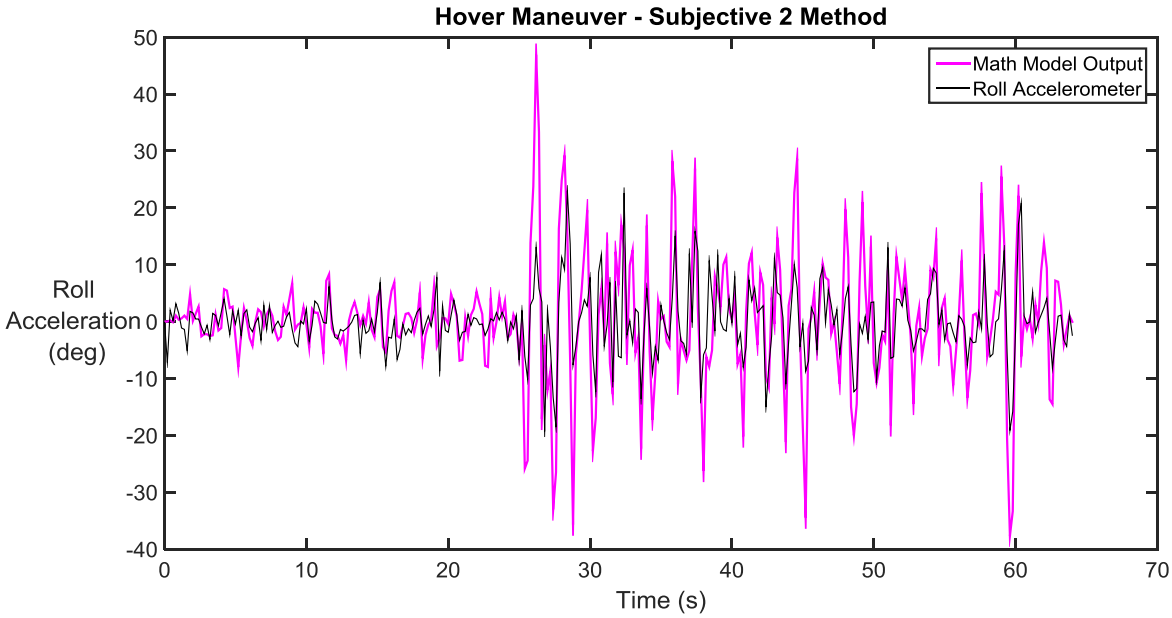
APPENDIX B

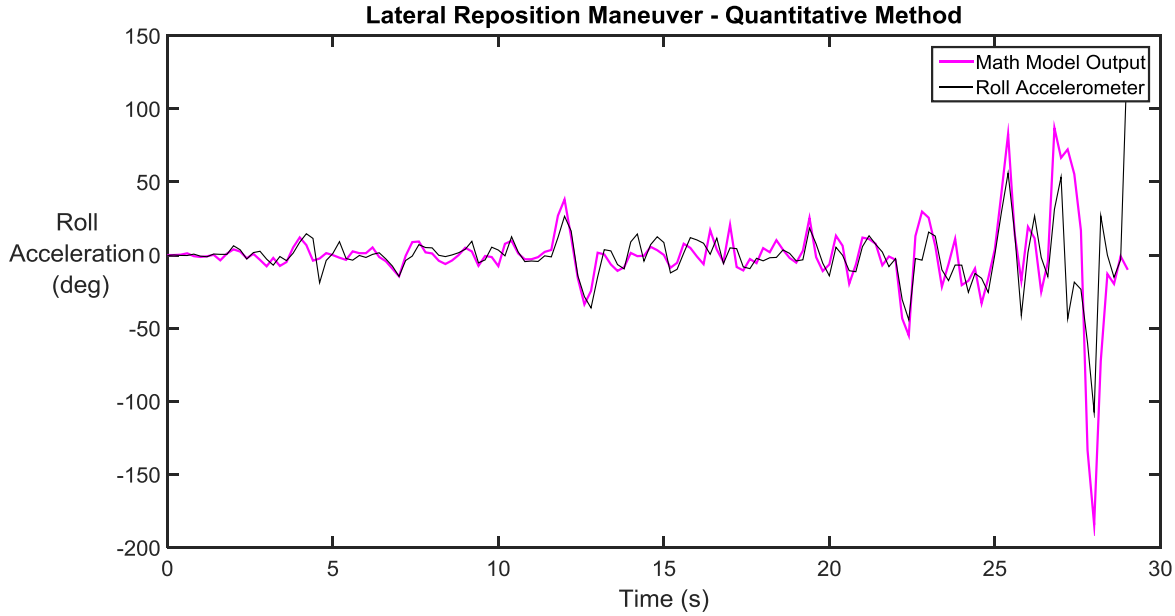
Task	Motion-Tuning Method	Motion Axis											
		Longitude		Lateral		Vertical		Roll		Pitch		Yaw	
		Gain	Wash out	Gain	Wash out	Gain	Wash out	Gain	Wash out	Gain	Wash out	Gain	Wash out
Hover	Quantitative	0.1	0.25	0.05	0.1	1	0.05	1	0.55	1	0.05	1	0.05
	Subjective 1	0.6	0.6	0.7	0.25	1	0.1	0.7	0.3	0.6	0.3	1	0.1
	Subjective 2	0.6	0.7	0.7	0.3	1	0.1	0.4	0.55	0.6	0.35	0.75	0.1
Lateral Reposition	Quantitative	0.05	0.1	0.1	0.5	0.9	0.2	0.85	0.7	1	0.1	0.85	0.15
	Subjective 1	0.7	0.7	0.7	0.3	1	0.1	0.4	0.55	0.8	0.3	0.75	0.1
	Subjective 2	0.6	0.7	0.7	0.3	1	0.1	0.4	0.55	0.6	0.35	0.75	0.1
Vertical	Quantitative	0.15	0.1	0.95	0.25	1	0.05	0.95	0.35	1	0.05	1	0.05
	Subjective 1	0.6	0.5	1	0.1	1	0.1	1	0.1	0.6	0.35	1	0.1
	Subjective 2	0.6	0.7	0.7	0.3	1	0.1	0.4	0.55	0.6	0.35	0.75	0.1

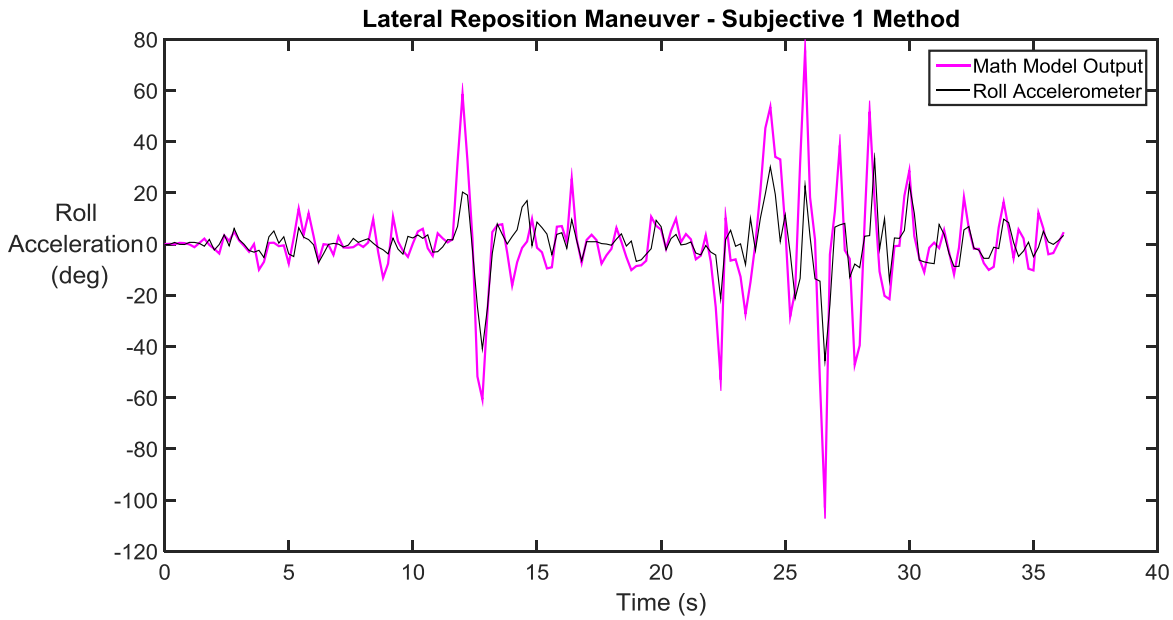
APPENDIX C

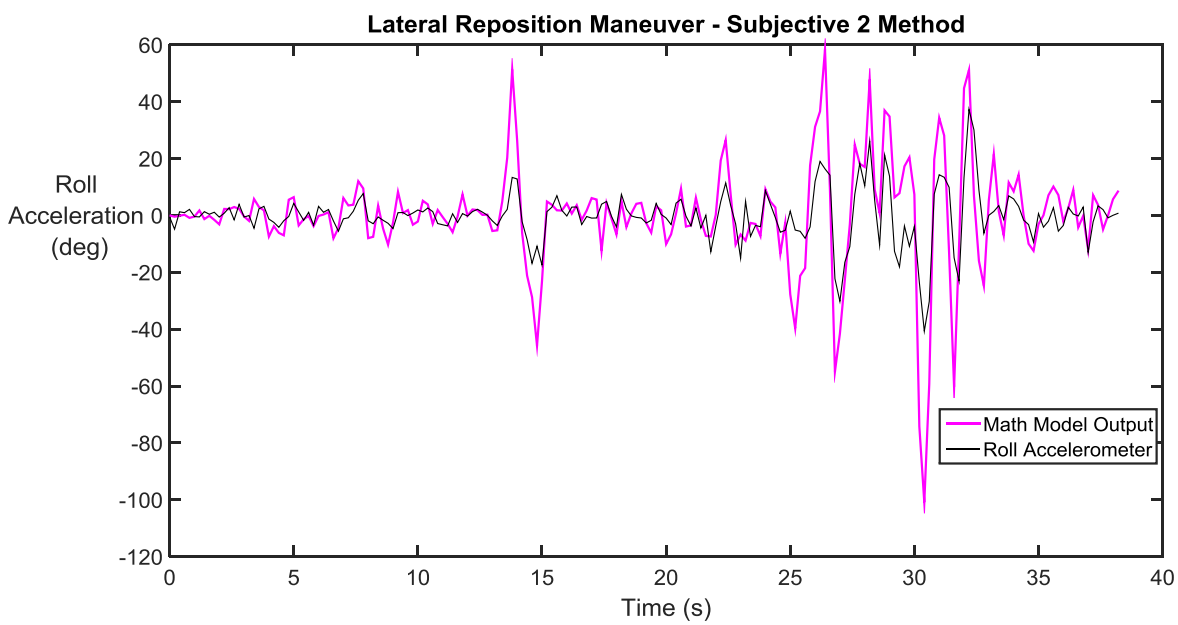

Hover Maneuver - Quantitative Method
Math Model Output
Roll Accelerometer
Roll Acceleration (deg)
Time (s)
40
30
20
10
0
-10
-20
-30
-40
0
10
20
30
40
50
60
70

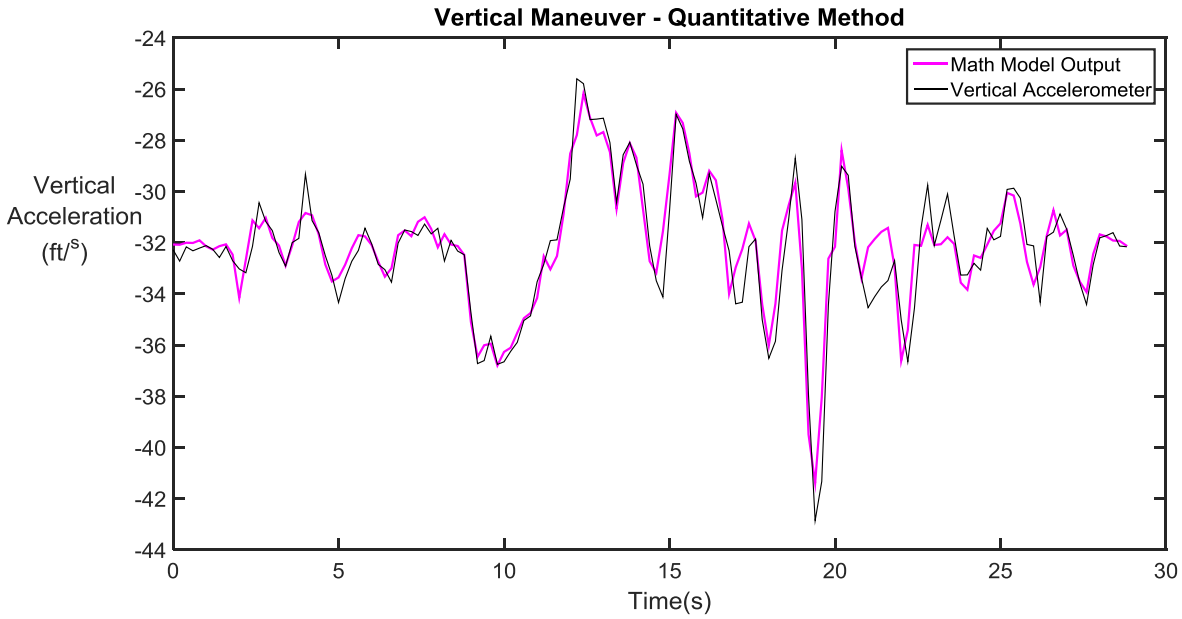

Hover Maneuver - Subjective 1 Method
Math Model Output
Roll Accelerometer
Roll Acceleration (deg)
Time (s)
60
50
40
30
20
10
0
-10
-20
-30
-40
0
10
20
30
40
50
60
70

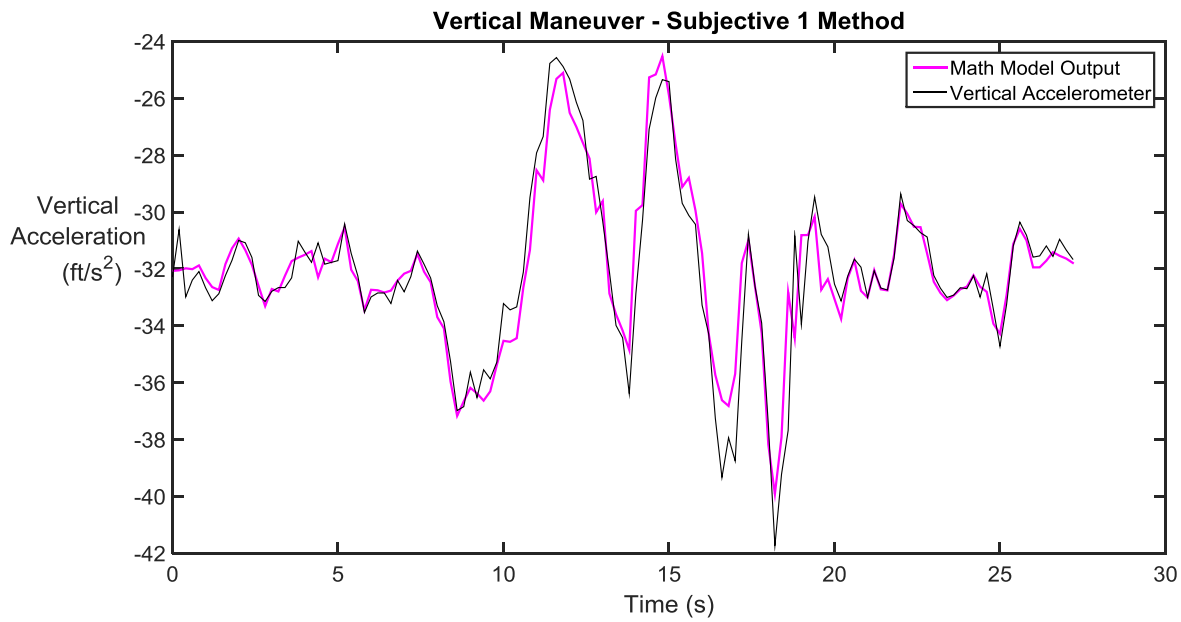

Hover Maneuver - Subjective 2 Method
Math Model Output
Roll Accelerometer
Roll Acceleration (deg)
Time (s)
50
40
30
20
10
0
-10
-20
-30
-40
0
10
20
30
40
50
60
70

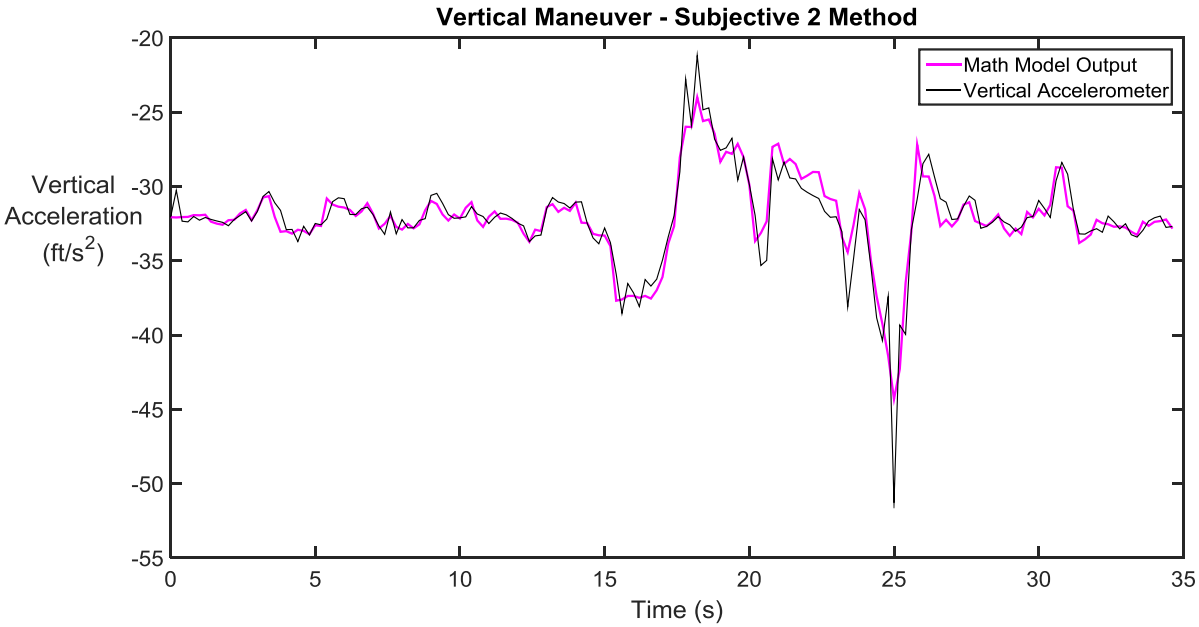

Lateral Reposition Maneuver - Quantitative Method
Math Model Output
Roll Accelerometer
Roll Acceleration (deg)
Time (s)
150
100
50
0
-50
-100
-150
-200
0
5
10
15
20
25
30


Lateral Reposition Maneuver - Subjective 1 Method
Math Model Output
Roll Accelerometer
Roll Acceleration (deg)
Time (s)
80
60
40
20
0
-20
-40
-60
-80
-100
-120
0
5
10
15
20
25
30
35
40


Lateral Reposition Maneuver - Subjective 2 Method
Math Model Output
Roll Accelerometer
Roll Acceleration (deg)
Time (s)
60
40
20
0
-20
-40
-60
-80
-100
-120
0
5
10
15
20
25
30
35
40


Vertical Maneuver - Quantitative Method
Math Model Output
Vertical Accelerometer
Vertical Acceleration (ft/s)
Time(s)
-24
-26
-28
-30
-32
-34
-36
-38
-40
-42
-44
0
5
10
15
20
25
30


Vertical Maneuver - Subjective 1 Method
Math Model Output
Vertical Accelerometer
Vertical Acceleration (ft/s2)
Time (s)
-24
-26
-28
-30
-32
-34
-36
-38
-40
-42
0
5
10
15
20
25
30


Vertical Maneuver - Subjective 2 Method
Math Model Output
Vertical Accelerometer
Vertical Acceleration (ft/s2)
-20
-25
-30
-35
-40
-45
-50
-55
0
5
10
15
20
25
30
35
Time (s)