NASA Technical Memorandum 86818

NASA-TM-86818 19860001741

Visual and Motion Cueing in Helicopter Simulation

Richard S. Bray

September 1985

National Aeronautics and
Space Administration

NASA Technical Memorandum 86818

Visual and Motion Cueing in Helicopter Simulation

Richard S Bray, Ames Research Center, Moffett Field, California

September 1985

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field California 94035

N86-11208 #

VISUAL AND MOTION CUEING IN HELICOPTER SIMULATION

Richard S. Bray

NASA Ames Research Center
Moffett Field, California 94035, U S.A.

SUMMARY

For the past decade, helicopter handling qualities have been the subject of piloted-simulator programs at Ames Research Center. Early experience in fixed-cockpit simulators, with limited field of view, demonstrated the basic difficulties of simulating helicopter flight at the level of subjective fidelity required for confident evaluation of vehicle characteristics More recent programs, utilizing large-amplitude cockpit motion and a multiwindow visual-simulation system have received a much higher degree of pilot acceptance. However, none of these simulations has presented critical visual-flight tasks that have been accepted by the pilots as the full equivalent of flight. In this paper, the visual cues presented in the simulator are compared with those of flight in an attempt to identify deficiencies that contribute significantly to these assessments. It is suggested that a non-optimum distribution of field-of-view elements, coupled with a severe lack of near-field detail, compromises the pilot's sensing of translational rates relative to nearby terrain or the landing surface. For the low-amplitude maneuvering tasks normally associated with the hover mode, the unique motion capabilities of the Vertical Motion Simulator (VMS) at Ames Research Center permit nearly a full representation of vehicle motion Especially appreciated in these tasks are the vertical-acceleration responses to collective control For larger-amplitude maneuvering, motion fidelity must suffer diminution through direct attenuation or through high-pass filtering "washout" of the computer cockpit accelerations or both. Experiments were conducted in an attempt to determine the effects of these distortions on pilot performance of height-control tasks. Results revealed that in holding position in the presence of vertical disturbances, pilot control-gain and resultant open-loop crossover frequency were significantly depressed as the fidelity of vertical motion was reduced. In height tracking of a moving reference, gain and crossover were not greatly affected, but phase margin and tracking performance improved with motion fidelity. Pilot-opinion ratings of varied vehicle vertical-response characteristics were significantly modified by changes in motion-cue fidelity.

INTRODUCTION

Subjective fidelity, or a sense of realism, in the flight simulator is essential to productive use in research or training Depending on the nature of the simulated flight task and the objectives of its use, varying degrees of objective, or engineering, similarity to the flight situation are required to create that realism. With effort, verified dynamic mathematical models of flight vehicles can be realized, and cockpit displays and controls can be duplicated. In two important areas of aircraft-state feedback to the pilot, however, the ground-based simulator usually fails to achieve a high level of objective fidelity. These are, of course, the representation of the scene outside the aircraft, and cockpit motion. The effects of these deficiencies, that is, their individual contributions to the diminution of subjective fidelity, are not clearly understood.

The experience at Ames Research Center has made it obvious that the subjective fidelity of helicopter simulation is especially sensitive to visual- and motion-cueing deficiencies. This sensitivity should not be unexpected in light of the experience with conventional aircraft simulation which has shown a tendency to produce exaggerated handling-qualities difficulties in simulations of vehicles with reduced stability, high control sensitivities, and cross-axes control coupling. Even the best helicopters tend to fit that description. Helicopters add a challenge to simulation technology because of the kinds of critical flight tasks they require in research evaluations and training. In recent programs, attempts have been made to simulate autorotation landing, landing aboard ship in adverse conditions of wind and sea-state, and helicopter air combat close to the terrain.

The primary simulation facility at Ames Research Center, the Vertical Motion Simulator (VMS), can provide unusual fidelity of cockpit motion in the low-amplitude maneuvers associated with hover and landing However, it is in this flight regime that visual-cueing capabilities are critical. The rapid growth of computer-graphics technology is providing the simulation community with visual-simulation systems that are much more capable than that which is the subject of discussion in this paper. On the other hand, it is unlikely that many motion systems as large as the VMS will be constructed. This review of recent simulation experience at Ames has two objectives (1) to formulate recommendations regarding the application of new visual simulation capabilities, and (2) to increase the understanding of the role of cockpit motion cues and the penalties that might be experienced by their absence or distortion. The Ames simulation capabilities are described, and the subjective assessment of the fidelity of recent helicopter simulations is discussed. A review of apparent limitations of the visual-cueing system is followed by the presentation of the results of tests that examined the relationship between vertical-motion fidelity and performance in height-control tasks. An assessment of helicopter simulation technology at Ames Research Center in 1982 is included in Ref. 1. This present paper can be considered an update of that report.

THE SIMULATION FACILITY

Flight simulation has been a research activity at Ames Research Center for the past 30 years, and for the past 20 years Ames has operated visual simulation and large-amplitude cockpit-motion devices.

However, when helicopter research became a simulation objective nearly a decade ago, it became obvious that facilities then useful for simulating conventional aircraft were poorly configured for use in studies of rotary-wing handling qualities The advent of the VMS in 1982 effected a reduction in these constraints. Since the discussions in this paper are for the most part related to experience with the VMS facility, its characteristics will be described in some detail

The VMS includes four reconfigurable cockpits, or cabs, that can be operated in a fixed mode or mounted on the large-ampltiude VMS motion system. The cabs include various arrangements of collimated video monitors for presentation of simulated visual scenes generated by a Single-Link DIG I computer-graphics system. The interior of one of the cabs, configured for helicopter simulation, is illustrated in Fig 1 The three primary windows are of the conventional 46° by 34° format, and the lower "chin" window is 24° by 34°

A cab is shown mounted on the motion system in Fig. 2. The cab is driven in rotational motions by a small, six-hydraulic-actuator "synergistic" device. This is mounted on a horizontally driven carriage with 12 m of travel along a beam which in turn can be moved vertically in a 17-m envelope. The second horizontal motion is limited to that which can be provided by the six-post system (about 1 m). However, alternative orientations of the cab allow either fore-and-aft or lateral motion to be represented by the large-amplitude horizontal drive Specifications for the visual and motion systems are given in Table 1.

SIMULATION FIDELITY ASSESSMENTS

Before the VMS was available, helicopter simulation was often conducted in a fixed cockpit, with a single-window, forward field of view generated by a TV-model-board system. In comparison, the capabilities of the VMS provide a marked improvement in the subjective fidelity of helicopter simulation. The four-window visual system obviously constitutes a primary contribution, at least according to pilot comments, also, it permits the simulation of flight tasks that are not practical with only a single forward window But in the same period, the dynamic models have improved in quality through more concerted efforts at verification, and cockpit motion is now included in all simulation programs addressing handling-qualities issues. This progress has produced the following advancements. (1) the time required for a pilot's performance in an unfamiliar vehicle and task to reach a plateau is shorter, (2) maneuver amplitudes and control "style" compare more favorably with those of flight, (3) there is less variation in performance and assessment across a group of pilots; and (4) ratings and commentary regarding handling qualities appear to be offered with greater confidence

But pilot criticism of simulation did not disappear with the advent of the VMS. Complaints of motion roughness and noise, occasional occurrences of "simulator sickness" brought on by poorly configured motion, and references to "lack of depth perception" are still with us, although they are not the barriers to successful research that they were in earlier days. We are left with more subtle questions, however, discrepancies that are obvious only when opportunities are presented to compare directly flight and simulator experiences. Then, the most critical tasks are frequently judged to be more difficult in the simulator than in flight In recent VMS operations, some degree of flight-simulator comparison was seen for five aircraft the XV-15 Tilt Rotor Research Aircraft, the H-60 Blackhawk, the SH-2 LAMPS helicopter, the SH-60 Seahawk, and the Harrier VTOL fighter Reference 2 addresses the XV-15 simulation experience, which spanned nearly the full decade of Ames helicopter simulation history. The most recent simulation, in the VMS, was assessed as a very good reproduction of the aircraft, though visual-system time delays were suspected in some instances of low augmentation-off stability. In the case of the XV-15, the simulation capabilities were not stressed with complex flight tasks, instead, the simulation was flown with some of the conservatism seen in flight tests. The Blackhawk simulation was conducted with the specific objective of fidelity assessment, it was coordinated with flight tests to obtain aircraft-describing data for model verification, as well as to obtain pilot assessments of the aircraft in maneuvers duplicated in the simulator. In Ref. 3, it is reported that the pilots perceived the simulated aircraft to have generally poorer handling qualities than the aircraft it represented. In light of what was considered to be positive model verification the cueing systems were questioned The other three simulations featured the task of shipboard landing in adverse sea-states for evaluations of control augmentation and displays. The SH-2 (Ref. 4) and SH-60 simulations received generally good marks except for an apparent exaggeration of task difficulty near touchdown, especially in higher wind conditions. There is some reason to suspect the turbulence model and the modeling of the aircraft's response to it, but it is probable that visual-cueing deficiencies were also a source of the difficulty. The most common observation by the pilots was an unrealistically high work load in nulling translational velocities in hover before touchdown. In particular, the perception of the onset of horizontal velocities appeared to be delayed

Although these simulations are considered to be effective, the failure to achieve the desired level of subjective fidelity creates the discomforting obligation to qualify the experimental results. Remaining deficiencies must be accurately defined so that improvements can be made. Pilot commentary has not been particularly helpful in identifying sources of cue deficiency pilots rarely verbalize clearly regarding deficiencies in motion or visual cues unless the problem exhibits itself as an obvious and distracting artifact. A pilot is probably no more practiced at analyzing his use of visual and motion feedback than is the average automobile driver. What will be attempted here is an examination of the limitation of our cueing devices when applied to simulations of typical helicopter flight tasks, and some reasoned speculation about how these constraints might be limiting the fidelity of the simulations. In the following sections, field-of-view issues and, to a lesser extent, the limitations in scene detail are discussed. The fidelity of VMS cockpit motion cues is examined, and some experimental evidence regarding the effects of vertical-motion-cue distortion on handling-qualities evaluations and on pilot-control bandwidth is offered.

VISUAL-SIMULATION FIDELITY

Field of View

In comparison with the single-forward-window scene provided by the TV-model-board system, the four computer-generated-image (CGI) scenes seemed at first to answer all the requirements for visual simulations in critical helicopter flight tasks. But with the simulation of shipboard landing, nap-of-the-Earth (NOE) operations, and autorotation came the reminder that even those four windows, at least as they are configured in the VMS, fall short of providing the visual information available in flight. Simulator fields of view are compared with those of an OH-58 helicopter in Figs. 3 through 6.

A representation of the pilot's view from the OH-58 at hover is shown in Fig. 3a. A wide-angle photograph (120° by 96°) of the Ames ramp area, from a height of 35 ft, is masked to present a single-eye-point field-of-view. Even this wide-angle scene does not include all of the potentially valuable viewing area of the helicopter, notably that to the right and down through the side door. At 15° nose-up (Fig. 3b), the view of the ramp ahead is relatively unrestricted For comparison, the same scene is shown through the four-window viewing area of a VMS cab in Fig. 4. (The other available window arrangement has a larger lower-right window, but there are wider gaps between the center, upper-right, and lower-right windows.) In hover (Fig 4a), a gratifying scope of visual information is included. However, in precision hover to touchdown, expecially on the small landing surfaces of ships or drilling-rigs, a sense of visual-field limitation is experienced with this configuration. Even in a runway depiction, visual work load seems high. Deficiencies in scene detail, discussed in the next section, may be the major part of this problem, but is we speculate on the location of the high-priority viewing areas, and recognize the somewhat conflicting visual-cueing needs for attitude and position control, the argument can be made that the viewing area provided by the four windows is poorly distributed

Visual information vital to control of velocities and position during hovering approach to touchdown is contained in the relatively near-field, that is, at least 20° to 30° below the horizon, however, sustained fixation at depressed viewing angles tends to interfere with attitude (translational acceleration) control. In the absence of definitive measures, it is hypothesized that in this maneuver the pilot directs his view 6° to 10° below the horizontal while roughly positioning his aircraft. Nearer touchdown, the landing surface, which is much closer to the aircraft (30° to 50° down), must be viewed foveally, at least intermittently, for precise positioning. Referring to Fig 3a, it is seen that such a scanning procedure in the aircraft, from far- to near-field, can be conducted in an uninterrupted scene, with the middle-distance field (from 15° to 25° down) always in either foveal or near-peripheral view In contrast, the same angular scan in the VMS, from the forward window to the lower-right window, has nearly a 20° scene interruption. Cues from the middle-distance field are essentially absent This absence may be a serious detriment to visual perception of aircraft motion. To obtain precise positioning information from the lower window, it is necessary to forego any far- or middle-distance cues to fixate momentarily at a highly depressed viewing angle. In the absence of associated peripheral middle-distance information, any perspective dynamics presented in the lower picture may lose much of their value. At the deceleration attitude (Fig. 4b), all meaningful information appears isolated in the lower window. In comparison with the view from the OH-58, it can be seen that there has been a severe diminution of visual information.

The VMS window arrangement is not the result of serious study of pilot-viewing requirements, instead, it is the result of concessions to the hardware geometry problems inherent in the mirror- beam-splitter collimators used to present the scenes. A window arrangement that will be available in the very near future will combine three of the windows in the joined configuration illustrated in Fig. 5. This total scene preserves continuity from the horizon to the nearest point-of-regard, which is depressed nearly 45°. The configuration shown, being symmetrical, is most appropriate to a single-place or two-place (tandem) aircraft, but the attributed virtues would still be realized if the left window were raised in simulation of a side-by-side cockpit The field of view that will be available to the VMS complex in 1987 is shown in Fig 6 Three edge-matched 40° by 60° scenes, generated by a Rediffusion CT5A system, will be projected inside a 6-m-diam dome In addition to the symmetrical location shown, the total field may be displaced vertically and laterally, and eventually may be head-position slaved.

Scene Detail

A real-world runway scene (Fig. 7a) is offered for comparison with a simulated version in the VMS (Fig 7b). In the flight photograph, the wealth of detail and contrasts is limited only by photographic resolution, whether in the near-field or in the far-field. In the computer-generated scene, there is no additional detail to discover, no finer textures to be seen than are apparent in the far-field 1,000 ft away. Detail that was quite acceptable at a distance becomes inadequate to define the surface at close range. The illustrated scene does not use the full capability of the generating system. A more recently modeled runway has at least twice the density of detail, but increases measured by orders of magnitude are required. An example of the significance of low scene-detail density is seen in the lower window (Fig 7b) The threshold stripes seen in this view represent one of the finer levels of detail in the total scene, but no cues of fore-and-aft motion are available The scene of the approach to a ship (Fig. 5a) might be assessed as very adequate for that phase of the landing maneuver, but near touchdown (Fig. 5b), there is negligible definition of the deck surface in the near-field. It has taken a long time for those working in the simulation field to recognize the magnitude of the visual-cueing diminution that is being incurred in this this low-hover situation. The pilot must compensate for the loss of near-field detail by concentrating on the more distant perspective, thereby suffering a loss in his perception of the low translational rates typical of the precision hover maneuver In the VMS window arrangements used to date, this compensation is made difficult by the vertical separation of the viewing areas.

Density of scene detail, or "spatial frequency," in visual simulation has been a subject of attention for some time, but primarily in regard to low-altitude, high-speed flight and other tactical maneuvers The literature contains suggestions for acceptable minimums of spatial frequency (visible contrasts per degree of visual field) that vary from 0 05 to 3 (The deck surface represented in Fig 5b might be assigned the value of 0 1.) For high-quality simulation of the hovering task, it is probable that values considerably less than 3 will suffice, and considering the cost of providing detail and texture in computer-generated scenes, experimental determination of the relationship between spatial frequency and simulation fidelity for critical research and training maneuvers should be given strong encouragement. Flight tests in which means to degrade the density of detail in the real visual scene were used, have demonstrated the detrimental effects of reduced scene detail, but the validity of extrapolating those results to computer-generated scenes can still be questioned at the present state of development of the technique. These experiments are discussed in Ref. 5.

This discussion of scene-detail limitations is based on the CGI system at Ames and others of its generation. Recently marketed systems have greater capacity for detail and can provide "texturing" of selected surfaces. It is hoped that these capabilities will be put to use immediately in pursuit of answers to the question of minimum scene-detail requirements.

Visual Time Delays

Computer graphics scene-generation systems require a finite interval in which to compute the scene elements. The total delay in the simulated scene, which can also include elements introduced by various simulator-system interfaces, can be an important fidelity issue This delay, added to that in the aircraft dynamics computation, must be considered, especially when aircraft-control modes exhibit high sensitivity and low damping. This time delay, assessed to be about 100 msec in the VMS, has yet to be firmly identified as a major problem in helicopter simulations, but it has been suspected in several cases in which high-frequency dynamic instabilities seemed exaggerated. As noted previously, this was seen in the XV-15 simulation. VMS tests of a linear lead-lag time-delay compensation method are reported in Ref. 6. A nonlinear delay-compensation method, currently being evaluated, is described in Ref 7

COCKPIT MOTION FIDELITY

As was seen in the comparison of fields of view of the simulator and in flight, the relationship of simulator cockpit motion to that of the aircraft can be explicitly defined, for motion, that relationship is described by the drive logic and by the dynamic performance of the motion system. Beyond these measures, the similarities between the two cueing modes ends. A list of measures is required to describe fully the contents of the visual scene, motion needs no further description. The visual scene defines the important elements of the pilot's tasks, cockpit motion is an adjunct, not normally a requirement for completing a simulated flight task Intelligently configured simulator cockpit motion, even of very limited amplitude, most often improves the subjective fidelity assessments (and emphasis must be placed on "intelligently configured"). Unfortunately, explicit definitions of "valuable" motion fidelity, for specific research or training objectives, remain for the most part undetermined. In the following paragraphs, the relationships between aircraft and VMS motions are described, and in the following section some experiments aimed at defining the contribution of cockpit vertical motion fidelity are discussed

The VMS Motion Logic, or "Washout"

The VMS cockpit motion system has an exceptionally large excursion capability in its two translational modes, but the approach to its utilization is similar to that used in much smaller motion systems. The computed motions of the modeled aircfaft cockpit are high-pass filtered, and sometimes directly attenuated, in order to be accommodated by the simulator motion system. Though virtues may remain to be demonstrated in the use of nonlinear filters, for reasons of simplicity and operational flexibility the VMS constraint logic, within "hard" logic defined by acceleration, velocity, and position limits of the machine, is basically linear. Rotational and linear accelerations computed for the cockpit are modified for representation in the simulator by the following general relationship

$$\frac{\text{simulator acceleration}}{\text{aircraft acceleration}} = \frac{GS^2}{S^2 + 1.4\omega S + \omega^2}$$

where ω is the characteristic frequency of the high-pass filter, S is the Laplace operator, and G is the high-frequency gain.

The motion-constraint logic is shown in some detail in Fig. 8, with supporting definitions given in Table 2 Body-axis rotational rates are transformed (approximately) to simulator coordinates, and pilot-sensed linear accelerations are manipulated to define the six primary inputs to the motion-constraint logic. (The VMS is usually considered to be a five-degree-of-freedom system, but a very limited sixth degree can be realized by driving the six-actuator hydraulic system in a linear mode.) The cab can be tilted to provide low-frequency and steady-state representations of longitudinal and lateral accelerations. What might appear to be awkward and imprecise aspects of this motion-logic implementation exist primarily for reasons of operational flexibility, simplicity, and the desire to accommodate acceleration, velocity, and position-limiting logic within the high-pass filters associated with the two large-amplitude linear drives. All of the gains (the G terms) and the filter frequencies are readily accessible variables, and are set to optimize the motion "recovery" for the particular task being simulated. Two sets of these variables (designated F and S versions) are defined in the motion-logic program, thus, a simulated task that comprises both a segment of large-amplitude maneuvering at high speed and a segment of low-amplitude, maneuvering at low speed can be accommodated by relating the variable sets to specific speed regimes and interpolating for speeds in between these ranges. Example sets of gain and frequency values suitable for a speed range from hover to cruise flight, involving typical handling-qualities assessment maneuvers, are presented in Table 2.

Fidelity of Vertical Motion

The experiments discussed in the following section deal almost entirely with height-control tasks Only the fidelity of the vertical motion mode of the VMS is discussed in detail. Being essentially uncoupled with other drive modes, simulator vertical acceleration can be completely described by the basic second-order washout transfer function together with a transfer function approximating the frequency response of the electrical vertical drive system. Together, they define the relation

$$\frac{\text{simulator acceleration}}{\text{aircraft acceleration}} = \frac{GZS^2}{S^2 + 1.4\omega_z S + \omega_z^2} \; \frac{12^2}{S^2 + 9.6S + 12^2}$$

The gain and phase variations with frequency represented by this combination of linear transfer functions, for three values of ω_z, are illustrated in Fig. 9. The values of ω_z were used as test points in the height-control experiments discussed later. In the cases shown, GZ was held at unity. Of course, greater constraint of the simulator motion is effected by increasing values of ω_z and decreasing GZ. The lowest value of ω_z shown, 0.2, is commonly used in the VMS during simulation of hover tasks near the ground or landing pad. The value of 0.5 is used, often with a reduction in GZ, to accommodate the maneuvers of up-and-away flight The highest value is an example of the constraint that might be required in a typical training simulator motion system, again with some reduction in GZ.

If it is somewhat arbitrarily assumed that motion phase distortion up to 20° (lead or lag) is representative of "high fidelity" motion, it is seen that for $\omega_z = 0.2$, a frequency range from 0.7 to 5.0 rad/sec is so described. This constitutes a major portion of the short-period maneuvering frequency range. At $\omega_z = 0.5$, the band of fidelity is constrained to frequencies above 1.5 rad/sec, thus still including important maneuver frequencies The increase of ω_z to 1.25 results in severe phase lead throughout most of the normal maneuvering range. As in any frequency-related motion-constraint system, a band of highly distorted motion about the characteristic frequency must be tolerated.

VERTICAL MOTION-CUE EXPERIMENTS

Effects of Motion-Cue Fidelity on Handling-Qualities Assessments

In conjunction with a general fidelity assessment of the XV-15 Tilt Rotor Aircraft simulation at Ames, a brief experiment was conducted to determine the effects of vertical motion on pilot assessments of height-control handling qualities. The test conditions consisted of a matrix of three values of ω_z and variations in gain and delays of the aircraft response to collective-control inputs. The pilot task was a series of NOE maneuvers, including terrain-following and a bob-up to visual contact with a target. Four pilots were requested to give Cooper-Harper (Ref. 8) pilot-opinion ratings for each combination of aircraft and motion in a blind series of exposures. The results, averaged for the four pilots, are presented in Fig. 10. It is seen that the assessment of the unmodified aircraft (circle symbols), considered to have good response characteristics, was affected only slightly by the reduction in motion cues. However, degradations of the control system that added less than one and one half rating numbers with high-fidelity motion resulted in nearly twice that variation when motion was tightly constrained. Assessments were consistent across the pilot evaluators, as indicated by the modest range of ratings for each condition (Fig. 10). Spot evaluations with no vertical motion at all produced ratings similar to those for the most constrained motion. It was apparent that visual-motion discrepancies were not intellectually considered in the course of the tests, control difficulties were always attributed to poor collective response and to "reduced heave damping."

Effects on Pilot Response in Height-Control Tasks

Subsequent to the XV-15 handling-qualities assessments, a variety of height-control tasks were mechanized in the VMS with the objective of determining the effects of vertical-motion-cue fidelity on pilot-response characteristics and task performance.

Vehicle simulation - The simulation of a very simple hovering vehicle was mechanized for these experiments. It included no aerodynamic forces of significance, other than vertical rate damping, at hovering translational velocities. Moments and vertical forces resulting from controller inputs and rate damping were completely uncoupled. Vehicle derivatives and controller characteristics are listed in Table 3 for two vehicle configurations intended to represent good and slightly degraded vertical response. For most tests, the pilot's station was located at the center of gravity of the vehicle. The lifting force acted through the center of gravity normal to the aircraft's longitudinal and lateral reference axes. Attitude control was effected with conventional stick and rudder pedals Total stick deflection, longitudinally and laterally, was approximately 23 cm, with force gradients of 0 3 kg/cm. Vertical control employed a left-hand "collective" level configured for a specific aircraft development program It was approximately 30 cm in length from grip top to its rotation point. Full travel of the lever was from horizontal (no lift) to 45° up (maximum lift). In steady hover, the lever was elevated about 30°. The controller employed light friction forces and no force-deflection gradient

Tasks and data collection - Two tasks were presented in the initial tests. In the first, using a visual-scene representation of a hovering aircraft as a height reference, the pilot attempted to hold altitude against a pseudoramdon vertical-acceleration disturbance imposed on his own aircraft. The disturbance was effected by adding the sum-of-sines function defined in Table 3 to the pilot's collective input signal. The forward-window scene during this task is shown in Fig. 11a. For the second task, the "target" aircraft, instead of the pilot's aircraft, was disturbed vertically by a similar sum-of-sines function, and the pilot maneuvered to maintain a fixed relative position. Further exploration of the visual-motion-cue relationship was conducted in a height-holding task, again against disturbances of the pilot's own aircraft, at various altitudes near the end of a conventional runway and in the absence of any other height references. The front-window scene for this task is illustrated in the photograph of Fig 11b. In all of these tasks, the pilot was asked to attempt to hold a fixed position laterally and longitudinally. In each run, 85 sec of pilot performance was recorded after a 20-sec warm-up period.

All pertinent vehicle states and inputs were recorded, together with position errors and error-rates An on-line dynamics analysis program was employed to produce a "pilot describing function," a linear representation of pilot-input gain and phase in response to aircraft height-error rate. These data were combined with the vehicle vertical-rate response to pilot input to define the open-loop characteristics of the tasks. The frequency at which open-loop gain approaches unity, the "crossover frequency," is considered a measure of the control bandwidth being exercised by the pilot, and the "phase margin" (phase + 180°) an indication of the level of stability being experienced. The effects of vertical-motion fidelity on these measures is the primary subject of the following discussions.

Results and discussion- Example open-loop characteristics documented for one pilot-and-aircraft combination in the tasks of height-holding with respect to another aircraft, for two levels of cockpit vertical-motion fidelity, are shown in Fig. 12. The data of Fig. 12a represent performance in the task of maintaining position relative to a stationary target against a pseudorandom vertical acceleration disturbance with components between 0.5 and 5.0 rad/sec. A crossover frequency of over 3 rad/sec was demonstrated, which might be considered a high value for height regulation. The pilot was exercising a maximum level of aggressiveness, as indicated by the phase margin at crossover of about 20° In this case, the visually perceived height errors are the second integration of the computed cockpit acceleration. For the case of high motion fidelity ($\omega_z = 0.2$), this acceleration is sensed by the pilot with minimum distortion, providing him valid lead information on the height and height-rate errors he will perceive visually. The slope of the amplitude-ratio variation with frequency, for the range of frequencies shown, approximates that of the aircraft vertical-rate response to collective-control input, indicating that the pilot gain response relative to vertical rate was essentially constant. This was generally true for all of the pilots and tasks in these experiments.

With the highly constrained motion ($\omega_z = 1.25$), good correlation of visually perceived rates and simulator acceleration is present only at frequencies above 2.5 rad/sec This reduction in motion cues results in a decrease of open-loop amplitude ratio (reflecting the same drop in pilot gain) of more than 3 dB, resulting in a crossover frequency of slightly more than 2 rad/sec. Again the pilot was operating on the edge of instability.

For the task of Fig. 12b, holding position relative to a randomly moving target, the variation in cockpit motion fidelity shows a different result. Pilot gain in both cases of motion fidelity is low, and the crossover frequencies for both conditions of motion are about 1.7 rad/sec. However, a marked difference is seen in the phase measured between 1 and 2 rad/sec. The phase lag of pilot response is reduced more than 30° by the increase in motion fidelity, with an increase of stability of control that is obvious to the pilot. It is this case that is most comparable to the handling-qualities evaluation task discussed in the previous section, where no disturbances were imposed on the pilot's aircraft. The higher-frequency components of the target-acceleration disturbance produce quite small rates and displacements that at the 50-m distance are not easily perceived visually. Perhaps this tends to inhibit the control bandwidth exercised by the pilot.

Crossover characteristics for the same pilot and tasks, with both aircraft configurations, are summarized in Fig. 13. The introduction of data for $\omega_z = 0.5$ reveals a systematic reduction in crossover frequency for the disturbance task and in phase margin for the following task, with increase in ω_z. As might be expected, the more lagged response of the second aircraft configuration produced lower crossover frequencies, but the phase-margin variation with motion fidelity was not significantly changed. Subjectively, this configuration seems more vulnerable to motion-cue degradation than configuration 1, but there is no obvious indication of this in the data

Data obtained in the task of holding altitude over a runway are summarized in Fig. 14. Crossover frequencies and phase margins are presented for three pilots and for conditions of full cockpit motion (no washout) and no motion at all. To be noted first is the large variation in pilot aggressiveness as indicated by their general levels of crossover frequencies and phase margins (pilot 1 produced the data of

Figs. 12 and 13) This spread in pilot behavior was observed in all phases of the experiments Across the performances, however, it can be seen that the addition of cockpit motion increased crossover frequencies by about 50%. The reduction in height and height-rate visual cueing introduced by increasing the altitude from 20 to 100 ft resulted in reductions in crossover frequency, more noted for the motion-on case than in the fixed-cockpit mode. Considering the no-motion case, the data indicate that visual perception of the very modest vertical rates seen in these experiments was still quite good at 100 ft. Further analyses of these and additional available data might provide a more complete understanding of the relative roles of visual and motion cues in this type of near-the-terrain task

The task of holding altitude at 20 ft included visual cues equal to or better than those seen in the task of holding altitude relative to the other aircraft, the tasks might be considered very similar. In comparing the data for pilot 1 of Fig. 14 with those for aircraft configuration 1 in Fig 13, it is seen that the variation in crossover parameters with reduction of motion from full to none is about equalled by the variations induced by changing ω_z from 0.2 to 1.25.

No performance data, in terms of rms height error or height-rate error, are shown here, though they were collected in these tests. The performances were not grossly affected by the experimental variables, but what differences could be observed tended to confirm the expectations generated by changes in crossover frequency and phase margin. Further analysis of these data will include more emphasis on performance measures.

A very small amount of data was obtained in examination of the effects of simple gain reductions in the motion. It was indicated that for $\omega_z < 0.5$, reduction in motion gain to 0.5 produces modest decreases in crossover frequency or phase margin, thus it appears to be a legitimate approach to the efficient use of a cockpit-motion system. The general conclusion from all these data is that for reasonably full fidelity in simulation of height-control maneuvers, vertical-motion-cue phase fidelity is required down to frequencies of 1-1.5 rad/sec. Even with large-motion systems, this fidelity can be produced only in very constrained flight tasks, thus, we are left with the requirement to account for the effects of reduced vertical-motion-cue fidelity in the general use of research and training helicopter simulators. It is conceivable that further modeling of pilot response to motion cues will provide us with the means to implement rational modifications in the dynamic response of the simulated vehicle to compensate for motion-cue deficiencies.

This emphasis on vertical motion was the result of the unique opportunity afforded by the VMS and the rationalization that in many cases the linear motions of the pilot's task are not supported by the strong visual stimuli experienced in rotational motions. It was predicted that a special sensitivity to absence of linear motion cues would be demonstrated. These data to some degree support that prediction, but further experiments are required to examine the effects of motion fidelity in the other motion modes, and especially in the combined linear and rotational modes associated with cockpit locations well off the rotational axes. On the basis of the cockpit motion experience at Ames, some general observations can be offered (1) phase distortion in vertical-motion cues resulting from increases in ω_z, though it does eliminate effective maneuvering frequency cues, seldom produces strong evidence of visual-motion cue conflict, and (2) phase distortion in cockpit rotations can produce severely disturbing effects at second-order washout filter frequencies above about 0.7 rad/sec, if maneuver accelerations are substantial and motion gains are near unity, no motion at all is much preferred. The vertigo experienced is presumed to arise from the conflicting strong visual and motion stimuli.

CONCLUDING REMARKS

Extensive recent experience with helicopter simulation in the Ames VMS facility indicates that even given a wide field-of-view, computer-generated visual-simulation system and uniquely large-amplitude cockpit motion, the desired levels of fidelity in simulation of important research flight tasks is not obtained. Considerations of the characteristics and capabilities of the visual system lead to the conclusion that the primary limitations on fidelity stem from the inability of the visual system to provide adequate texture and detail in renditions of the near-field scenes in hover and landing. This constraint is compounded by nonoptimum distribution of the four viewing fields. Experiments to define adequate field-of-view and, especially, the near-field spatial frequency of detail, are needed. Considering the cost of present visual-simulation systems, imaginative efforts should be made to answer these questions. Unfortunately, the present approach of the simulation community appears to be one of waiting for the next more expensive device to be developed, optimistically assuming that its capabilities will make the present questions academic.

The vertical-motion experiments reported here disclose that high-fidelity motion cues make a significant contribution in the performance of height-control tasks. Further expansion and analysis of the data may lead to improved test procedures and to better interpretation of results in simulations that do not include vertical-motion cues at maneuvering frequencies. The real objective of further motion-cueing experiments will be, of course, the generation of enough information to support the development of practical pilot-response models incorporating motion-sensing modes that are realistically varied in accordance with the associated visual cues.

REFERENCES

1 Bray, Richard S. Helicopter Simulation Technology An Ames Research Center Perspective. NASA CP-2219, 1982, pp 199-208.

2 Churchill, G B Use of Simulation in the XV-15 Program. AGARD FMP Symposium on Flight Simulation, Cambridge, U.K., 1985

3. Clement, Warren F., Cleveland, William B., and Key, David L. Assessments of Simulation Fidelity Using Measurements of Pilot Technique in Flight. AGARD Conference Proceedings No. 359, Monterey, Calif , 1984

4. Paulk, C. H., Jr., Astill, D L , and Donley, S T. Simulation Evaluation of the SF-2F Helicopter in a Shipboard Environment Using the Interchangeable Cab System NASA TM-84387, 1983

5. Hoh, Roger H. Investigation of Outside Visual Cues Required for Low Speed and Hover. AIAA Paper 85-1808-CP, Snowmass, Colo., 1985.

6. Crane, D. F. Compensation for Time-Delay in Flight Simulator Visual Displays. Proceedings of the AIAA Flight Simulation Technologies Conference, Niagara Falls, N.Y., 1983.

7. McFarland, R. E. CGI Delay Compensation NASA TM-86703, 1985.

8 Cooper, George E., and Harper, Robert P., Jr. The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities. NASA TN D-5153, 1969.

TABLE 1 VMS VISUAL- AND MOTION-SYSTEM SPECIFICATIONS

DIG I visual simulator

Full daylight scene capability
Four channels (windows)
1024-line raster format
30-Hz update (non-interlaced)
8,000 polygons
256 edge crossings per scan line

Motion System of VMS

Motion	Total displacement	Velocity	Acceleration
Lateral	12.0 m	2.5 m/sec	4.5 m/sec^2
Vertical	17.0 m	5.0 m/sec	7.0 m/sec^2
Roll	40°	20°/sec	60°/sec^2
Pitch	40°	20°/sec	60°/sec^2
Yaw	40°	20°/sec	60°/sec^2

TABLE 2. DEFINITIONS OF VMS MOTION LOGIC VARIABLES (see Fig. 8)

p_b	aircraft body-axis roll rate, rad/sec
q_b	aircraft body-axis pitch rate, rad/sec
r_b	aircraft body-axis yaw rate, rad/sec
a_{xp}	pilot-perceived longitudinal acceleration, m/sec^2
a_{yp}	pilot-perceived lateral acceleration, m/sec^2
a_{zp}	pilot-perceived vertical acceleration, m/sec^2
g	acceleration due to gravity, m/sec^2
ϕ	roll attitude, rad
θ	pitch attitude, rad
ψ	yaw angle, rad
θ_{tx}	pitch tilt to simulate a_{xp}, rad
ϕ_{ty}	roll tilt to simulate a_{yp}, rad
Y_ϕ	simulator lateral acceleration for roll coordination, m/sec^2

Subscripts

a	aircraft
s	simulator

Motion logic variables		Example values Low speed	 High speed
GP	roll gain	0.7	0.3
GQ	pitch gain	0.5	0.5
GR	yaw gain	0.5	0 7
GX	longitudinal gain	0.5	0.5
GY	lateral gain	1.0	0.6
GZ	vertical gain	1.0	0.5
ω_p	roll washout frequency, rad/sec	0.5	0.7
ω_q	pitch washout frequency, rad/sec	0.5	0.5
ω_r	yaw washout frequency, rad/sec	0.4	0.6
ω_x	longitudinal washout frequency, rad/sec	3.0	3.0
ω_y	lateral washout frequency, rad/sec	0.4	0.5
ω_z	vertical washout frequency, rad/sec	0.2	0.6
GQX	pitch-tilt gain	0.6	0.6
GPY	roll-tilt gain	0.6	0.6
GYC	lateral-roll coordination ratio	1.0	1.0
ω_{qr}	pitch-tilt lag-filter frequency, rad/sec	2.0	2.0
ω_{pr}	roll-tilt lag-filter frequency, rad/sec	3.0	3.0

TABLE 3 HEIGHT-CONTROL TEST PARAMETERS

Vehicle characteristics[a]		
Roll acceleration per unit controller deflection, rad/sec^2	1.5	
Pitch acceleration per unit controller deflection, rad/sec^2	1.5	
Yaw acceleration per unit controller deflection, rad/sec^2	1.5	
Vertical acceleration per unit controller deflection, m/sec^2	14.0	
Roll acceleration due to roll rate, 1/sec	-2.0	
Pitch acceleration due to pitch rate, 1/sec	-2.0	
Yaw acceleration due to yaw rate, 1/sec	-2.0	
	Conf. 1	Conf. 2
Vertical acceleration due to vertical rate, 1/sec	-0.3	-0.1
Collective control output lag, sec	0.1	0.25

Sum-of-sines disturbance (equivalent collective deflection)

Frequency, rad/sec	Amplitude
0.58	-0.035
0.87	0.050
1.31	-0.075
1.75	0.075
2.62	-0.050
3.49	0.030
5.24	-0.017

---

[a] All accelerations are in body axes, unit deflections for the altitude controllers are full deflections from center (trim), unit deflection for the collective controller is from full down to full up.

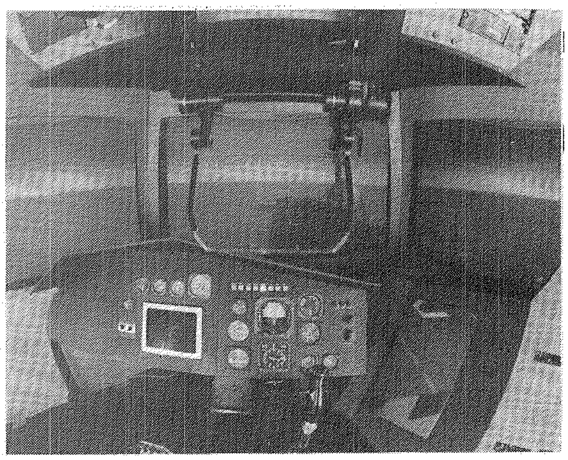
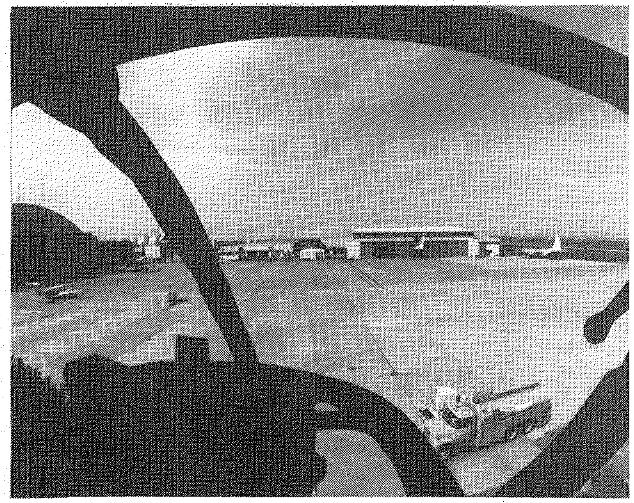
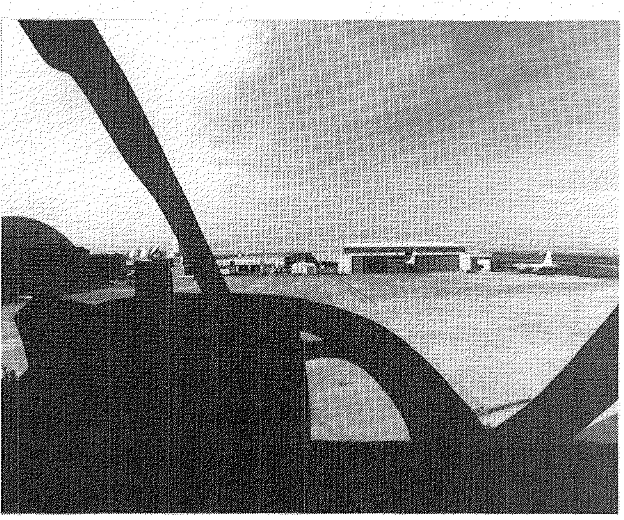


Fig. 1. The interior of one of four interchangeable cabs available for use with the Ames Vertical Motion Simulator (VMS).



(a) Hover.



(b) Deceleration (15° nose up).

Fig. 3. Representation of the forward view from an OH-58 helicopter.

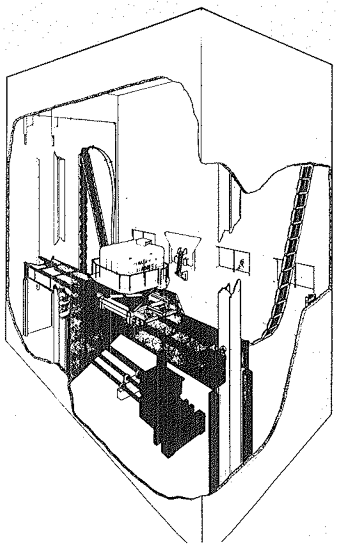
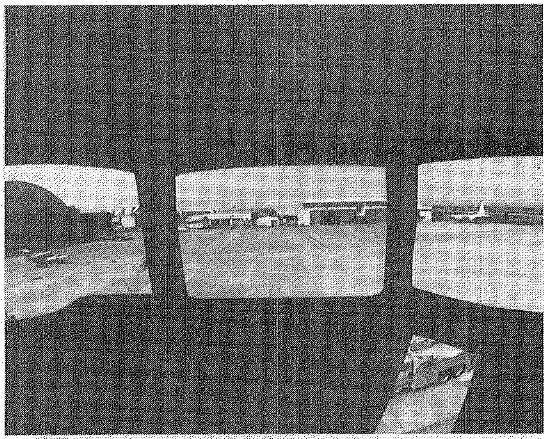
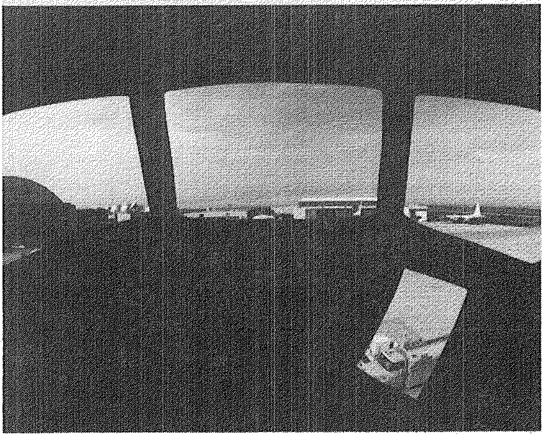


Fig. 2. VMS with an interchangeable cab installed.

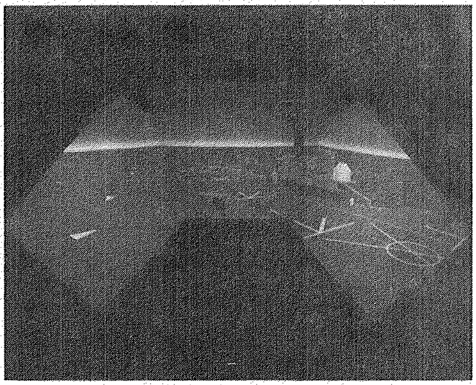


(a) Hover.

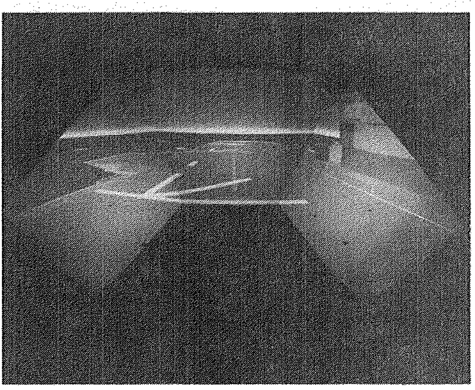


(b) Deceleration (15° nose up).

Fig. 4. Ramp scene viewed through a representation of the simulator's fields of view.



(a) Approach.



(b) Near touchdown.

Fig. 5. Scenes of approach to a shipboard landing as presented by an arrangement of three joined collimators.

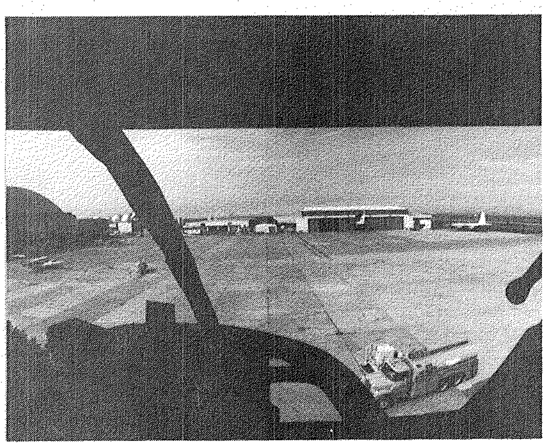
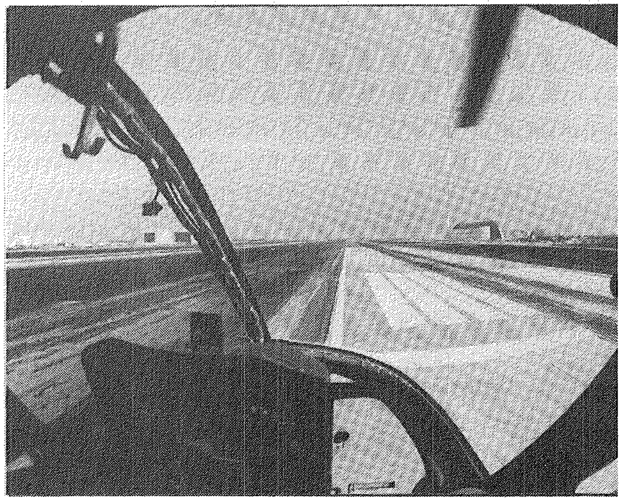
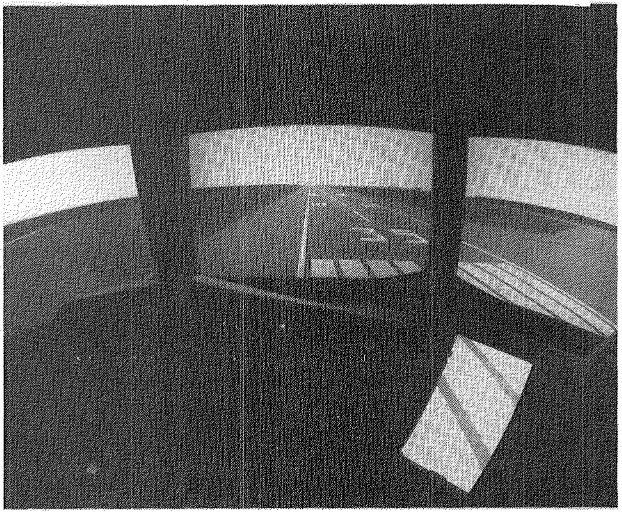


Fig. 6. Ramp scene presented in the field to be available with three edge-matched projections (each projection 40° by 60°).



(a) Flight (OH-58).



(b) VMS.

Fig. 7. Comparison of scene detail present in flight and in the VMS.

$$\begin{bmatrix} p_b \\ q_b \\ r_b \end{bmatrix} * \begin{bmatrix} 1 & 0 & \theta_a \\ 0 & 1 & -\phi_a \\ 0 & \phi_a & 1 \end{bmatrix} = \begin{bmatrix} p_{in} \\ q_{in} \\ r_{in} \end{bmatrix} \qquad \begin{aligned} X_{in} &= a_{x_p} - g * \theta_a \\ Y_{in} &= a_{y_p} - Z_s * \phi_s \\ Z_{in} &= a_{z_p} + g/\cos\phi_a \end{aligned}$$

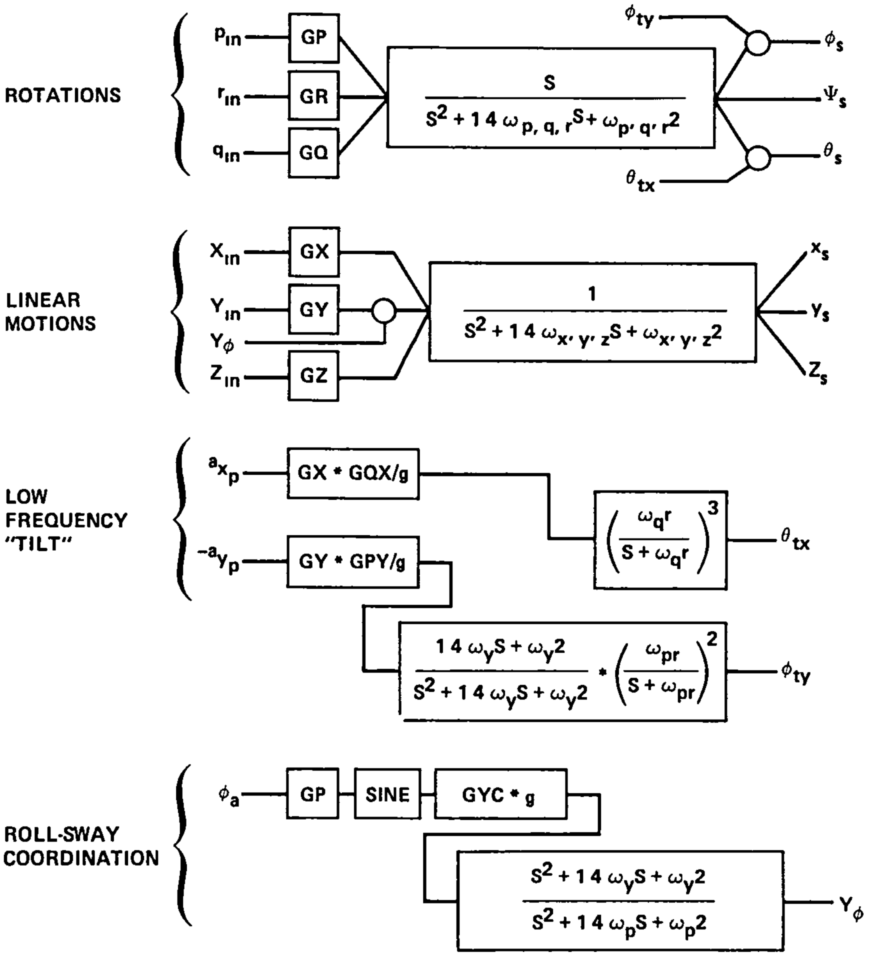


Fig 8. Elements of the VMS motion-constraint, or washout logic

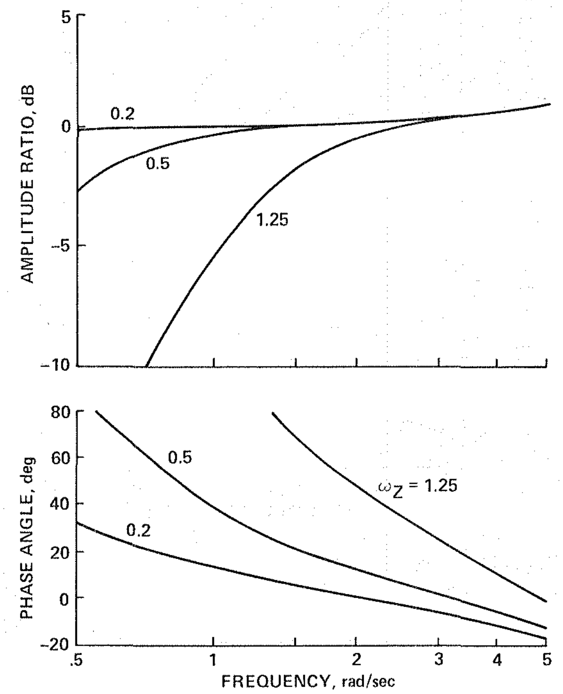
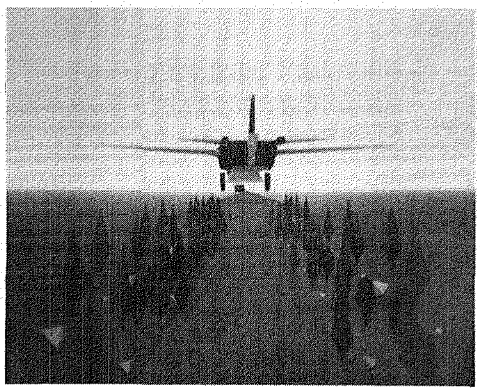
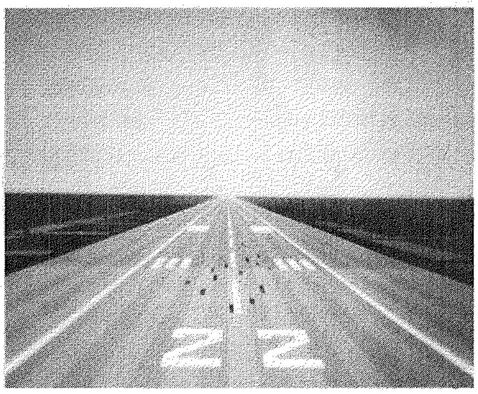


Fig. 9. Amplitude and phase of VMS vertical-acceleration response with respect to computed cockpit vertical acceleration for several values of washout characteristic frequency.



(a) Height-reference aircraft.



(b) Altitude-hold runway scene.

Fig. 11. Forward-window views as seen in the height-control experiments.

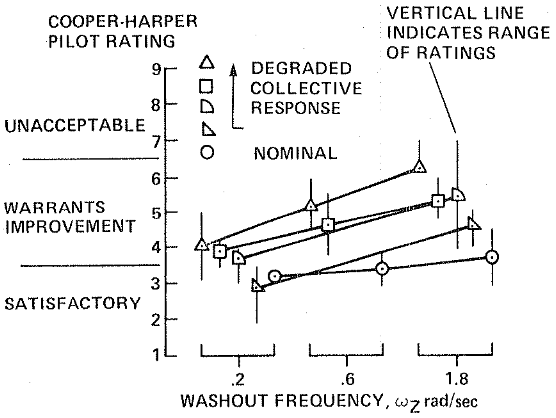


Fig. 10. Variation of pilot opinion ratings of vehicle vertical-response handling qualities with vertical-motion fidelity.

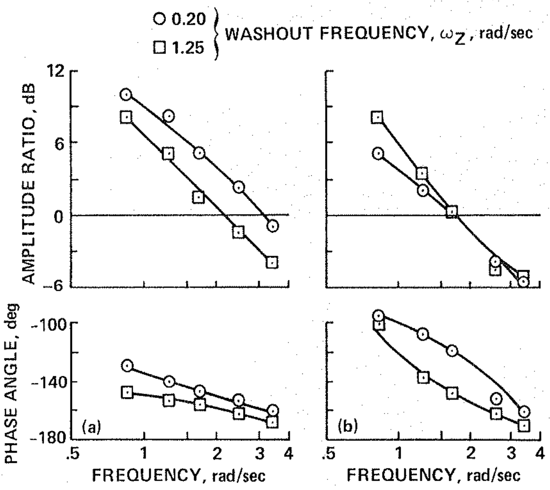


Fig. 12. Effects of cockpit-motion fidelity on open-loop gain and phase variations with frequency for two vertical-position-holding tasks.
(a) Stabilizing against a disturbance. (b) Tracking a moving target.

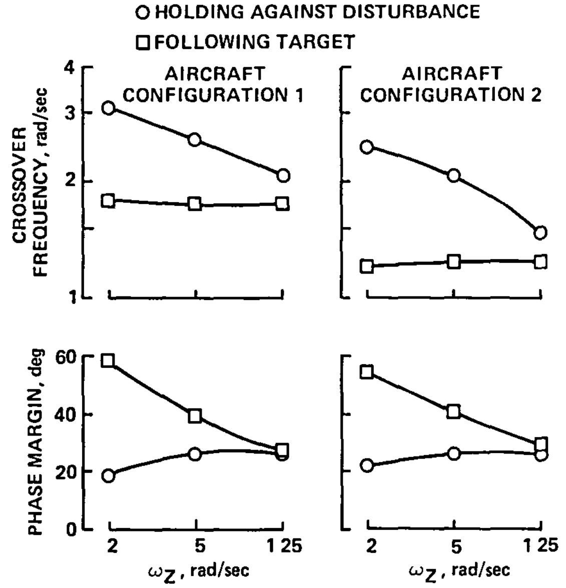


Fig. 13. Variations of crossover frequency and phase margin seen in altitude-control tasks with variations in vertical-motion fidelity and aircraft-response characteristics

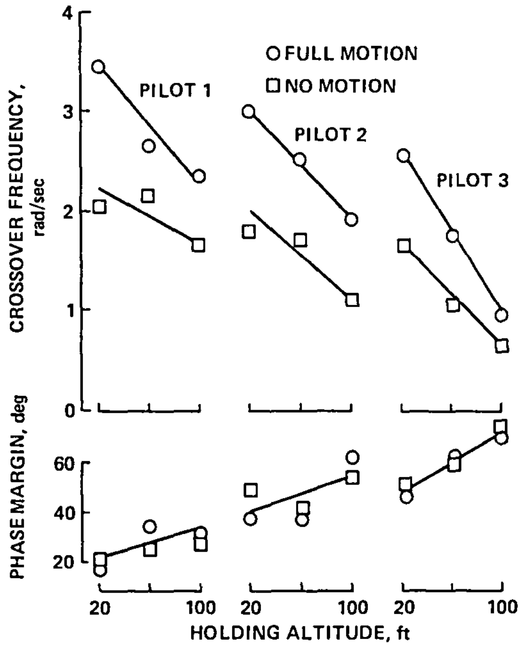


Fig 14 Effects of vertical motion and altitude on crossover frequency and phase margin measured for three pilots in the simulated task of holding altitude over a runway against a vertical disturbance.

1 Report No
NASA TM-86818

2 Government Accession No

3 Recipient's Catalog No

4 Title and Subtitle
VISUAL AND MOTION CUEING IN HELICOPTER SIMULATION

5 Report Date
September 1985

6 Performing Organization Code

7 Author(s)
Richard S. Bray

8 Performing Organization Report No
85371

9 Performing Organization Name and Address
Ames Research Center
Moffett Field, CA 94035

10 Work Unit No

11 Contract or Grant No

12 Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, DC 20546

13 Type of Report and Period Covered
Technical Memorandum

14 Sponsoring Agency Code
505-35-31

15 Supplementary Notes
Point of Contact: Richard S. Bray, Ames Research Center, MS 211-2,
Moffett Field, CA 94035 (415)694-6229 or FTS 448-6229

16 Abstract

For the past decade, helicopter handling qualities have been the subject of piloted-simulator programs at Ames Research Center Early experience in fixed-cockpit simulators, with limited field of view, demonstrated the basic difficulties of simulating helicopter flight at the level of subjective fidelity required for confident evaluation of vehicle characteristics More recent programs, utilizing large-amplitude cockpit motion and a multiwindow visual-simulation system have received a much higher degree of pilot acceptance However, none of these simulations has presented critical visual-flight tasks that have been accepted by the pilots as the full equivalent of flight. In this paper, the visual cues presented in the simulator are compared with those of flight in an attempt to identify deficiencies that contribute significantly to these assessments. It is suggested that a non-optimum distribution of field-of-view elements, coupled with a severe lack of near-field detail, compromises the pilot's sensing of translational rates relative to nearby terrain or the landing surface For the low-amplitude maneuvering tasks normally associated with the hover mode, the unique motion capabilities of the Vertical Motion Simulator (VMS) at Ames Research Center permit nearly a full representation of vehicle motion Especially appreciated in these tasks are the vertical-acceleration responses to collective control. For larger-amplitude maneuvering, motion fidelity must suffer diminution through direct attenuation or through high-pass filtering "washout" of the computer cockpit accelerations or both. Experiments were conducted in an attempt to determine the effects of these distortions on pilot performance of height-control tasks Results revealed that in holding position in the presence of vertical disturbances, pilot control-gain and resultant open-loop crossover frequency were significantly depressed as the fidelity of vertical motion was reduced In height tracking of a moving reference, gain and crossover were not greatly affected, but phase margin and tracking performance improved with motion fidelity. Pilot-opinion ratings of varied vehicle vertical-response characteristics were significantly modified by changes in motion-cue fidelity

17 Key Words (Suggested by Author(s))
Visual simulation
Cockpit motion simulation
Helicopter simulation
Flight simulation

18 Distribution Statement
Unlimited

Subject Category - 09

19 Security Classif (of this report)
Unclassified

20 Security Classif (of this page)
Unclassified

21 No of Pages
19

22 Price*
A02

*For sale by the National Technical Information Service, Springfield, Virginia 22161

End of Document