Effects of Motion Filter Parameters on Simulation Fidelity Ratings

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ABSTRACT

An experiment at NASA Ames' Vertical Motion Simulator (VMS) evaluated simulation motion fidelity using a Bob-up task with a UH60 Blackhawk helicopter model. The experiment used ten different motion cueing configurations that varied the motion gain and washout frequency in the high-pass motion filter located between the aircraft math model and motion system. Ideally the actual aircraft would represent the Baseline configuration, however this can be a prohibitive constraint. The VMS' large motion envelop enabled an unfiltered, one-to-one, motion configuration as a surrogate for the actual aircraft. The Simulation Fidelity Rating (SFR) scale developed by the University of Liverpool and the Canadian National Research Council was used to subjectively rate the motion fidelity. The SFR scale requires the pilot to subjectively compare their performance and technique adaptation in the simulator to that of a baseline. All but two of the configurations tested were characterized as "Fidelity Warrants Improvement" on the SFR scale. The only configuration assessed as "Fit for Purpose" on the SFR scale was the Baseline configuration. The results from the technique adaptation portion of the SFR ratings showed some similarities with the Modified Sinacori Criteria. This indicates that the pilot's technique adaptation level in the simulator may be predicted based on motion filter parameters.

INTRODUCTION

Perhaps the Holy Grail of ground-based motion flight simulation is to quantitatively assess motion fidelity. The main challenge to achieving a quantitative simulator motion fidelity rating is that the complexities of human perception have yet to be adequately modeled for real world applications. Until a quantitative method is developed, subjective motion fidelity assessments, based on pilot perception, will have to suffice. There are two types of subjective methods for determining simulator motion fidelity, one is the Direct method and the second is the Indirect method. The Direct method uses experienced pilots to rate the simulation based on their experience in the actual aircraft. The advantage of the Direct method is that the pilots giving the subjective fidelity ratings are directly comparing the simulation with the actual aircraft. The Indirect method assesses the motion simulator fidelity level based on the motion filter parameters. The motion simulator fidelity levels for the Indirect method were also assessed subjectively using pilots. The advantage of this method is that it can be applied to any simulator, even though the aircraft used to develop the fidelity levels may be different than the aircraft being simulated.

There are many examples of the Direct method for evaluating simulator fidelity over the years. In 1970 NASA conducted a simulation for the XB-70 program in which a rating scale was developed to validate the simulator's fidelity for handling quality studies[1]. The pilots would first evaluate if the simulator was a satisfactory representation and then read through sub-category descriptions of the scale to complete the fidelity assessment. More recently, the University of Liverpool (UoL) in collaboration with the National Research Council of Canada developed the Simulation Fidelity Rating (SFR) Scale to assess the fidelity of a simulation including motion[2]. The SFR scale is similar in architecture to the Handling Qualities Rating (HQR) scale[3] but uses pilot precision and pilot technique adaptation

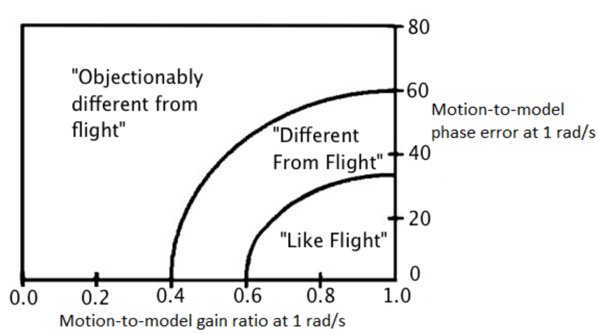


Figure 1. Modified Sinacori Criteria

in the simulator, as compared to flight, to arrive at a fidelity level (See Appendix A).

Sinacori postulated the fidelity of a motion simulator could be determined indirectly by the value of the motion gain and phase error at 1 rad/s of the high pass motion cueing filter that is usually placed between the aircraft math model and motion drive command accelerations[4](See Figure 1). Sinacori defined the high, medium, and low fidelity regions on a gain versus phase error plot based on experience. Schroeder experimentally tested Sinacori's fidelity criteria at the NASA Ames Vertical Motion Simulator (VMS)[5]. The VMS's large vertical and horizontal travel allowed Schroeder to develop baseline tasks incorporating one-to-one motion without encountering motion envelope limits. Schroeder then tested various combinations of motion gains and washout frequencies for these tasks and asked the participating test pilots to rate them as high, medium, and low fidelity compared to the Baseline. Schroeder used these results to develop the Modified Sinacori Criteria[5] for rotational and translational motion (see Figure 1).

The SFR scale can potentially be useful for evaluating the fidelity of training simulators but the requirement to compare the simulator to flight can be difficult. To properly use the SFR scale, the user needs access to test pilots that are current on the simulated tasks and aircraft. In addition to the difficulties in obtaining access to the aircraft to perform the desired task, the requirement makes the pilot pool small, difficult to find, and expensive. An Indirect method, using the SFR scale as the subjective criteria, would be useful for estimating simulator motion fidelity in terms of pilot performance and technique adaptation when it is not possible to use a Direct method.

The objective of the experiment presented in this paper is to develop an indirect motion fidelity criteria using the subjective SFR scale while varying the motion filter parameters that were outlined in Schroeder's experiment. This was accomplished by performing a bob-up maneuver in a simulated UH-60 Blackhawk helicopter at the VMS.

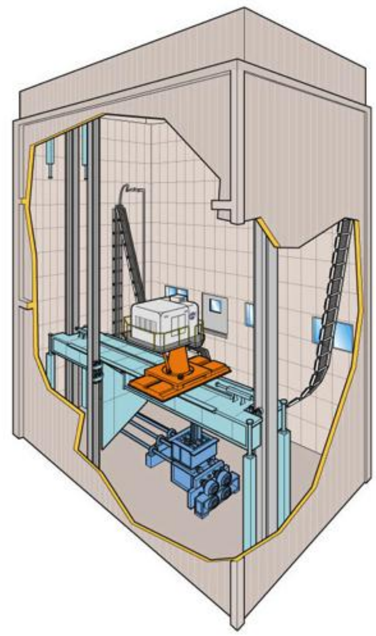


Figure 2. Vertical Motion Simulator.

VERTICAL MOTION SIMULATOR

Description

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. 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[6].

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.

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

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[7]. The custom digital-control interface allows for comprehensive adjustment of the controller's static and dynamic characteristics. 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.

Simulator Cockpit

The generic rotorcraft ICAB was used to simulate the cockpit of the UH-60 Blackhawk, with a field-of-view of 160 degree horizontal, 20 degree vertical, and included a chin window (see Figure 3). The force feel characteristics of the hydraulically driven cyclic, collective, and pedal controls were the same as the actual aircraft. The pilot was also provided with three glass head down displays containing one primary flight display and two data displays. The data displays provided end-of-run performance data and controller input time history plots to reference while rating each configuration.

Figure 3. Rotocraft Cockpit

Motion Cueing Algorithm

The cockpit motion cueing algorithms use high-pass (washout) filters and a rotational/translational cross-feed arrangement shown schematically in Figure 4. The computed 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 the following equation where K is the motion gain, ω_n is the washout frequency and ζ is the damping ratio that has a constant value of .707.

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

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 and provide the correct cues at the pilot's station. A low-pass filter tilts the simulator to

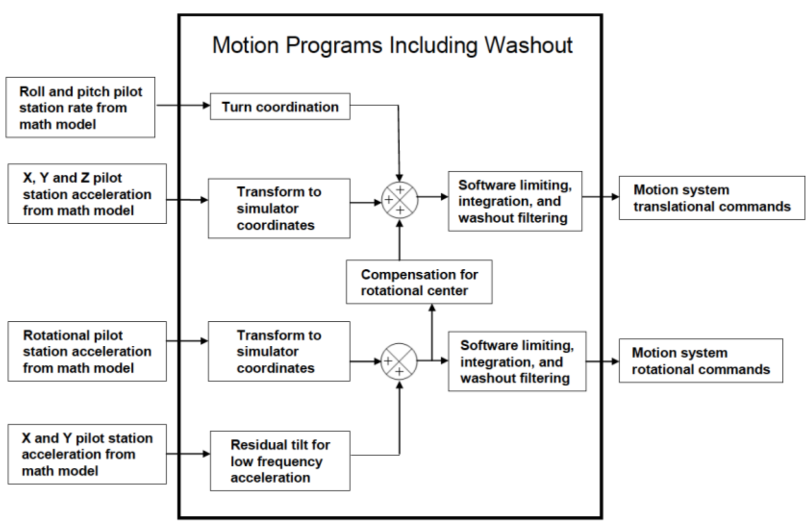


Figure 4. VMS motion algorithm schematic

provide steady-state longitudinal and lateral acceleration cueing at low frequency.

The motion cueing dynamics as defined by the selected motion gains and washout parameters can be assessed against the modified Sinacori criteria described by Schroeder. The Modified Sinacori Criteria show the gain and phase error imposed by motion filters at 1 rad/sec. The following equation shows the phase error (PE) for a second-order high pass filter as a function of the washout frequency and damping ratio.

$$PE = tan^{-1}\left(\frac{2\zeta\omega_n}{1-\omega_n{}^2}\right)$$

To attain true flight motion cues or unfiltered motion, the high pass filter would be defined by a zero phase shift and unity gain and therefore would reside in the bottom right hand corner of the Modified Sinacori plot (see Figure 1). Fixed-base simulators would have a motion gain of zero and would reside along the left hand axis of Figure 1.

OBJECTIVES AND APPROACH

The VMS can be tuned to operate with a 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 limits. One-to-one motion can be considered equivalent to flight because the motion being commanded by the aircraft math model is unattenuated, therefore the pilot is not subjected to false motion cues. However, when nearing the end of travel and corresponding derivative limits of the system, mechanical and software safety mediums could result in attenuated motion.

Since the VMS can run a one-to-one motion configuration as a baseline, it can be used to study simulation motion fidelity without needing flight data for comparison. The one-to-one Baseline configuration can be compared to attenuated motion configurations without changing cockpit environments, isolating the motion. The objective of this study is to develop SFR motion criteria to define the motion fidelity levels based on the motion gain and phase error. In addition, the pilots were also asked to rate the motion as high, medium, and low fidelity in comparison to the baseline as Schroeder did when developing the Modified Sinacori Criteria[5].

EXPERIMENTAL SETUP

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. Performing a system identification analysis on the UH-60 model revealed a reduced bandwidth when compared to the model exercised in Schroeder's experiment[5].

Task Description

The evaluation task was a modified ADS-33[8] bob-up maneuver as seen in Figure 5. The maneuver starts from a stabilized hover at the lower hover board (see Figure 5). The pilot signals the start of the task and rapidly ascended 10 ft to the upper hover board. The pilot signals when stable and holds that position for five seconds. After the five seconds is over the pilot signals the start of the descent to the lower hover board. At the lower hover board the pilot signals when stable and holds that position for 10 seconds.

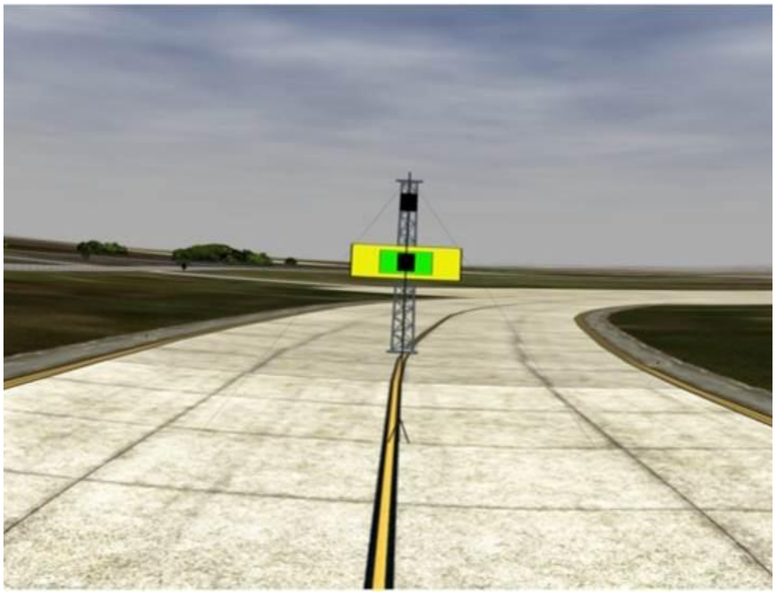


Figure 5. OTW view of bob-up lower hover target

Table 2. Experimental Configurations

Configuration	Acceleration Gain	Washout Frequency	Phase Error
1 (Baseline)	1.000	0.060	4.867
2	0.901	0.245	20.231
3	1.000	0.521	45.318
4	1.000	0.885	80.172
5	0.650	0.245	20.231
6	0.670	0.521	45.318
7	0.300	0.245	20.231
8	0.309	0.521	45.318
9	0.377	0.885	80.172
10	0.000	----	----

Considering the vertical operational position limit of the VMS to be 44ft, the task was designed to ensure the motion cues were unattenuated for the Baseline configuration, providing an accurate representation of a UH-60 Blackhawk.

The SFR scale requires meeting defined performance criteria similar to the Cooper Harper Handling Qualities Ratings[3] with the help of a supplementary questionnaire (See Appendix B). The performance criteria for the bob-up were defined as:

Desired Performance:

- Complete translation and stabilization within 7 sec and with no objectionable oscillations.
- Altitude excursions within ±0.375 ft from hover board center after stabilization.
- Heading excursions within ±5 deg of desired heading throughout maneuver.
- Lateral and longitudinal excursions with 3 ft of the hover board width after stabilization.

Adequate Performance:

- Maintain desired performance taking more than 7 sec to bob-up (or down) and stabilize. Maintain desired performance for most of task except for occasional excursions, but are followed by return to desired performance limits.

Experimental Procedures

Five test pilots flew ten experiment configurations (see Table 2 and Figure 6). The motion gain and washout frequency of each configuration tested were the same as those used by Schroeder to develop the Modified Sinacori Criteria. The five pilots were asked to fly the Baseline configuration at least once before flying each configuration. After flying the Baseline configuration, the pilots were asked

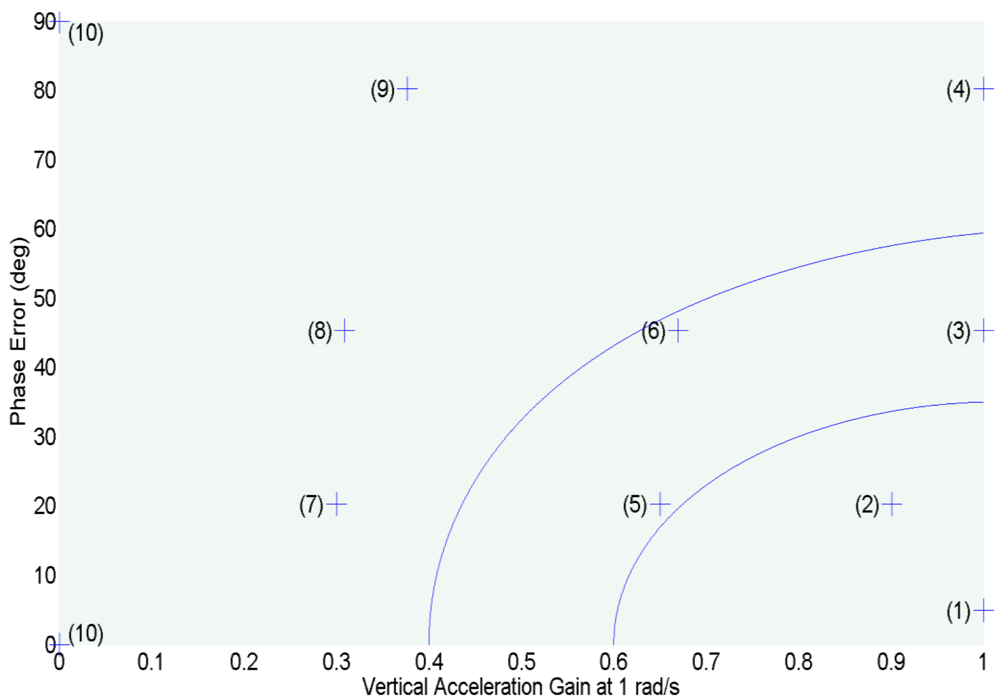


Figure 6. Configurations shown on Modified Sinacori Plot

to fly each configuration at least three times before giving an SFR using the Baseline configuration for comparison. In addition to giving an SFR, the pilots were also asked to provide a Motion Fidelity Rating (MFR), assessing the motion fidelity as high, medium, or low as compared to the baseline, as in Schroeder's study. All configuration parameters were concealed from the pilots and the Baseline configuration, Configuration 1, was tested in the same manner as the other configurations. Configuration 1 was developed to be representative of actual flight while Configuration 10 reflects a fixed base simulator.

Table 3. Test Pilot Experience

Pilot	Total Rotocraft Time	UH-60 Time	Active Pilot
1	2070	1800	Y
2	2350	120	Y
3	3500	0	N
4	4000	800	Y
5	2900	45	N

Pilots

Five pilots with extensive rotorcraft experience ranging from 2070 to 4000 hours evaluated the configurations, see Table 3. All the pilots were Test Pilots.

RESULTS

The motion fidelity ratings (MFR) of high, medium, and low fidelity motion as compared to the Baseline are plotted on the Sinacori plot shown in Figure 7. The eleven crosses on the plot represent each configuration, with Configuration 10 being duplicated at zero phase error, and the number in parenthesis next to the cross is the average MFR for all five pilots (see Table 4). Configuration 10 was transposed to a phase error of zero degrees enabling the interpolation method to assess the bottom left hand corner of the Sinacori plot. The green region represents the high fidelity responses, the yellow represents the medium fidelity responses, and the

Table 4. Motion Fidelity Ratings by Pilot

Configuration	Motion Fidelity Rating					Ave. MFR	Std. Dev.
	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5		
1 (Baseline)	1	1	1	1	1	1	0
2	3	1	4	1	4	2.6	1.4
3	4	1	7	4	2	3.6	2.1
4	7	7	5	7	5	6.2	1.0
5	4	2	4	4	2	3.2	1.0
6	5	7	5	1	4	4.4	2.0
7	1	1	7	4	7	4	2.7
8	5	2	3	6	3	3.8	1.5
9	4	4	5	1	5	3.8	1.5
10	7	5	5	7	7	6.2	1.0

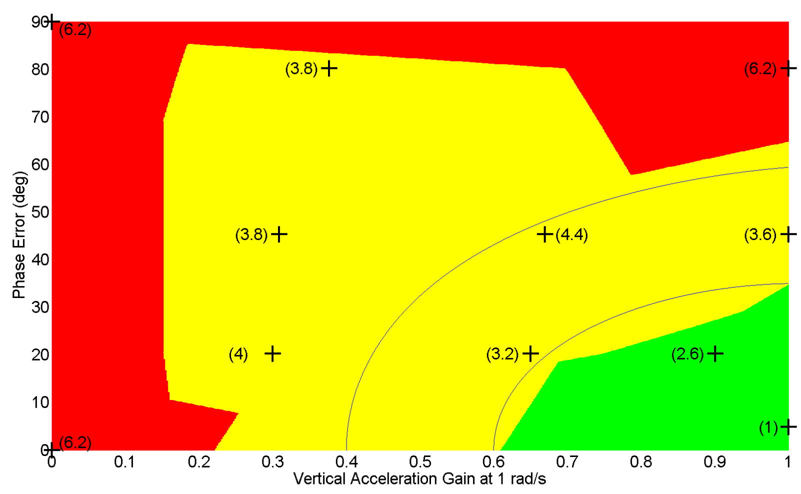


Figure 7. Average MFRs on a Sinacori Plot

red represents the low fidelity responses. A high fidelity MFR was defined as a value of one, medium fidelity was defined as a value of four, and low fidelity was defined as a value of seven. In addition, pilots were allowed to interpolate between fidelity regions providing ratings of two and three when between high and medium fidelity levels and ratings of five and six when between medium and low. The color region was determined by interpolating between the configurations. If the average MFR was less than three then the region is green, if between three and five then yellow, and if greater than five it is red.

The green region in Figure 7 matches closely with the “Like Flight” region of the Modified Sinacori Criteria. The yellow, or medium fidelity region, is significantly larger than the “Different from Flight” region of the Modified Sinacori Criteria. This result is largely due to the favorable pilot ratings given to Configuration 9 from Pilot 1, Pilot 2 and Pilot 4. One possible explanation for this difference would be the pilots attributing the change in simulator motion to problems with the aircraft. As an example, Pilot 4 assessing Configuration 9 as high fidelity, commented "Only thing was a problem were the overshoots, however there were good motion cues to indicate overshoot, but the control power from the collective wasn't very precise in locating stable positions resulting in some bobbles in both the ascent and descent." Although the pilot assessed the configuration as "high fidelity,” he was able to discern degradation in the motion but attributed it to the aircraft. If Pilots 1, 2 and 4 attributed the aircraft's fidelity decline to the motion system, the yellow medium fidelity region would potentially be much closer to the “Different from Flight” region of the Modified Sinacori Criteria.

Table 5. Simulation Fidelity Ratings by Pilot

Configuration	Simulation Fidelity Rating					Ave. SFR	Std. Dev.
	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5		
1 (Baseline)	1	1	3	2	1	1.6	0.8
2	3	2	2	5	3	3	1.1
3	5	8	6	6	2	5.4	2.0
4	9	8	6	7	6	7.2	1.2
5	5	2	4	5	3	3.8	1.2
6	5	6	5	5	3	4.8	1.0
7	2	2	6	5	8	4.6	2.3
8	6	3	3	6	2	4	1.7
9	5	6	6	7	5	5.8	0.7
10	8	5	5	7	5	6	1.3

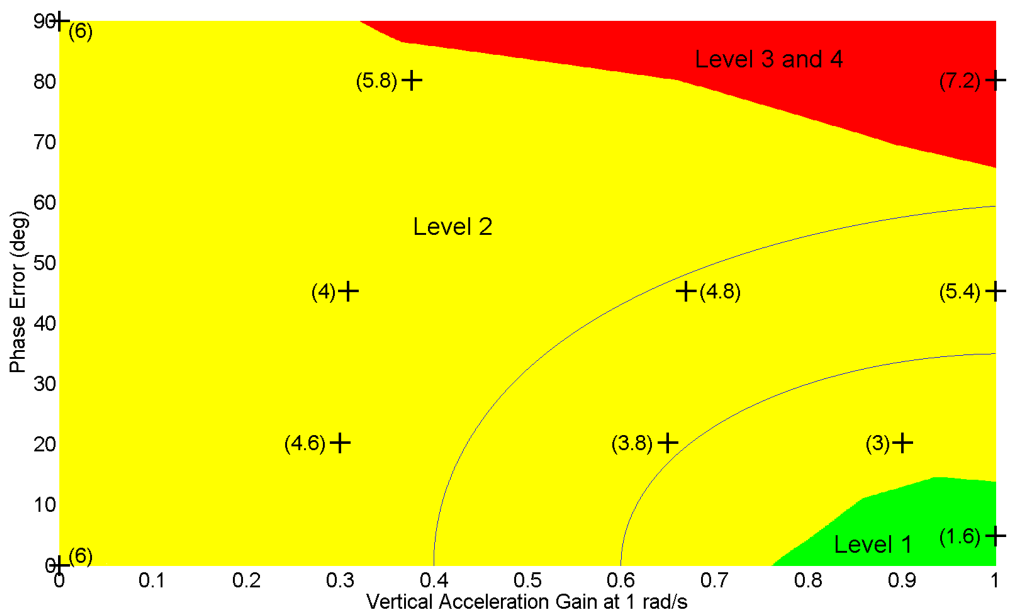


Figure 8. SFR Ratings as a function of Motion Gain and Phase Error

Figure 8 shows the average SFR ratings plotted on a Sinacori plot for each configuration. The ten crosses on the plot represent each experimental configuration and the number in parenthesis next to the cross is the average SFR for all five pilots (see Table 5). The colored regions represent the fidelity levels defined on the SFR scale. The green area represents Level One fidelity (SFR < 2.5) on the SFR scale and is characterized as "Fit for Purpose." The yellow area represents Level Two fidelity (2.5 ≤ SFR < 6.5) on the SFR scale and is characterized as "Fidelity Warrants Improvement." The red area represents Level Three and Four fidelities (SFR ≥ 6.5) that are characterized on the SFR scale as "Not Fit for Purpose." The fidelity level boundaries on the plot are determined by interpolating between the average SFR values for each configuration.

The "Fit for Purpose" region is less than half the size of the "Like Flight" or high fidelity region of the Modified Sinacori Criteria. Nearly the entire plot has a Level Two SFR fidelity level, which is characterized as "Fidelity Warrants Improvement." The Level Three and Four regions characterized as "Not Fit for Purpose" occupy a small region in the high phase error region on the plot.

The small Level One region shows that in order to achieve desired performance with minimal technique adaptation the motion gain needs to be greater than 0.65 with less than ten degrees of phase error. The small Level One region is difficult to achieve in a large simulator like the VMS and will be even more challenging in less capable training simulators.

Figure 9 shows the level of technique adaptation without taking into account task performance. The colored regions represent the technique adaptations defined on the SFR scale. The green area represents SFR ratings of less than 3.5, which has negligible or minimal technique adaptation. The yellow area represents SFR ratings of 3.5 to 5.5, which requires moderate technique adaptation. The red area represents SFR ratings of 5.5 to 10, which requires considerable to excessive technique adaptation. The technique adaptation boundaries on the plot are determined by interpolating between the average SFR values.

It is interesting to note that Figure 7 showing average MFRs, which is independent of performance on a Sinacori Plot, define similar fidelity envelopes to SFR ratings grouped by the level of technique adaptation, which also does not consider performance in Figure 9. There appears to be similar motion fidelity criteria between the Modified Sinacori Criteria plots regions and pilot technique adaptation. If the motion filter parameters are in the "Like Flight" region on the Modified Sinacori Criteria plots, negligible to minimal technique adaptation can be expected. If the motion filter parameters are in the "Different than Flight" region on the Modified Sinacori Criteria plots then moderate technique adaptation could be expected. If the motion filter parameters are in the "Objectionably Different than Flight" region on the Modified Sinacori Criteria plots, then considerable to excessive technique adaptation could be expected. It appears that technique adaptation level can be predicted based on the motion filter parameters.

CONCLUSIONS

The Indirect Modified Sinacori Criteria developed from Schroeder's simple fidelity scale was shown to be consistent with some deviations from the Motion Fidelity Rating results. The Motion Fidelity Rating scale high fidelity region mirrored the Modified Sinacori Criteria's "Like Flight" region while the medium fidelity defined a larger area than the "Different than Flight" region of the Modified Sinacori

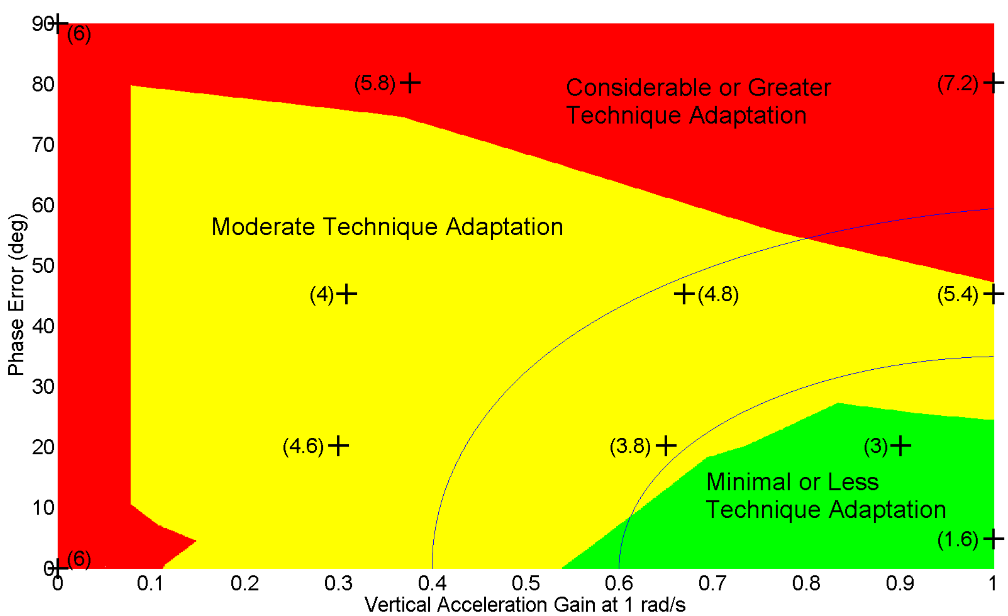


Figure 9. Technique Adaptation as a function of Motion Gain and Phase Error

Criteria. This difference may be attributed to a few pilots rating certain motion configurations as higher fidelity because they attributed the difference of the Baseline to the aircraft model. Therefore the Motion Fidelity Ratings produced by this experiment further validate the Modified Sinacori Criteria as defined by Sinacori[4] and Schroeder[5].

The only configuration that was characterized as "Fit for Purpose" on SFR scale was when the baseline was compared to the baseline. All of the other configurations except one were characterized as "Fidelity Warrants Improvement" using the SFR scale. The configuration with a gain of one and 80 degrees of phase error at 1 rad/sec was characterized as "Not Fit for Purpose" which was worse than the no motion configuration.

If the results from the technique adaptation portion of the SFR ratings are displayed on a Sinacori plot, a strong association can be observed. The negligible to minimal, moderate, and excessive adaptation ratings all compare well to the fidelity ratings using Schroeder's simple scale. From this observation, it appears to be possible to predict technique adaptation level based on the motion filter parameters.

FUTURE WORK

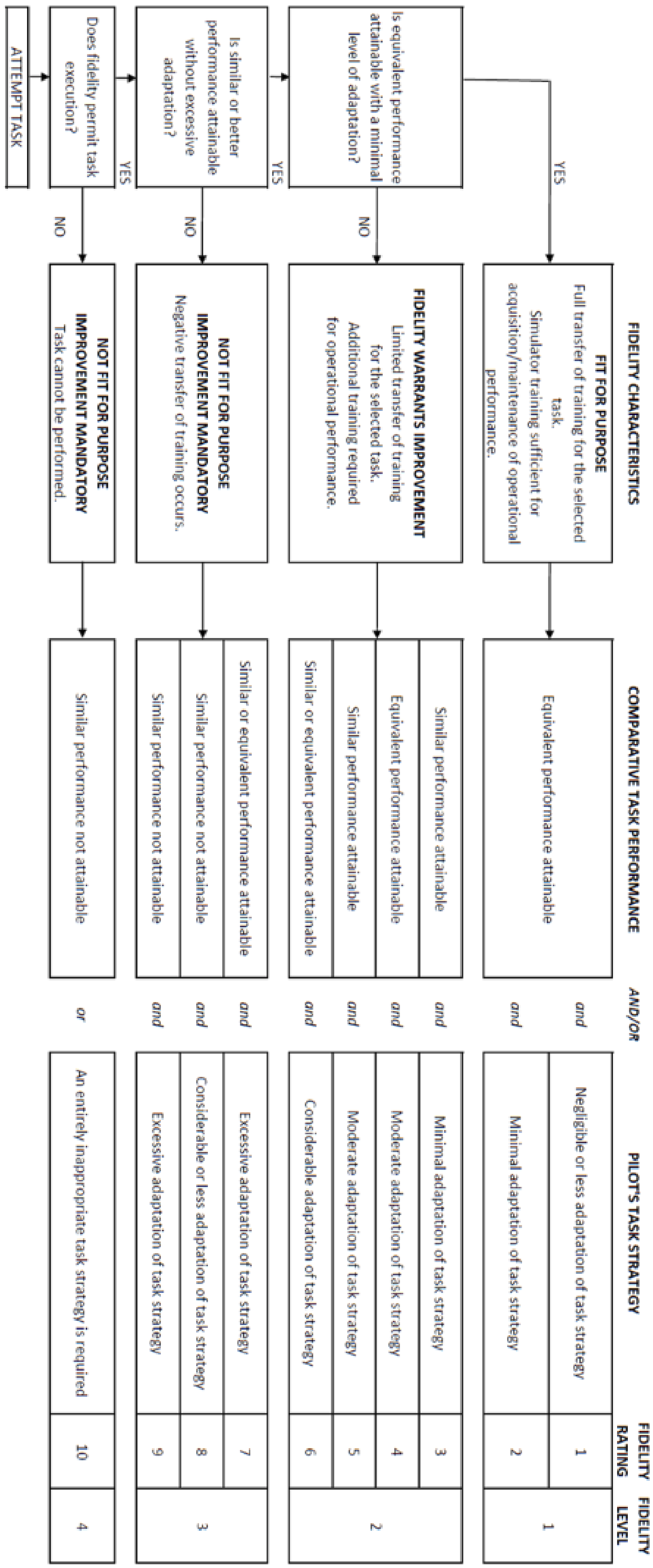
Rotorcraft varying in dynamic performance to the UH-60 and additional flight tasks will be tested to check the robustness of the Indirect method developed to predict SFR ratings. Additional flight tasks will include rotational axis-dependent and frequency-dependent maneuvers to further explore a general solution in quantifying motion fidelity.

Another area of interest is the effect of task performance requirements on piloting techniques. The goal of the motion simulation in training is to teach proper piloting technique. Typically, it is more difficult to fly precision tasks in a motion base simulator than it is in the actual aircraft. The motion and visual cues are not as accurate as in the actual aircraft, yet the pilot is asked to perform the simulation with the same performance requirements. In order to teach proper piloting technique it may be beneficial to relax the simulation performance requirements to achieve "minimal/negligible" technique adaptation for a wider range of simulator motion parameters. For instance, in the bob-up task, the transition time could be increased from seven to ten seconds, which may result in the pilot developing a technique that is used in the actual aircraft. With the proper technique developed in the simulator the performance should improve in the aircraft with that technique.

Finally, there needs to be further investigation on how to achieve more consistent SFRs from the test pilots. The pilot's perception of the amount of technique adaptation needs to be somehow calibrated to gain better consistency in the SFR data.

APPENDIX A

Simulation Fidelity Rating Scale Flowchart



APPENDIX B

Simulation Fidelity Rating Scale Questionnaire

Task Performance/ Aggressiveness (only rate the states featured in task definition)		Far worse performance achieved in modified model (dissimilar)	Worse performance achieved in modified model (similar)		Achieved Performance Equivalent		Better performance achieved in modified model (similar)		Far better performance achieved in modified model (dissimilar)	
Heave/Vertical Pos.	N/A									
Speed	N/A									
Overall	N/A									
	Aggressiveness									
Comments										
Task Strategy (Flight dynamics)	Modified model characteristics give represetative strategy	Minimal strategy adaptation required	Moderate startegy adaptation required		Considerable strategy adaptation required		Extensive adaptation required		Completely dissimilar strategy required	
Collective										
Comments highlight worst case										
Task Strategy (Cueing Environment)	Cueing characteristics give representative startegy	Minimal strategy adaptation required	Moderate startegy adaptation required		Considerable strategy adaptation required		Extensive adaptation required		Completely dissimilar strategy required	
Motion Cues										
Aural Cues										
Comments highlight worst case										
Motion Fideltiy compared to baseline	High, Medium, Low									
Baseline										
Modified										
Comments highlight main influencing factor(s)										
SFR	1	2	3	4	5	6	7	8	9	10
Comments highlight main influencing factor(s)										

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