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EFFECTS OF SIMULATOR MOTION AND VISUAL CHARACTERISTICS ON ROTORCRAFT HANDLING QUALITIES EVALUATIONS

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ABSTRACT

The pilot's perceptions of aircraft handling qualities are influenced by a combination of the aircraft dynamics, the task, and the environment under which the evaluation is performed. When the evaluation is performed in a ground-based simulator, the characteristics of the simulation facility also come into play. Two studies were conducted on NASA Ames Research Center's Vertical Motion Simulator to determine the effects of simulator characteristics on perceived handling qualities. Most evaluations were conducted with a baseline set of rotorcraft dynamics, using a simple transfer-function model of an uncoupled helicopter, under different conditions of visual time delays and motion command washout filters. Differences in pilot opinion were found as the visual and motion parameters were changed, reflecting a change in the pilots' perceptions of handling qualities, rather than changes in the aircraft model itself. The results indicate a need for tailoring the motion washout dynamics to suit the task. Visual-delay data are inconclusive but suggest that it may be better to allow some time delay in the visual path to minimize the mismatch between visual and motion, rather than eliminate the visual delay entirely through lead compensation.

INTRODUCTION

Ground-based simulation is an important tool in the assessment of handling qualities for both research and development. The strengths and limitations of simulation are well known and recognized in the handling qualities community. What is not as well documented, however, is the relative impact of various elements in the simulator itself on perceived handling qualities. For example, past studies (Ref. 1) have demonstrated that rate-augmented vehicles that exhibit good handling qualities in flight are much more difficult to control on ground-based simulators (e.g., Fig. 1).

Besides the obvious issues of simulation fidelity and flight/simulation transference (Ref. 2), there are other fundamental issues in simulation design that also impact the use of ground-based simulators for handling qualities research. All of these issues, such as inherent time delays and their compensation (Refs. 3 and 4), simulator sickness (Ref. 5), and the requirements on motion (Refs. 6, 7, 8, and 9), have been investigated in great detail in terms of their impact on human operator response dynamics and assessments of fidelity. Few studies, however, have explored the specific impact of these issues on handling qualities evaluations.

A two-part study was conducted on NASA Ames Research Center's Vertical Motion Simulator (VMS) to evaluate the effects of simulator characteristics on handling qualities. The primary focus of the two piloted simulations was on piloted assessment of the variations — i.e., Cooper-Harper Handling Qualities Ratings (HQRs; Ref. 11) and comments. Evaluations were conducted with several sets of vehicle dynamics, using a simple transfer-function model of an uncoupled helicopter, with Level 1 handling qualities based on Aeronautical Design Standard ADS-33C (Ref. 10). Changes in the simulation environment were made by adding time delays in the visual path and in the overall simulated response, and by changing motion system washout filter dynamics. The pilots were instructed to evaluate each variation in the environment as if it were a new aircraft; therefore, it may be assumed that differences in HQRs were due entirely to the pilots' perceptions of handling qualities, rather than to changes in the aircraft model itself.

The first simulation (Simval I) was an exploratory study of the tradeoffs in the motion and visual elements. A more systematic evaluation of these tradeoffs was conducted

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in the second simulation (Simval II). This paper reports on the overall results and conclusions from both simulations.

FACILITY

Hardware

The VMS is a six-degree-of-freedom simulator with a cab mounted on a Rotorcraft Simulator Motion Generator (RSMG) gimbal (Fig. 2). Translational motion is limited by hard stops at ± 30 ft vertically, ± 20 ft laterally, and ± 4 ft longitudinally. Software trips in the motion system further limited the available range of linear travel from center position to ± 25 ft vertically, ± 18 ft laterally, and ± 2.5 ft longitudinally. The cockpit was representative of a single-pilot helicopter configuration. In the first simulation three horizon-level monitors provided the out-the-window view; the rightmost window included a view of the ground environment near the helicopter as well. In this simulation visual display generation was via a Singer-Link Digital Image Generator (DIG I). In the second simulation, a four-window cab was used with three forward-looking windows and one downward-looking chin window. For this simulation a three-channel CT5A CGI system was used; since only three channels were available for four windows, the leftmost forward display was not used. In both simulations the cockpit head-down instruments were conventional, with the addition of a digital altimeter. No head-up displays were used. Cockpit controls were also conventional, with a center-mounted cyclic, left-hand collective, and pedals. The command signals were displacement for all controllers.

Motion Description

The general structure of the VMS cockpit stick-to-motion response is shown in Figure 3. Control inputs made by the pilot result in aircraft model accelerations, rates, and positions. The motion washout software generates motion commands in the simulator axes reference frame from the aircraft model accelerations. In the motion washout software, first the aircraft accelerations are transformed into simulator axes. Then, each of the six simulator axes accelerations is sent through a washout filter. The washout filter is a linear, constant-coefficient, second-order high-pass filter of the following form:

$$\frac{\text{simulated acceleration}}{\text{model acceleration}} = \frac{K_{wo}\, s^2}{[s^2 + 2\zeta_{wo}\omega_{wo}s + \omega_{wo}^2]}$$

Different sets of motion washout filter gains, damping ratios, and break frequencies were devised and evaluated in the two experiments. These washout filter sets were designed to transmit different forms of acceleration information to the pilots. Details of the washout filter sets are given in the Description of the Experiment section of this paper.

The washed-out commands are sent to the lead compensation software, where phase lead is added to the motion drive commands to compensate for some of the lags in the motion drive hardware. No modifications were made to the lead compensation software.

The motion drive has dynamics associated with the hardware in each axis. The response of the combination of lead compensation and motion hardware constitutes the motion response. If the effective delay of the motion response is large enough, then it will be noticeable to the pilot. The effective delays in each axis of the motion response (feedforward and motion drive hardware dynamics combined) are presented in the next section.

The roll-lateral washout configuration will be explained in more detail as an example of the interplay between the motion system axes. Without compensation, the rotational accelerations of the Vertical Motion Simulator induce a spurious linear acceleration since the rotational axis of the simulator is below the pilot's seat. This effect is compensated by subtracting the induced angular acceleration term from the linear motion command. The correction factor is washed out through the same filter as the rotation that generated the lateral acceleration; it is multiplied by the rotational washout filter and divided by the lateral washout filter before the command is sent to the lateral washout.

In a constant lateral acceleration maneuver, the aircraft linear accelerations are eventually washed-out by the high-pass filter. In this case, the cab is tilted to change the relative orientation of the gravity vector to the cab, simulating the sustained lateral accelerations that are not achievable with finite linear motion. Similar coordination is achieved between the pitch and surge axes.

Time Delays

Delays in the Motion System. During the simulation, the dynamics of the motion response to motion command were quantified by measuring these responses to a cockpit controller input. The inputs, generated by a random number generator, were shaped with a Gaussian distribution over the frequency range of 0.1 to 30 rad/sec and added directly to the cockpit control signal of interest. The result of the Gaussian distribution was that the higher frequency inputs were of smaller magnitude, and no saturation occurred in the motion hardware. The resulting motion command and motion response to these inputs were recorded, CIFER (Ref. 12) was used to generate frequency responses and the generalized transfer-function fitting program NAVFIT (Ref. 13) was used to identify an effective time delay of the combined feedforward and motion drive dynamics.

The effective delays in each axis of the motion response are presented in Table 1. Recall that the sway and roll axes were necessary to provide rotation about the aircraft center: although the motion washout software generates the correct commands for an aircraft rotation, the sway and roll motion responses were asynchronous (a time difference of 30 to 40 msec existed between the responses). It was found that this difference between the sway and roll axes in the lateral response was noticeable in many of the evaluated configurations.

Delays in the Visual System. The sources of time delay in the stick-to-visual response with the CT5A CGI (used in Simval II) are shown in Figure 4 and identified delays are listed in Table 2. It takes 10 msec for the cockpit stick position signal to get to the host computer, and the host computer updates the model states based upon the stick position and the aircraft rates. The computation time of the model acceleration is T_{cycle}, but the model positions and rates are forward integrated by one cycle so that they are concurrent with the accelerations of the next time frame (when they will be used in the calculation of the next frame's accelerations). The forward integrated positions and rates are sent to the Image Generator (IG); there is a 2 msec transport delay in this transmission. The IG takes 3 internal CGI cycles to display the visual scene, consisting of one cycle for the object manager, one cycle for the geometric processor and the polygon manager, and one cycle for the display processor. The IG then requires 1/2 cycle to prepare the data and 1/4 cycle to draw half of the model response to the stick on the screen. The IG computer cycles at 60 Hz (16.67 msec), resulting in an IG transport delay of 62.5 msec (3.75 cycles). The overall delay of stick-to-visual response is 74.5 msec - T_{comp}, with a standard deviation of 3 msec. The overall stick-to-visual response was varied by adjusting the visual lead compensation, T_{comp} (Ref. 16).

While Simval II used the Evans and Sutherland CT5A CGI as described above, Simval I used a Singer-Link Digital Image Generator (DIG I). There is a small difference in the update rates between these systems resulting in an IG transport delay for the DIG I of 83.3 msec compared to 62.5 msec for the CT5A. The visual variations for the experiments are outlined in the Description of the Experiment section of this paper.

Interactions of Motion and Visual Delays

The dynamics of the tested configurations were characterized in terms of their pitch and roll attitude Bandwidth parameters (Ref. 10), i.e., Bandwidth frequency ω_{BW} and phase delay τ_p. Each of the time-delay sources in the VMS facility outlined above can have a very large effect on the values of these parameters. For ground-based simulation, it is necessary to properly account for three separate response elements, the math model, the visual scene, and the motion system, since the pilot is, to some extent, aware of and operating in response to all of them. In the case of the VMS it is possible for the Bandwidths of these three responses to be quite different for the same configuration. An example of this is shown in Figures 5 and 6.

The frequency-response plot of Figure 5 illustrates the dramatic effects of cascading the individual elements of the simulation onto the ideal math model. The model (shown as solid lines in Figure 5) is the transfer function for an ideal rate-augmented helicopter model with roll damping L_p = -4 rad/sec; p/δ represents the model response to measured control actuator position (i.e., after the A/D and D/D interfaces in Figure 4). As expected, in the absence of time delays this ideal system exhibits a Bandwidth frequency of $\omega_{BW_\phi} = -L_p = 4$ rad/sec, and phase delay $\tau_{p_\phi} = 0$.

The response of the compensated visual display (p_v/δ_{as}) in Figure 5 introduces the 10-msec control position measurement delay for the A/D and D/D (Fig. 4). This delay has no effect on magnitude and only a slight effect on phase angle. Bandwidth frequency is reduced from 4 rad/sec to 3.7 rad/sec, and phase delay increased from zero to 0.01 sec. Turning the visual compensation filter off also does not affect the magnitude curve, but there is further phase lag, with ω_{BW_ϕ} = 2.4 rad/sec and τ_{p_ϕ} = 0.07 sec.

The motion response of the VMS cab (p_m/δ_{as} in Figure 5) is quite different from the model and visual responses. The combination of washout filter and effective motion time delay contributes low-frequency phase lead and high-frequency phase lag. The low-frequency lead introduced by the motion washout serves to increase the Bandwidth frequency to ω_{BW_ϕ} = 3.9 rad/sec, but the motion-system lags increase phase delay to τ_{p_ϕ} = 0.05 sec.

Figure 5 serves to illustrate several important points. First, it shows the beneficial effect of the visual compensation filter, since the phase curve of the compensated response is closer to ideal to higher frequencies. Second, the phase distortions and gain reductions introduced by the washout are evident, as the responses of the ideal math model and cab roll motion are in phase for effectively only a single frequency. Third, Figure 5 shows that in terms of visual-motion synchronization, the uncompensated visual response actually corresponds most closely to the motion response, especially at high frequencies.

The significance of the Bandwidth differences of Figure 5 is illustrated by Figure 6. This figure shows the eight possible measurements of the Bandwidth parameters to describe the responses of Figure 5. The parameters for the ideal model are the most straightforward, especially for position-referenced values of measured roll rate to measured control actuator deflection (p/δ). The visual-display Bandwidth, with compensation on, is referenced back to cockpit control position inputs, ϕ_v/δ_{as}, and hence reflects 10 msec of time delay; with compensation removed the Bandwidth decreases and phase delay increases. The phase delays for motion are about equal to those for the uncompensated visual display, but with increased Bandwidths due to the washouts. Addition of stick force feel dynamics, typical of those used in the two simulations, greatly increases τ_{p_ϕ} and decreases ω_{BW_ϕ} when these values are referenced to force.

DESCRIPTION OF THE EXPERIMENT

Effects of variations in the three major elements of the simulation — the motion and visual systems and math model — were evaluated. Specific variations and the philosophies behind them were as follows.

Motion System

Even though the VMS provides a large range of linear and angular travels, there are still very tight limitations on maneuvering space that necessitate lowered response gains and high washout break frequencies (Ref. 9). The selection of such gains and washouts is a compromise between the desire for realism in motion and the realities of space limitations. Potential criteria for determining washout limits (both gain and break frequency) for linear washouts have been developed (Refs. 14 and 15). These limits generally indicate that for minimum loss of motion fidelity, washout filter break frequencies should be no greater than about 0.3 rad/sec (for a second-order filter with damping ratio of 0.7). Ideally, the values selected reflect the requirements of the particular maneuvers to be flown and the expectations of the pilot.

As Figure 5 indicates, the combined effects of motion washouts and delays results in only a narrow range of frequencies for which the phase angle of the motion response accurately reflects the model response. In addition, the reduced gain in the motion system results in an attenuation in the motion response at all frequencies. This difference between the ideal system and the achieved motion is complex and is a function of frequency. Nonetheless, it is useful to find a simpler metric for judging the fidelity of the motion response. In terms of phase differences, it has been suggested (e.g., Refs. 14 and 17) that a phase distortion of less than about 30 deg corresponds to high motion fidelity. Therefore, in this paper we will consider two parameters to define the model-to-motion differences as shown in Figure 5: 1) the washout gain, or reduction in motion response as compared to full-scale motion; and 2) the frequency range for which the phase distortion (difference in phase angles between model and motion) is 30 deg or less. While these parameters are not as explicit as complete transfer-function plots, they will greatly facilitate the comparison of the different motion washout values evaluated in these simulations.

Baseline Washout Dynamics

The Baseline set of motion washouts used in this experiment was developed for the Simval I simulation by NASA engineers. This Baseline set followed the NASA philosophy of transmitting initial accelerations at the expense of motion/visual/model phasing (Ref. 9). Scaling of the initial response was on the order of 30% to 60% of full scale, with washout break frequencies of 0.2 to 0.7 rad/sec.

The frequency range where the phase distortion of the motion washout filter is less than 30 degrees is plotted versus washout filter gain for the Baseline washouts in Figure 7. The plots were produced by concatenating the identified motion system dynamics with the washout filters. The high-frequency end of this low-phase-distortion range is almost entirely a function of motion dynamics and delays and cannot be increased. At the low-frequency end, the low-distortion range can be improved by reducing washout break frequency. The gain of the washout filter must also be reduced, however; otherwise, saturation of the motion drive occurs in position, rate, or acceleration.

The Baseline motion system represents a typical design for helicopter low-speed handling qualities studies on the VMS. The washout filters were selected conservatively, so that the motion system did not saturate during any of the Simval I tasks. The motion washout filters can be designed independently for each task of a simulation, to take full advantage of the capabilities of the motion system; the gain and phase distortion would be dependent on the task aggressiveness in each of the motion system axes and on the simulator capabilities. This is not always done, however, as it is a difficult and sometimes time consuming process to perform. The more that is understood about the effects of the motion washout filters on pilot performance and pilot opinion, the better they can be adjusted for handling qualities evaluations.

Modified Washout Dynamics (Simval I). An alternate set of Modified washouts was developed during the Simval I simulation. This set was designed with the specific goal of reducing the phase distortions in motion around the frequencies of pilot closed-loop control (and maximum acceleration sensitivity), 0.5-5 rad/sec. Since this requires a washout break frequency below that of the Baseline washouts, the decreased phase distortion comes at the expense of further attenuated amplitude of motion. The phase-distortion ranges for the Modified washouts are compared with the Baseline set in Figure 7. These washouts emphasized the large-amplitude axes of response of the VMS — pitch, roll, and heave.

Systematic Variations in Washout Dynamics (Simval II). In the second experiment, only two tasks were evaluated, a precision hover and a sidestep, so that the development of the motion washout filters could be studied in greater detail. The precision hover allows for a substantial increase in gains (including one-to-one), due to the relatively small aircraft positions and attitudes generated during the task. Schroeder et al. performed a VMS simulation that successfully utilized gains of one in all six motion system axes (Ref. 18). The Simval II hover task actually consisted of a 6-8 knot translation to hover and a precision hover, and consequently the gains had to be reduced below one-to-one.

The sidestep task is an aggressive task that primarily emphasizes the roll and sway axes, secondarily emphasizing the heave axis. The design of the motion washout filters for the sidestep task addressed the interplay between roll, sway, and heave axes of the simulator; the yaw, surge, and pitch washout filters were not varied among the sidestep configurations.

Three motion washout configurations were designed for the sidestep to investigate the gain attenuation versus phase distortion trade-off. Phase-distortion plots are shown in Figure 8. The washout break frequency for the roll, sway, and heave axes was systematically varied and the gains adjusted so that the pilots did not run into any motion limits while flying the task. The yaw, surge, and pitch washout filters were similar to the Baseline washouts. The roll and sway washouts cannot be designed independently because of the interdependence of the rotational and linear axes of the VMS, mentioned previously. It can be seen in Figure 8 that while variation was made in the roll gain, sway gain remained 0.3 or less for all three Sidestep washout configurations.

Visual System Delays

While the visual compensation filter (Ref. 3) used on simulations on the VMS effectively removes the overall visual delays, it increases the mismatch in phasing between the visual and motion responses: the motion system experiences unavoidable delays due to anti-aliasing filters, mass, inertia, and control limiting effects that cannot be removed entirely. Past studies of time delays in either the visual or motion path, resulting in a visual/motion mismatch, show mixed results. For example, a simulation on the NASA Ames Six-Degree-of-Freedom (S.01) simulator (Ref. 19) suggests that based upon measures of pilot performance, 1) it is better to have the motion response lag visual rather than to intentionally lag the visual just to reduce mismatch, and 2) in terms of pilot high-frequency lead generation, motion compensation is more important than visual compensation. A study of a vertical pursuit tracking task on the NASA Langley Visual/Motion Simulator (Ref. 20) investigated visual/motion mismatch by introducing delays in the visual system. Pilot performance measures of total tracking error and control activity were taken. Slight improvements in performance were found for the case where total visual delay most closely matched the effective delays of the motion system (approximately 97 ms).

Effects of removing the visual delay compensation were evaluated in both simulations. The total visual time delays for both Simval I and II are listed in Table 3.

MATH MODEL

The mathematical model for the rotorcraft was a generic, uncoupled stability-derivative model that has been used for several simulations at Ames (Ref. 21). Changes in dynamic response characteristics are effected by altering the basic aircraft stability and control derivatives; for example, the transfer function for pitch attitude response to longitudinal cyclic for the rate-augmented aircraft was represented by

$$\frac{\theta}{\delta_\theta} = \frac{M_{\delta_\theta}}{s^2 - M_q s}$$

TASKS

Simval I

Seven tasks were evaluated in the preliminary simulation. These tasks consisted of precision and aggressive maneuvers at hover and in low-speed flight as defined by Section 4 of ADS-33C (Ref. 10). The precision tasks were a one-minute hover, vertical translation (a surrogate for landing), and pirouette. The aggressive tasks were a bob-up/bob-down, dash/quickstop, and sidestep. A 40-kt lateral slalom task, which has no counterpart in ADS-33C, was included to emphasize a combination of precision and aggressiveness. Desired and adequate performance limits were defined for each task, based as much as possible on ADS-33C limits but adapted when necessary to the specific visual environment of the DIG. Details of the tasks are given in Refs. 22 and 23.

Simval II

The second simulation focused on two tasks, a precision hover and a sidestep. The visual scenes for these tasks were tailored to adhere to recently revised task definitions, and performance limits were consistent with those for the revised tasks.

Because of the emphasis on these two tasks for the systematic study of motion and visual variations, an analysis of the pilots' control activity was performed to verify that the tasks were sufficiently demanding (i.e., exhibited sufficient task bandwidth) to elicit the desired effects in pilot performance and opinion. Figure 9 shows frequency-response plots of an example power-spectral density (PSD) for lateral cyclic activity. These plots show that 70 percent of all input power (corresponding to the pilot's "cut-off frequency," Ref. 24) occurs at 2.4 rad/sec for the hover (Fig. 9a) and 1.1 rad/sec for the sidestep (Fig. 9b). As expected, these frequencies confirm that the hover is a higher-bandwidth task than the sidestep. They also suggest that the pilots will be more sensitive to visual delay variations in the hover (where visual delay introduces high-frequency phase rolloff), and more sensitive to motion delay variations in the sidestep (where the cut-off frequency is very near the low edge of phase distortion as introduced by the washouts, Fig. 8).

PILOTS

Seven pilots, with varying backgrounds and levels of experience, participated in the first simulation. Two pilots had relatively little previous experience in ground-based simulation, and none in the VMS. In Simval II four pilots participated, including two with over 300 hours in the VMS. The other two pilots in Simval II had no previous VMS exposure. Two of the experienced pilots flew in both simulations.

RESULTS

Effects of Task

Motion and task effects were evaluated in Simval I. The seven tasks were evaluated fixed-base and with the Baseline and Modified motion washouts. Figure 10 is a summary plot of the HQRs for the tasks. Average HQRs are depicted by solid symbols that are connected by a solid line for clarity. Each data symbol represents a single rating. There is evidence in Figure 10 of rating differences across the tasks. Generally, the easiest tasks (in terms of best average HQR) were the hover, bobup/bobdown, and dash/quickstop. Since no turbulence, gusts, or winds were simulated, the one-minute precision hover was low-workload as long as the helicopter was reasonably well stabilized before starting the formal maneuver. Pilot comments indicated that the bobup/bobdown was relatively easy because of the decoupled helicopter model, making this almost entirely a single-axis task, while the dash/quickstop was rated well because of the ample forward field-of-view for initiating the maneuver. By contrast, the vertical translation, pirouette, and slalom maneuvers were inherently multi-axis and thus tended to receive higher HQRs, while pilot comments indicate that the poor ratings for the sidestep maneuver are due primarily to the lack of a sideward field-of-view for adequately determining the endpoints of the maneuver.

Effects of Motion Washout Filters

The effects of motion washout filters were investigated in both of the experiments. Simval I was an exploratory study that looked at a variety of tasks for only two motion washout configurations (Fig. 10). Simval II concentrated on understanding washout filter design for two tasks; results for the sidestep task are discussed below.

Simval I. Figure 10 illustrates the importance of motion on pilot opinion: all tasks were Level 2 fixed-base, and average HQRs improved by 1/2 to 2 rating points when motion was introduced. Comparison of the HQRs for the Baseline and Modified washouts in Figure 10 shows a general trend for slightly improved ratings with the Modified set. There are exceptions, however, as the average ratings for the bobup/bobdown and sidestep tasks are slightly worse. The slight improvements for the other tasks suggest that the pilots were either aware of the more consistent motions provided by the Modified set, or, conversely, that the rapid washouts of the Baseline set mitigated the beneficial effect of the increased initial accelerations provided by the higher gains. It is likely that the answer is a blend of the two, supported by the degraded ratings for the bobup/bobdown (where initial accelerations are an important cue to the pilot) and the sidestep (where the Modified motion washouts overdrove the vertical axis in response to lateral commands).

By their nature, aggressive tasks involve rapid changes of state — i.e., large initial accelerations — compared to the precision tasks. Since the Baseline motion gains transmitted more of the initial acceleration onset cues, it might be expected that this set would be preferred for the aggressive tasks, and this is the case for the bobup/bobdown and sidestep (Figs. 10e and 10g). By contrast, the Modified motion set was designed to provide more accurate phasing of the motion and visual responses, at the cost of reduced gain. Therefore, it is reasonable to expect this system to be preferred for those tasks that involve continuous closed-loop operations, such as the precision tasks, and this is the case as well (Figs. 10a, 10b, and 10c).

Several important factors must be considered in comparing the HQRs for the two motion gain/washout sets: first, the Modified set as developed for Simval I was intended to be exploratory in nature, and it did not take advantage of all axes (see Fig. 7); and second, since the basic aircraft was good to begin with, small changes in average HQR may or may not be significant. Simval I indicated that further testing was required, in a more systematic fashion, as was conducted on Simval II.

Simval II. The pilot ratings for the Sidestep task with the medium bandwidth helicopter dynamics are shown versus the motion washout configuration in Figure 11. As was found in Simval I, there is a substantial improvement in the pilot ratings for all the motion configurations over the fixed-base case (1/2 to 1-1/2 rating points). Of the three configurations developed for the sidestep task, the lowest phase distortion (and lowest gain) configuration, SS1, was preferred by all the pilots, as indicated by the pilot ratings in Figure 11 and the pilot comments outlined below.

Pilot A thought that both the Baseline and the low-phase-distortion, low-gain combination (SS1) were good configurations (HQR = 3). He perceived stronger motion cues in the medium phase distortion case (SS2), "Motion seemed a little strong ... you got bounced around pretty good... [I] could feel the difference between this and the previous configuration (SS1) just by the high level of motion... and that lowered the rating" (HQR = 4.5). The highest gain washouts brought the impression that the simulator was always moving around, and "[the motion response] felt like it was not in sync with the control movements or visual movements" (HQR = 4).

Pilot B was the most sensitive of the pilots to the strong movements of the simulator, preferring the low phase distortion (SS1) configuration over all the others. For example, with SS2, the medium gain configuration, "Every time I made any kind of aggressive rollout, then I was feeling a negative motion cue during the roll out to the hover" (HQR = 5). But for SS1, "I was getting good positive cues, but the negative cues that I felt before weren't present... In most of these cases where you do have a problem, you excite the problem by being more aggressive... [this] system lets me be more aggressive and then attain a tighter performance... this is good" (HQR = 3). It is possible that the pilots were feeling the effect of the mis-coordination between the roll and sway responses, in which the sway motion response to a lateral stick input was delayed by 30-40 msec behind the roll response (Table 1). The roll-axis bandwidth in this case was 4.3 rad/sec, and the effect of the asynchronous responses would have been magnified as the gain of the motion system was increased. These results suggest that the higher gain, higher phase distortion cases are not as robust to changes in pilot technique.

Pilot C's comments indicate that out of the three sidestep washout configurations, SS1 was the best because it was less jerky, easier to control, and required slightly less workload than the others. SS1 was also the only configuration where he noted that the motion system felt like it was in synchronization with what he was seeing and doing.

The low-phase-distortion, low-gain configuration SS1 offered two advantages over the others. The first advantage was that the phase distortion between the visual and motion responses was minimized for the roll, sway, and heave axes, as described earlier (Fig. 8). This was apparent in the pilot comments where they noted that the responses were more in synch and the helicopter was easier to control. The second advantage of the low-phase-distortion, low-gain configuration was that any motion miscues, such as those mentioned above, were diminished by lowering the gains. The pilots were very attuned to these motion miscues, as indicated in their comments.

For this study, the 30 degree phase distortion has been used as a reference by which the motion configurations were compared. The lower end of the low-distortion frequency range of the SS2 configuration is well above 1 rad/sec in all axes, while the SS1 configuration range spans down to almost 0.7 rad/sec (Fig. 8). The PSD of the Sidestep in Figure 9b indicates that the pilot cut-off frequency (the frequency below which 70 percent of control power is contained) was 1.1 rad/sec. So 70 percent of the control power is below the lower bound of the 30-deg phase-distortion frequency range for SS2, while more control power is contained above the lower bound of the SS1 configuration. It is therefore suggested that pilots preferred the SS1 washout configuration because they perceived lower phase distortion in the frequency range in which they were operating, i.e., below 1.1 rad/sec, even though it had lower motion gains.

Effects of Visual Delays

The baseline visual transport delay of the Vertical Motion Simulator is 63 - 83 msec, depending on the Computer Image Generator, as seen in Table 2. The effect of adding lead to the visual command to compensate for visual delay was investigated in both studies. When comparing the results from the two studies, the baseline visual delay case refers to the uncompensated visual delay for both studies, while the compensated visual case refers to the added visual lead compensation.

Sensitivity to Visual Delays. Before reviewing the pilot ratings for the visual-delay evaluations on the moving-base simulation, it is important to establish that the pilots were sensitive to the relatively small change in visual delay resulting from the addition of the lead compensation. To answer this question, we look at the results of fixed-base evaluations, where the pilots' only cue is visual. Five pilots flew back-to-back evaluations of the compensation on and off for the hover task, fixed base during the two simulations. The HQRs, shown in Figure 12, indicate that there was a preference for the compensated visual case, as expected.

Effects of visual delays were further investigated by calculating the improvement in phase margin at the pilot cut-off frequency (Fig. 9b) for the compensated visual case. For the Simval II high-bandwidth helicopter response, the phase margin at 2.4 rad/sec was increased from 67 to 75 degrees when the visual delay was compensated. This eight-degree increase in the phase margin alone is not enough to explain the improvement in ratings from Level 2 to Level 1. The bandwidth of the stick-to-visual response was greatly improved with the compensated case, from 4.8 rad/sec to 8.9 rad/sec in roll, and from 2.8 rad/sec to 4.0 rad/sec in pitch. So it is assumed that the reduction in pure time delay in the open-loop aircraft response was the major factor in the improved ratings.

Simval I. For this simulation, the baseline visual delay was 83.3 msec (Table 2), and the compensated visual delay was effectively zero; the model and motion responses remain unchanged. These evaluations were made with the Baseline motion washout filters (Fig. 7).

The pilot ratings for two precision tasks from the Simval I simulation, chosen because the same pilots flew both visual delay configurations and because the tasks are similar to the Simval II hover, are shown in Figures 13a and 13b. The results indicate that Pilots Mc and M preferred the visual-delay case over the no-delay case, while the third pilot (Pilot S) was just the opposite.

Comments by pilot S for the baseline visual delay case deal almost exclusively with motion problems, rather than visual. It is not clear whether the adverse comments about motion for these evaluations reflect the change in the motion/visual relationship, or simply Pilot S's dissatisfaction with the motion response.

Pilots M and Mc had relatively little previous exposure to ground based simulation. These pilots generally preferred the baseline visual delay case over the compensated case because of the reduction in the crispness of the response. For pilot M, "The [baseline visual configuration] was the least as far as the crispness goes... This last one is more in tune... It was easier to control." Pilot Mc commented that "[The baseline visual case]..., overall, felt more like flying than any of the others... The motion and visual cues seemed to be the most consistent between my inputs and the aircraft response."

Simval II. For this simulation, the baseline visual delay was 62.5 msec, and the compensated visual delay was effectively zero; the motion dynamics were held constant for the visual delay evaluations, but they were slightly different than the Simval I motion dynamics. These dynamics were used because the Simval II pilots felt that this set of washouts was slightly better than the baseline dynamics. However, the one pilot who flew both simulations gave almost identical ratings for these precision tasks, so the motion system difference does not appear to have affected results.

Pilot ratings for the hover task evaluations of the baseline and compensated visual are shown in Figures 13c and 13d. Two helicopter response configurations are represented here. The pilots rated the high-bandwidth helicopter better than the medium-bandwidth helicopter, but the trends are the same for both sets of dynamics. Pilots B and A, experienced VMS pilots, preferred the compensated visual in both cases, and the novice VMS pilot (Pilot C) preferred the baseline visual.

Pilot B, a veteran VMS pilot who flew both simulations (Pilot S in Simval I), noticed the motion system more with the baseline visual: "The visual system seems to be still correlating with the inputs, however, the motion seems to be giving me some uncorrelated response... causing me to make inputs to correct something that I don't think was wrong." It appears that Pilot B was compelled to pay more attention to the motion response with the baseline visual: "Maintaining the precision took all of my capacity... [the response] was slow when I gave my first input to move over to the hover position." With the compensated visual, however, "I didn't detect any time delay in the visual displays or the motion...the cues seemed very succinct and very in tune with the inputs... I could be as aggressive as I felt necessary... actually it did have spare capacity in this case...even though I was pretty active on the control.... The initial inputs to arrest the translation seem just a hair abrupt... It is a very sharp response, but very predictable."

Pilot B's ratings and comments are backed up by his performance, shown for the hover task with the medium bandwidth helicopter model in Figure 14a. The lateral and longitudinal errors are appreciably reduced with the compensated visual configuration.

Pilot C, the novice VMS pilot, agreed with the novice pilots in Simval I (Pilots M and Mc), but directly contradicted the other two pilots from Simval II. For the baseline case, "The motion I was picking up and the visual scene seemed to be in sync... minimal pilot compensation" (HQR = 3), whereas for the compensated case, "Motion/display cues were worse than the [baseline case]... the visual and motion felt out of phase.... [I] was working a lot harder to control height, and there was a lot of cyclic activity.... [Compared to the baseline, this system was] less sensitive. I thought you changed the control system, it seemed like lower bandwidth" (HQR = 4).

An example of Pilot C's performance for the hover task with the medium bandwidth helicopter model is shown in Figure 14b. Here we can see that, in contrast to Pilot B's performance, Pilot C's longitudinal and lateral errors were reduced in the baseline visual case.

General Conclusions on Visual Delay Effects. While the pilots do not agree on the visual configurations, the results are consistent between the two simulations. A summary of the HQRs from the two simulations is presented in Figure 15.

Based on the HQRs, the experienced VMS pilots prefer the visual compensated. It was seen that these pilots actually get better performance with this configuration, because they use primarily the visual cues for the task. Even Pilot B mentioned, however, that the response for the compensated visual was abrupt; it was this same abruptness that made some of the other pilots dislike the compensated case. It seems that the pilots with experience on the VMS have the ability to filter out the adverse motion responses.

The novice pilots prefer the baseline visual, where the motion and visual responses were most closely matched (Fig. 15). There is some rationale for this, since the high-frequency response of the visual scene with the baseline visual exhibits approximately 63-83 msec of total delay (depending on the CIG), and the VMS cab motion in pitch and roll exhibits 70-90 msec of effective delay due to high-frequency lags. Thus the baseline visual and motion responses are nearly in phase, whereas the implementation of the visual filter actually increases the discordance between visual and motion responses (Fig. 5).

It appears that the most practical solution is to match the motion and visual responses as closely as possible in the frequency range that is being exercised, even though some pilots may be able to achieve better performance with the visual response leading the motion response. With the visual and motion responses in phase, the simulation represents a more realistic helicopter response.

CONCLUSIONS

This two-phase study of the interactions of simulator motion, visual, and response dynamics on rotorcraft handling qualities has both confirmed previous observations and revealed areas deserving of more indepth study. Unlike most previous motion/visual simulation studies, the primary goal of this study was the measurement of these interactions on perceived handling qualities, rather than on objective performance measures.

Motion was necessary to obtain satisfactory handling qualities: none of the tasks received Level 1 average HQRs fixed-base. Improvements in HQRs when motion was added were generally 1/2 to 2 rating points.

Based on average HQRs, motion washouts with low break frequency and low response gain are slightly better than correspondingly high-gain, but high-break-frequency, washouts for the low-speed tasks evaluated. This may be a function of task aggressiveness.

The data suggests that the best handling qualities occur with the lowest motion/model phase distortion, even though this occurs at the cost of a reduction in the motion gain. The results of the motion washout configurations may have been mitigated by anomalies encountered in the motion system.

Pilots with little or no experience in the VMS or other ground-based simulators expect the visual and motion responses to be synchronized, and they are sensitive to changes in the phasing between the motion and visual responses. As a result, they prefer the situation where the visual response, although delayed, best matches the motion response. On the other hand, experienced VMS pilots were able to improve their performance with the visual delays compensated, apparently because they were able to filter out the mismatched motion responses and use the visual response as their primary cue.

The best solution to problems with visual/motion/model mismatches would be to improve the delays in the motion response, but this has proven to be difficult due to hardware limitations. The most practical solution may be to match the motion and visual responses as closely as possible in the frequency range that is being exercised, even though some pilots may be able to achieve better performance with the visual response leading the motion response. With the visual and motion responses in phase, the simulation represents a more realistic helicopter response.

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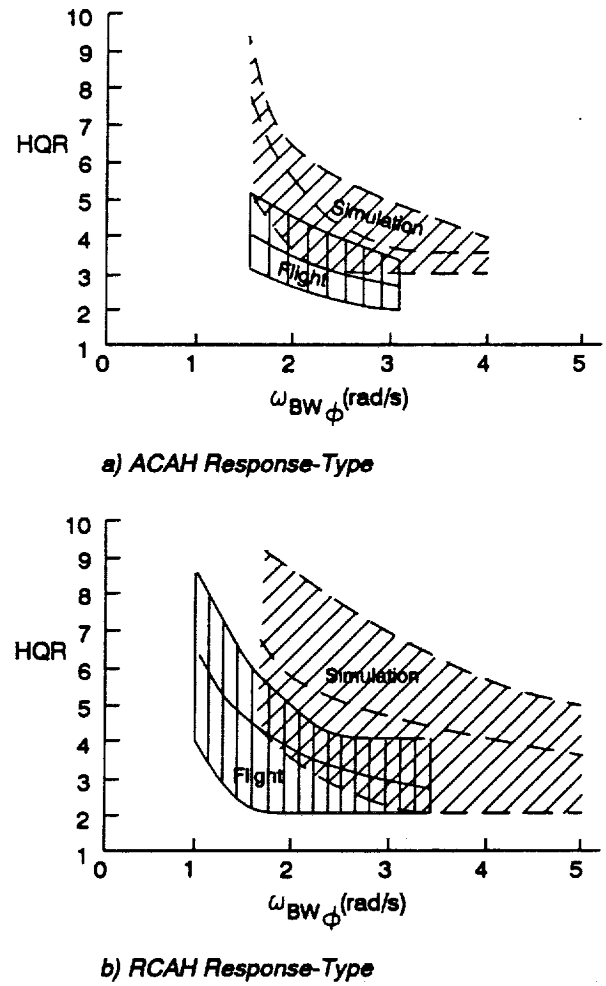
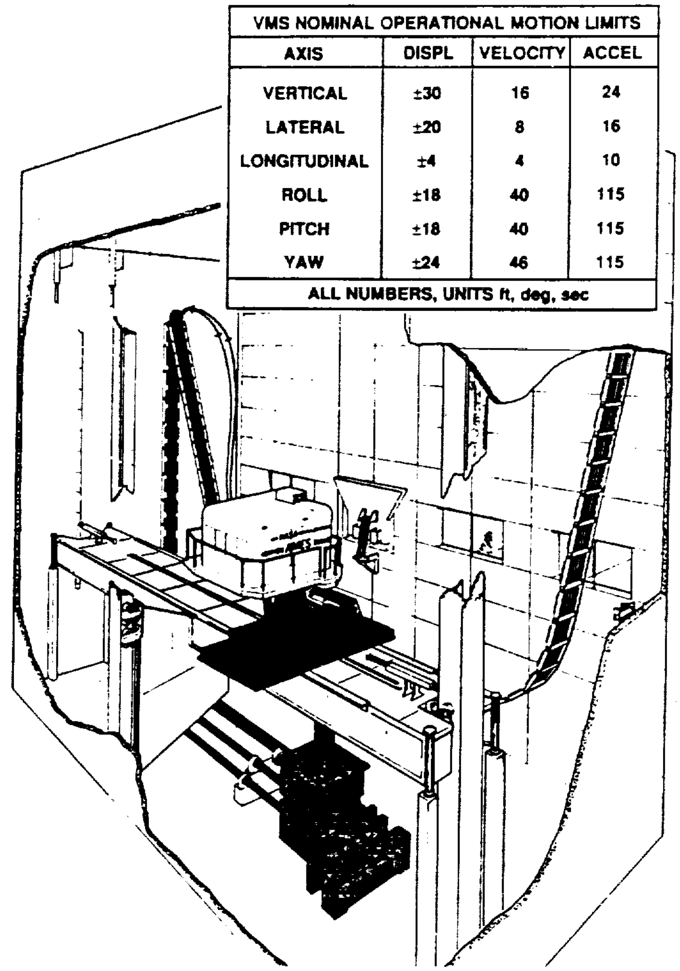


Figure 1. Comparison of HQR Ranges from Simulation and Flight for Landing (Ref. 1)



VMS NOMINAL OPERATIONAL MOTION LIMITS			
AXIS	DISPL	VELOCITY	ACCEL
VERTICAL	±30	16	24
LATERAL	±20	8	16
LONGITUDINAL	±4	4	10
ROLL	±18	40	115
PITCH	±18	40	115
YAW	±24	46	115
ALL NUMBERS, UNITS ft, deg, sec			

Figure 2. Vertical Motion Simulator

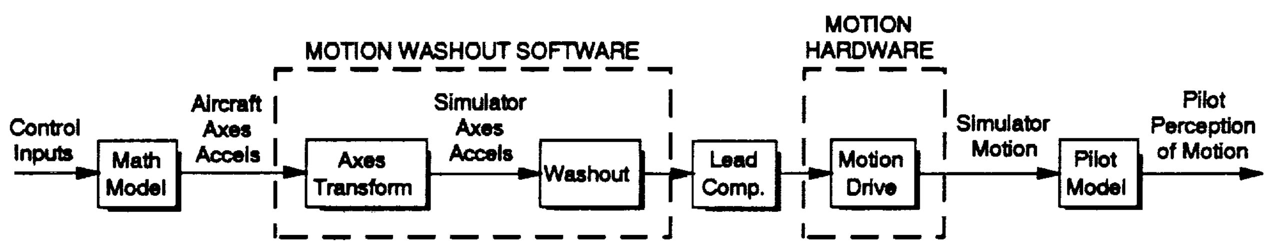


Figure 3. General Structure for the VMS Motion Response

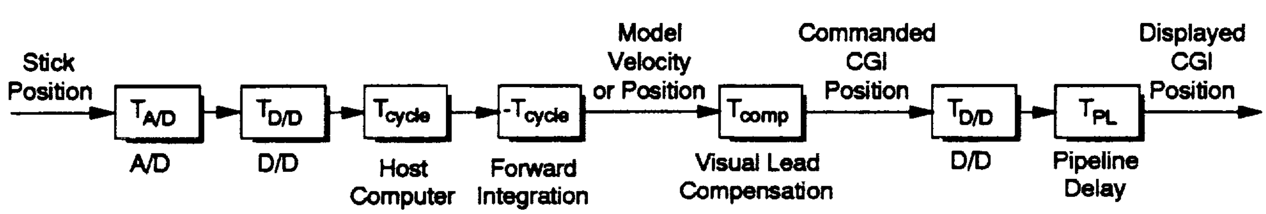


Figure 4. Stick-to-Visual Path Timing Diagram

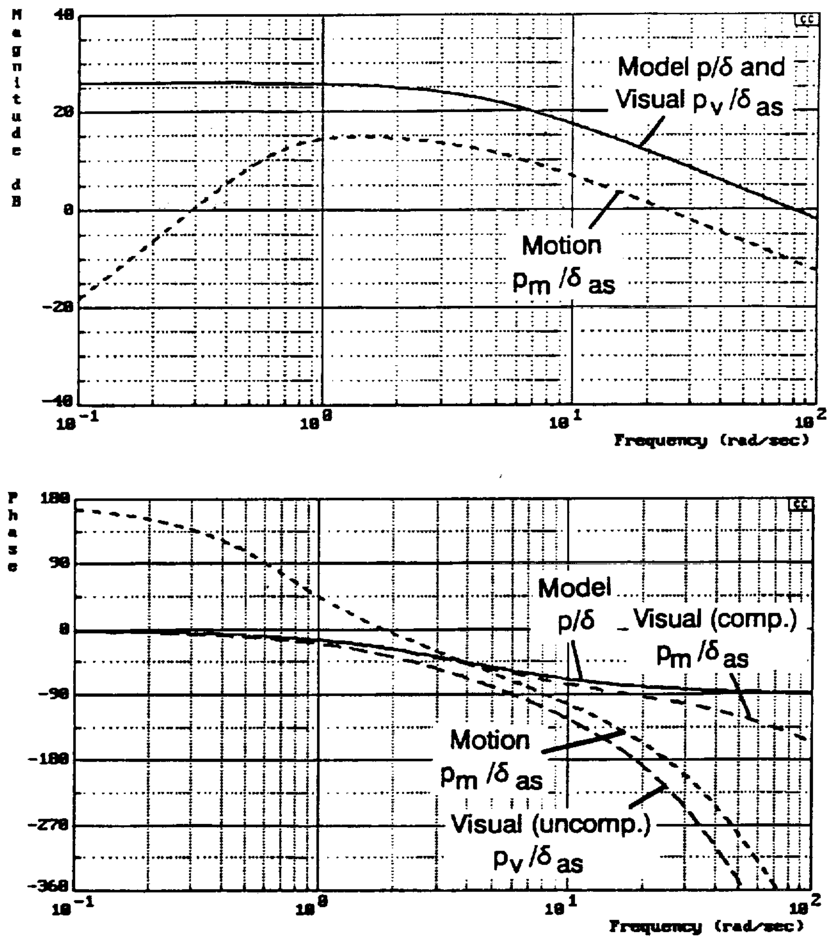


Figure 5. Frequency-Response Comparisons of Roll Rate to Control Input (Inputs are Measured Control Position, δ, and Cockpit Control Actuator Position, δ_{as}; Outputs are Roll Rate for Model, p, Visual Display, p_v, and Motion, p_m)

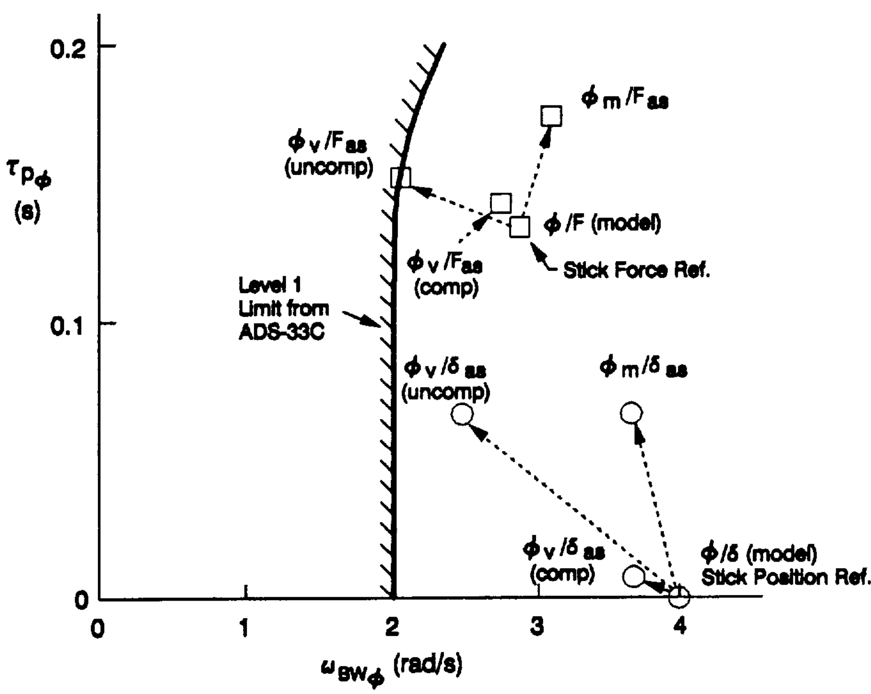


Figure 6. Migration of Bandwidth Parameters as Stick Force/Deflection, Visual, and Motion Effects are Introduced

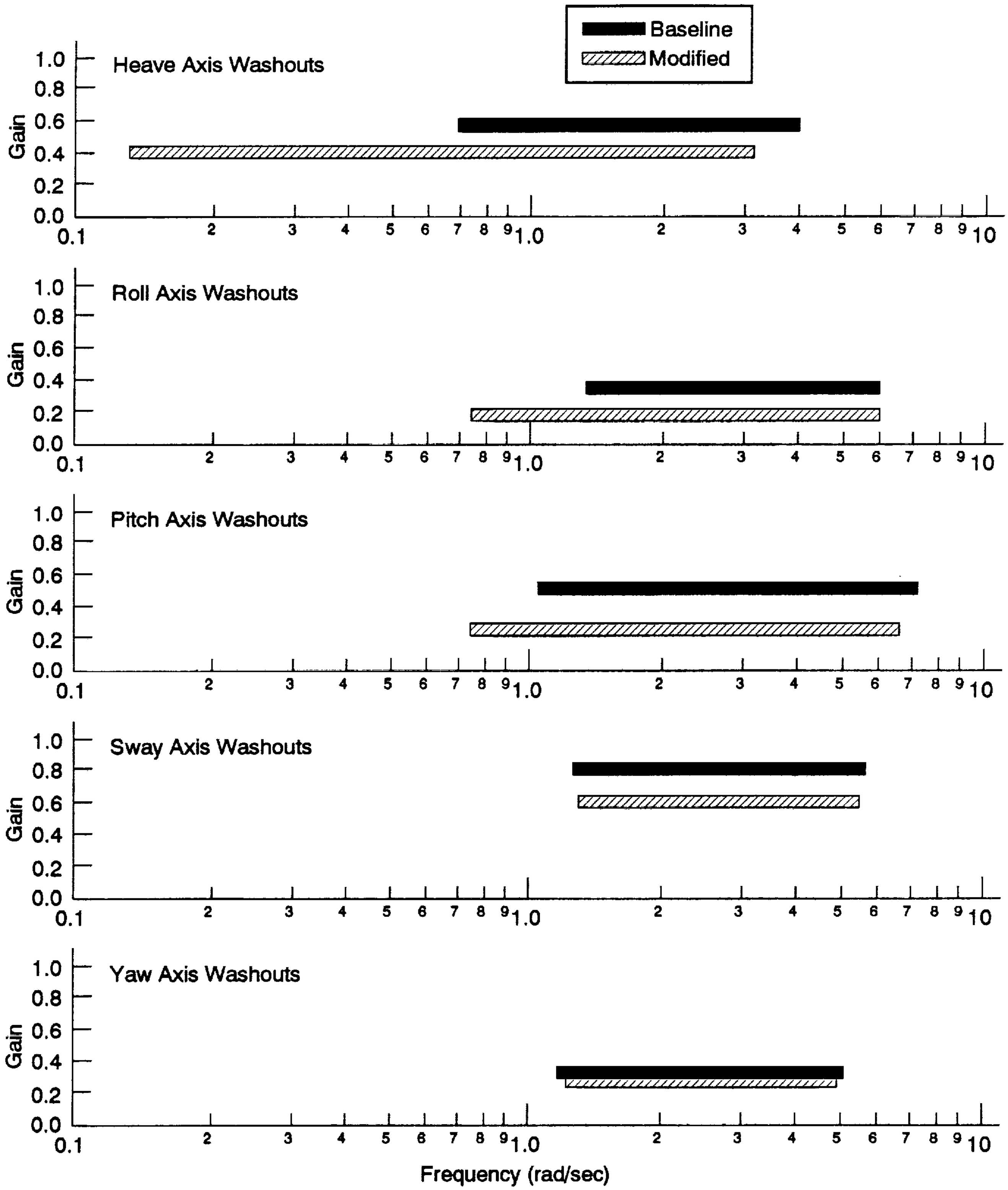


Figure 7. Frequency Range for Less than 30° Motion-to-Model Phase Distortion for Baseline and Modified Washout Configuration

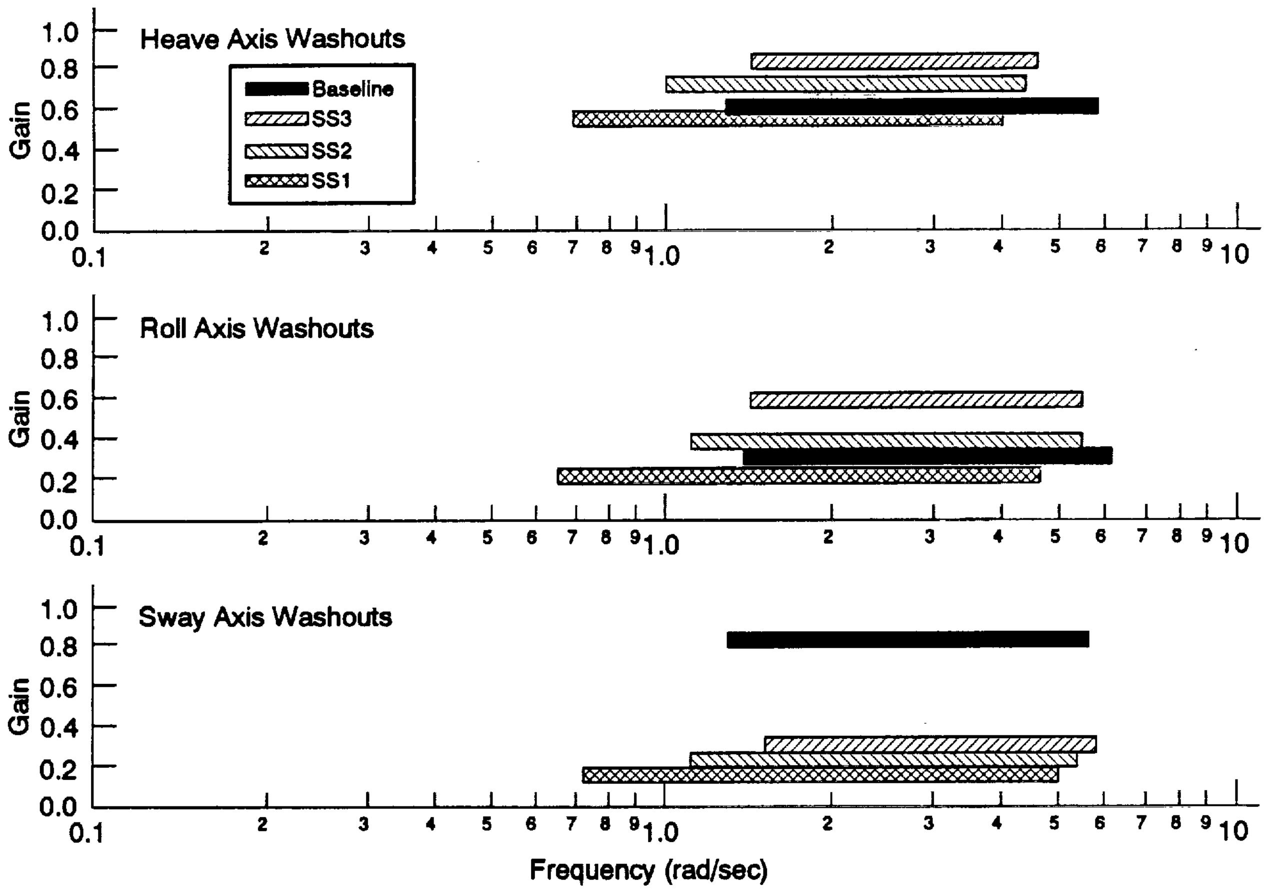


Figure 8. Frequency Range for Less than 30° Motion-to-Model Phase Distortion for Sidestep Washout Configurations

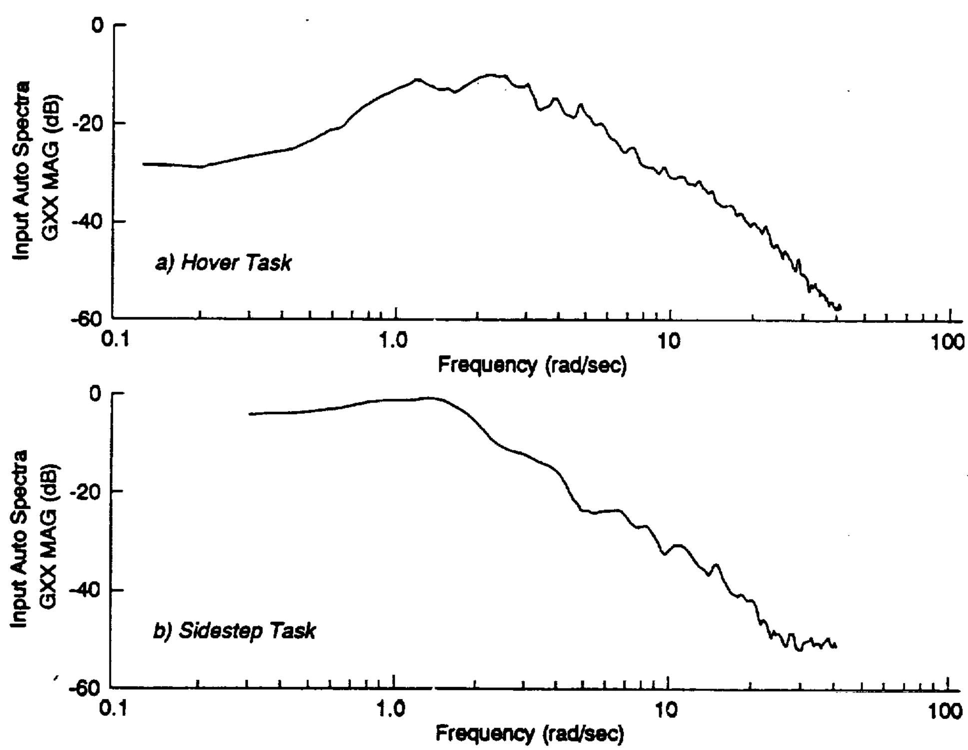


Figure 9. Lateral Stick Frequency Content (Pilot A)

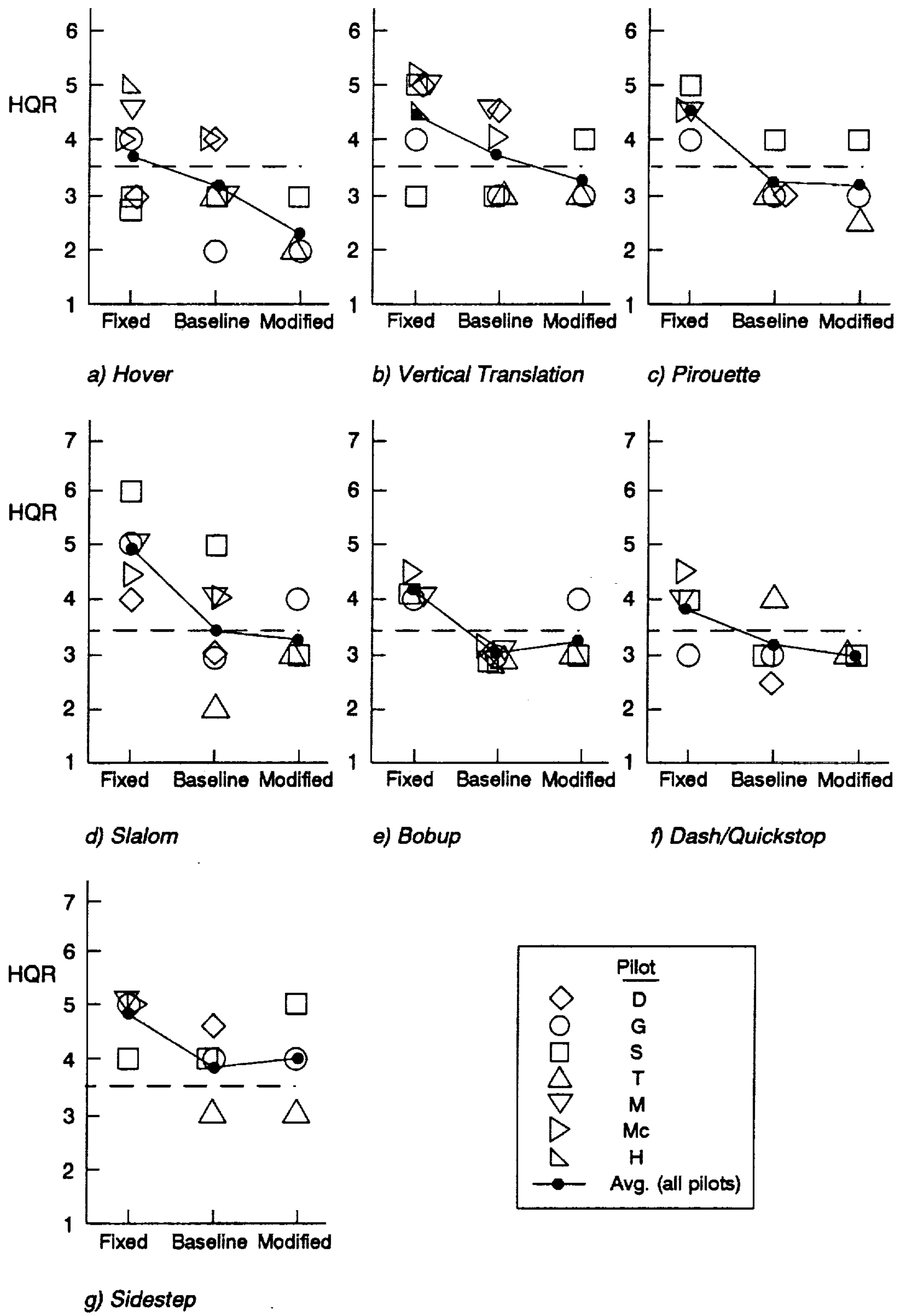


Figure 10. Effects of Task and Motion on HQRs from Simval I
(Baseline Motion, Visual Compensation On)

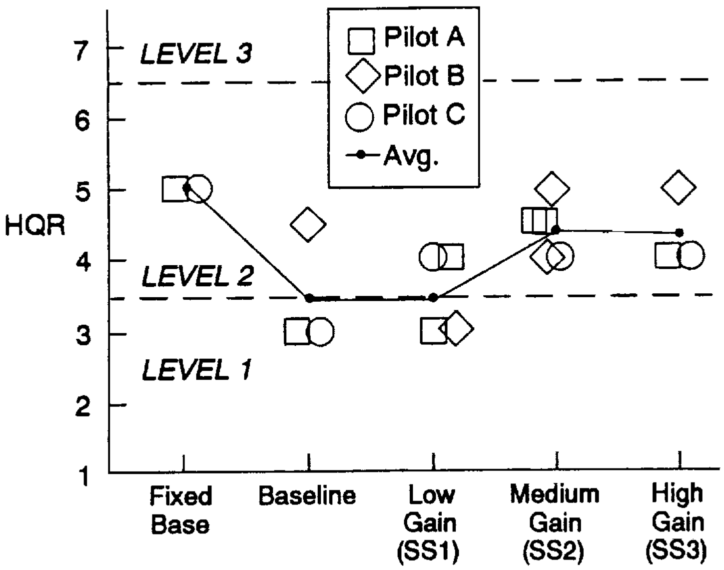


Figure 11. Pilot Ratings for Sidestep, Motion Variations from Simval II (Medium-Bandwidth Helicopter)

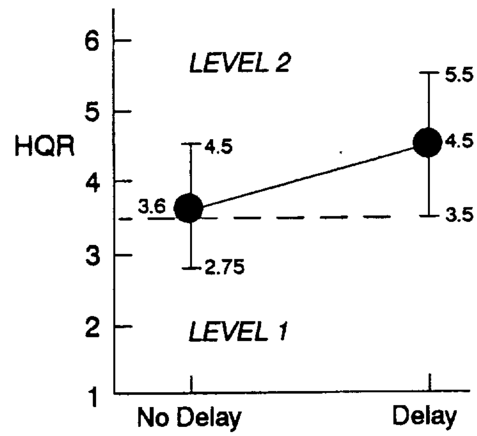


Figure 12. Effects of Visual Time Delay on Average HQR, Fixed Base

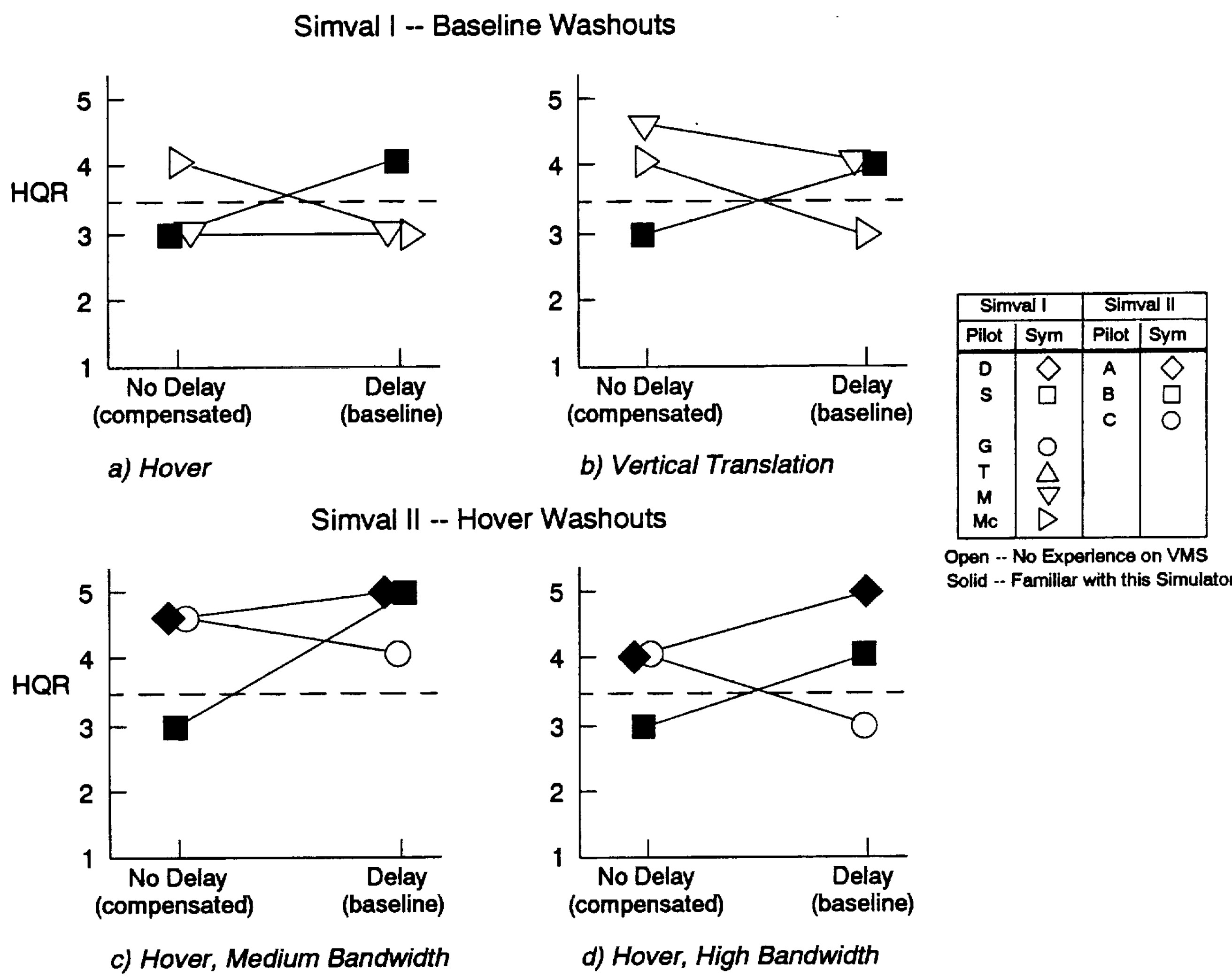


Figure 13. HQRs for Hover Task with Visual Delay Compensation (Moving Base)

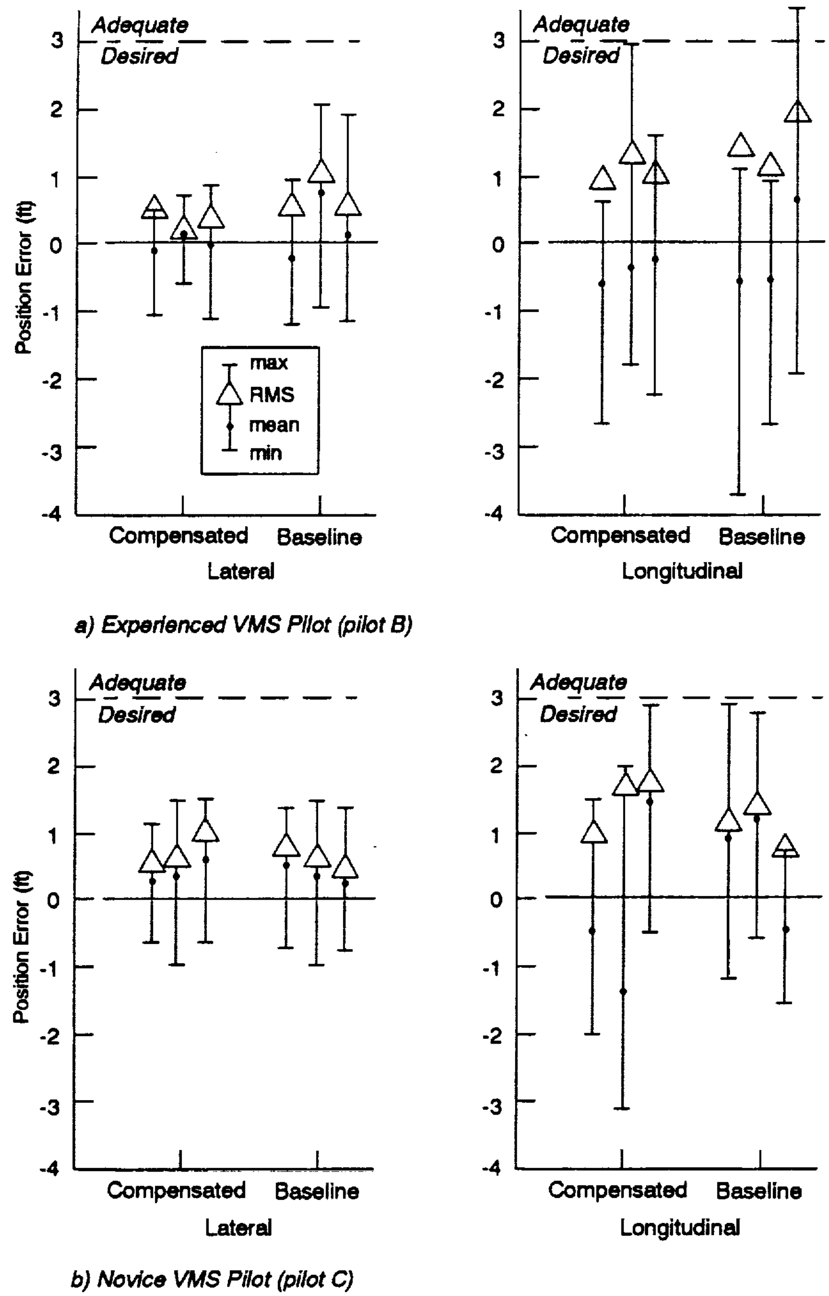


Figure 14. Hover Performance with Visual Delay Compensation On and Off for Experienced and Novice VMS Pilots (Simval II)

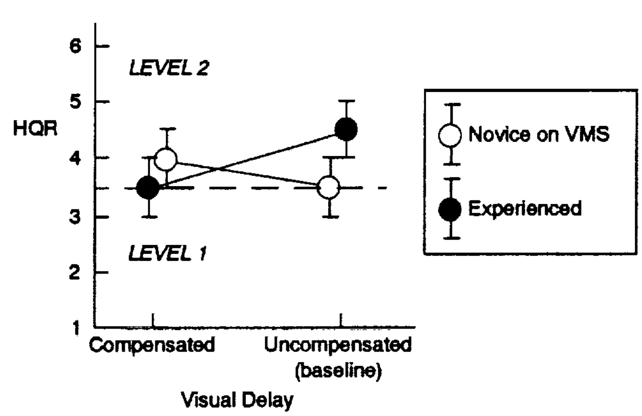


Figure 15. Effect of Visual Delay Compensation on HQRs for Experienced and Novice VMS Pilots

TABLE 1. EFFECTIVE TRANSPORT DELAY OF MOTION SYSTEM (INCLUDING MOTION LEAD COMPENSATION)

Axis	Delay (msec)	
	Simval I	Simval II
Pitch	70	91
Roll	70	88
Yaw	70	157
Surge	170	169
Sway	100	128
Heave	130	168

TABLE 2. SOURCES OF VISUAL TIME DELAY

Source	Delay (msec)	
	Simval I	Simval II
A/D (Stick measurement)	8	8
D/D	2	2
Host Computer (T_{cycle})	20	25
Forward Integration ($-T_{cycle}$)	-20	-25
Visual Lead (T_{comp})	variable	variable
D/D	2	2
Visual Transport Delay	83.3	62.5
Overall	95.3 - T_{comp}	74.5 - T_{comp}

TABLE 3. VALUES OF STICK-TO-VISUAL DELAY EVALUATED

	Simval I	Simval II
COMP ON	12	14.2
COMP OFF	95.3	74.5