NASA Technical Memorandum 102830

Simulation of Nap-of-the-Earth Flight in Helicopters

Gregory W. Condon

(NASA-TM-102830) SIMULATION OF NAP-OF-THE-EARTH FLIGHT IN HELICOPTERS (NASA) 20 p CSCL 01C

N91-21131

Unclas

G3/05 0008116

February 1991

NASA
National Aeronautics and
Space Administration

NASA Technical Memorandum 102830

Simulation of Nap-of-the-Earth Flight in Helicopters

Gregory W. Condon, Ames Research Center, Moffett Field, California

February 1991

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035-1000

SIMULATION OF NAP-OF-THE-EARTH FLIGHT IN HELICOPTERS

by
Gregory W. Condon
Chief, Flight Systems and Simulation Research Division
NASA Ames Research Center
Moffett Field, California 94035, U.S.A.

SUMMARY

NASA Ames Research Center, in conjunction with the co-located U.S. Army R&T Laboratory's Aeroflightdynamics Directorate, has conducted extensive simulation investigations of rotorcraft in the nap-of-the-Earth (NOE) environment and has developed facility capabilities specifically designed for this flight regime. This paper reports on the experience gained to date in applying these facilities to the NOE flight regime and on the results of specific experimental investigations conducted to understand the influence of both motion and visual scene on the fidelity of NOE simulation. Included are comparisons of results from concurrent piloted simulation and flight research investigations. The results of a recent simulation experiment to investigate simulator sickness in this flight regime are also discussed.

INTRODUCTION

Over the past decade great strides have been made in developing piloted simulation capability. The main enabling capability has been computer technology, which has permitted the calculation of sophisticated mathematical models of aircraft motions, the dynamic modeling of complex avionic systems, and, most visibly, the computer-generation of realistic images of the outside environment. These advances have resulted in major improvements in the "reality" of piloted flight simulators.

These advances in simulation capability have also substantially advanced the use of piloted simulation in the development, acquisition, and operation of all types of aircraft under the conditions of a broad spectrum of missions. The drivers for this use are cost and safety improvements. A current example is the use of ground-based simulation to certificate transport airline pilots without requiring flight time in the actual aircraft. Piloted simulation has also played an increasing role in the research, development, and acquisition of new aircraft by (1) discovering and remedying problems before flight-test articles are fabricated, (2) aiding in understanding anomalies during flight development, and (3) assisting procuring agencies (for military systems) in mission evaluation for scenarios that cannot be actually tested.

Obviously, the successful use of piloted simulation in these roles depends on the fidelity, both subjective and objective, of the simulator relative to the real airplane. In civil airline training, the assessment of fidelity is relatively straightforward, since the actual aircraft exists and almost all mission elements can be flown. However, in the case of the development of a new aircraft, the assessment of fidelity cannot be made directly, because the aircraft does not exist and, for military aircraft, certain mission segments cannot be flown. In this case, a priori confidence in simulator fidelity is crucial and much more difficult to accomplish.

Ames Research Center has been applying ground-based piloted simulation to the research and development of aircraft for over 20 years. Over the past 10 years there has been a major emphasis on the flight dynamics, guidance, and control of rotorcraft, usually in conjunction with the co-located Aeroflightdynamics Directorate of the U.S. Army R&T Laboratory. The mission scenarios of prime interest to this class of aircraft result in flight close to either the ground or obstacles at low airspeeds and at low g levels. Recent programs have included investigation of helicopter air combat in nap-of-the-Earth (NOE) flight; helicopter autorotative landings; tilt-rotor and helicopter scout/attack missions; helicopter accident investigation; and pilot night-vision systems in NOE. In particular, the driving element of rotorcraft simulation at Ames has been the mission requirement to fly in the near-Earth environment, down to and including NOE (Fig. 1).

Experience at Ames with rotorcraft piloted simulation for the near-Earth environment has shown that pilot acceptance is particularly sensitive to visual and motion cueing. For high-fidelity flight and mission evaluation in the near-Earth environment, the pilot requires precise information about the range to obstacles or terrain and about the rate of closure on those obstacles or terrain. The prime source of this information is the visual scene. The motion system provides feedback on the maneuvering characteristics of the usually unstable, nonlinear, highly coupled dynamics of these vehicles. Accurate modeling of these basic dynamics is important but can, in general, be accomplished satisfactorily with state-of-the-art computers.

The specific issue of the fidelity of piloted simulation for rotorcraft in the near-Earth environment has been addressed over the last 10 years at Ames Research Center in conjunction with advanced R&D programs aimed at understanding and improving the flight dynamics, control, and guidance of rotorcraft operating in this environment. Assessments of helicopter simulation technology at Ames have been previously reported (Refs. 1,2). Those assessments addressed the key issues of visual and motion fidelity. Since the latest of these summary reports (Ref. 2) was published, the motion system of the Vertical Motion Simulator at Ames Research Center has been upgraded, and several research investigations specifically addressing simulator fidelity have been undertaken.

The objective of this paper is to provide an overview of the results of specific investigations into the factors influencing the validity of simulated NOE flight. Although a comprehensive program to quantify an understanding of simulator fidelity does not exist, the results of several individual studies conducted at Ames do provide some valuable insights. First, the Ames simulation capabilities are described, followed by a discussion of three investigations specifically concerned with simulation validity: (1) the influence of simulator motion and visual cue variations on helicopter autorotative landing; (2) a comparison of simulator and flight results for a UH-60 performing selected NOE maneuvers; and (3) the influence of simulator motion and maneuvering intensity in NOE flight on symptoms of simulator sickness. The paper concludes with a discussion of approaches to mitigate the effects of poor simulator fidelity on NOE simulation results.

AMES SIMULATION FACILITY

The primary simulation facility used for rotorcraft piloted simulation studies at Ames Research Center is the Vertical Motion Simulator (VMS) complex. The VMS, shown in Fig. 2 , is a six-degree-of-freedom, large-motion simulator with the motion capabilities listed in Table 1. As shown in Fig. 3, the cab is mounted on a gimbal system that provides independent pitch and roll rotation. This gimbal system is mounted on an independent cone that provides yaw rotation. The cone-with-gimbal-assembly then moves horizontally, perpendicular to the main beam, for translation in one axis; the complete carriage with cone and gimbal moves horizontally along the main beam for translation in the second axis. The entire beam/carriage/cone/gimbal moves vertically to generate the third degree of linear motion. The cab can be oriented with the x-axis either along the beam, for greater x than y motion, or transverse to the beam, for greater y than x motion. The gimbal, cone, and carriage assembly is a recent upgrade to the VMS, made in order to add the third linear degree of freedom and to substantially increase the rotational motion performance, particularly simultaneous rotational motion. A previous five-degree-of-freedom configuration (three rotational and two linear) is described in Ref. 1; the motion system performance is described in Table 1. The VMS, particularly with its recent upgrade, provides unparalleled six-degree-of-freedom motion capability.

The VMS system (Fig. 4) consists of the VMS motion simulator, two fixed-base simulator stations, and five interchangeable cabs. This system allows the development and checkout of cabs when not installed on the motion base, the changing of cabs quickly (in less than 1 day), and the conduct of concurrent fixed-base and motion-base simulations, either independently or linked together. Four of the cabs use various arrangements of collimated video monitors for presentation of simulated visual scenes generated either by Singer-Link DIG I or Evans and Sutherland CT-5A computer graphics systems. The insides of the four cabs are shown in Fig. 5, with example cockpit furnishings and Singer DIG simulated scenes. The fifth cab uses light valves with combining and projection optics to project an E&S CT-5A computer graphics scene on the inside of a 20-ft-diam dome, as shown in the artist's rendering in Fig. 6. This dome cab has been operated in fixed-base simulation and is currently undergoing rework operation in motion.

Each of the three investigations reported herein utilized one or more of the collimated-CRT cabs driven by the Singer DIG I computer-graphics system. It should be noted that the Singer DIG I system uses 10-year-old technology and is not representative of state-of-the-art capability. The specifications for the system are as follows: (1) full daylight scene capability; (2) four channels (windows); (3) 1024-line raster format; (4) 30-Hz update (non-interlaced); (5) 8,000 polygons; and (6) 256 edge crossings per scan line. The artificial, visual-enhancing scenes were so constructed as to provide the pilot with the needed range and range-rate motion cues in a quantifiable and controlled manner.

HELICOPTER AUTOROTATIVE LANDING

A joint NASA/FAA simulation program was conducted to provide background data to assist the FAA in developing certification criteria for helicopter training simulators. The program was specifically focused on pilot control in the autorotative landing task (Refs. 3,4). The autorotative landing task imposes a great challenge on simulator fidelity, since landing requires that the pilot's attention be directed outside the cockpit at a time when he must rely almost solely on visual, motion, and sound cues. The results of a VMS experiment undertaken to enhance the understanding of landing performance and pilot control strategy under conditions of varying simulator motion-system performance and varying visual scene content and detail are reported in detail in Ref. 4. The general findings regarding motion and visual fidelity are synopsized below.

Visual Scene Content

The visual display was provided by a four-window computer-generated image. Three visual scenes were used during the autorotation landing task evaluations. Figures 7 through 9 depict each of these scenes just prior to touchdown.

A major objective of the experiment was to evaluate the influence of visual scene elements on landing performance and pilot workload. Individual scene elements were tailored to maximize the important cues of aircraft attitude and of range and range rate from the terrain. The evaluation was based mainly on pilot commentary.

Figure 7 shows an airfield scene with a black-and-white checkerboard landing zone. Pylons along the right side and pylons beyond the landing zone provided cues in addition to those contained in the basic airfield scene. The pylons along the right side provided height and velocity cues, whereas the tall pylons in the distance provided pitch-attitude cues during the landing flare. This scene provided adequate cues for most pilots.

Figure 8 illustrates further modifications to the airfield scene. Prominent are the shift to a gray-shaded checkerboard, smaller squares in the final portion of the checkerboard, and the addition of a person and vehicles surrounding the landing zone. This modified checkerboard landing scene provided a distinct improvement over the Fig. 7 scene. The lower-contrast gray shading of the cross-hatching appeared more natural and brighter to the pilots. The half-size squares of the final quarter of the landing zone provided a useful cue for judging the final touchdown rate. The smaller cross-hatched area of the final quarter of the landing zone, which was in full view during the final seconds before touchdown, provided the pilots a finer gradation for height control. The addition of the man and trucks around the landing zone provided easily recognized scene scaling. Compared with the rather abstract appearance of the original black and white checkerboard scene of Fig. 7, the human-scaled additions of the modified scene provided a much more usable scene. The lack of recognizable texture in the computer-generated image was compensated for by artificial scene elements such as the checkerboard, pylons, man, and truck, and provided the necessary cues.

The canyon scene of Fig. 9 provided a contrast to the abstraction of the checkerboard airfield scenes. Pilots commented favorably on the strong attitude cues provided by the trees, canyon wall, and floor junction. The double row of trees provided better velocity cues than those available on the airfield scenes. Pilots commented that no scene provided good height cues in the critical period just before touchdown. Height judgment just before touchdown contributed to the large dispersions in touchdown sink rate and rotor speed.

Motion System Performance

To identify the effects of motion-system performance on pilot task performance, four levels of motion cueing were investigated. These ranged from full VMS capability, values typical of a large-travel hexapod and a small motion "nudge" base, to fixed base. The measures used to evaluate the influences of motion-system performance on landing task performance were (1) changes in pilot control strategy, and (2) aircraft ground velocity at touchdown (within safe rotor rpm constraints).

The piloting technique that is taught for autorotative landing flare is a steady increase in collective stick to full throw just as the helicopter touches down. Figure 10 illustrates collective stick time-history traces for different motion levels by pilot B. In general, this pilot exercised the proper control technique with the full VMS motion. As the motion performance degraded, his use of collective control changed. Many landing flares with degraded motion performance showed signs of ballooning, stair-stepping, and overcontrol in the collective time-histories. Note that the maximum collective control was not used at touchdown when motion cues were not available. Pilots differed in their behavior, some showing poor control techniques even with full VMS motion. However, the trend shown did occur for several pilots.

The landing performance statistics for pilot B are plotted in Fig. 11 for an 8,000-lb baseline configuration. Although the touchdown sink rate degrades with reduced motion cueing, the fixed-base result is very similar to that of the full motion. Note, however, that the fixed-base sink-rate result is obtained at the expense of a large variation in forward velocity. Pilot B reported that degraded motion cues could distract him more than fixed base. The low forward speed at touchdown for the nudge-base was achieved at the expense of low rotor speed. Both the hexapod and nudge-base motion levels tended to distract this pilot.

For pilot A, the touchdown sink rate improved with increased motion performance (Fig. 12). However, the touchdown forward velocity tended to be higher with greater deviation for increased motion cueing. Using the full VMS motion result as the standard, reduced motion cueing for pilot A resulted in a shift of landing strategy to deemphasize touchdown sink rate.

Higher vehicle gross weight had a dramatic effect on landing performance trends for pilot F (Fig. 13). In spite of the higher landing speed technique used by pilot F, the landing performance (particularly the touchdown sink rate and forward velocity) shows distinct degradation with degraded motion cues. Pilot F was less affected by motion-system variations at the lower gross weight. The higher gross-weight configuration forced a more critical flight task requiring use of all available simulator cues.

The landing performance results for variations in motion-cue levels for all pilots may be summarized as follows: (1) degraded motion cueing generally degraded landing performance, thus causing some shifts in landing strategy and control technique; (2) motion-level variations affected pilots who sought to obtain the best performance from the helicopter (lowest forward speed and low sink rate) more than it did those pilots who used a run-on landing technique; and (3) reducing the helicopter performance margin by increasing the aircraft gross weight created a more critical flight task, which caused some pilots to become more sensitive to motion-cue variations.

UH-60 SIMULATION VALIDATION

In the early 1980's, NASA and the U.S. Army conducted a systematic evaluation and validation of a U.S. Army UH-60 helicopter simulation on the Ames VMS for nap-of-the-Earth flight tasks. The results of the initial experiments in 1982 are reported in Refs. 5 and 6. Because of deficiencies discovered during these experiments and the keen interest of both agencies in continuing improvement of the fidelity of helicopter simulation for this flight regime (and for the UH-60 in particular), efforts have continued to address these shortcomings. The improvements that have been made will be briefly described and several overall findings of a recent simulation/flight evaluation of these improvements will be discussed. A detailed report is being prepared for publication elsewhere.

Early Experiments

The experiments in the early 1980s used the Ames VMS with a four-window CGI scene provided by the Singer DIG I image-generation system. The details of the experimental setup are described in Refs. 5 and 6.

Figure 14 shows a comparison of the mean and extreme Cooper-Harper handling-qualities ratings (HQR) (Ref. 7) between the VMS simulation and flight tests for three of the NOE maneuvers: bob-up (BU), sidestep (SS), and dash/quick-stop (D/QS). The mean ratings for all of the tasks in flight were Level 1, whereas in the simulator they were Level 2. In addition, there was no overlap in any of the ratings for any of the tasks. The pilot commentary identified the following deficiencies of the simulation: (1) inability to judge range and height as accurately as in flight; (2) larger thresholds of visual perception of motion; (3) insufficient damping in all axes; (4) vertical and roll pilot-induced-oscillations; (5) exaggerated control inputs; and (6) deceptive motion cues.

Not surprisingly, these problems were attributed to the following characteristics of the visual, motion, and modeling systems: (1) insufficient CGI scene field-of-view, content, and texture; (2) basic transport delay of 120 msec as a result of the inherent architecture of the CGI and host computers; and (3) phase distortion of the motion system.

Simulation Improvements

Over the past 5 years, extensive efforts have been undertaken to improve the fidelity of the VMS system and the validity of the UH-60 simulation. The improvements to the VMS included (1) doubling of the angular rate and acceleration performance, (2) addition of motion in the third translational axis, (3) incorporation of compensation for the CGI to reduce the overall transport delay to approximately 20 msec, and (4) incorporation of an Applied Dynamics Inc. AD100 host computer to reduce the model cycle time to 6.7 msec (with a 20-msec input/output cycle). The fields of view of the available cabs are unchanged (Fig. 15). Although the capabilities of the CGI system also remain unchanged, the scenes for the specific NOE tasks have been tailored to increase content and detail, as will be discussed below. There has been a significant effort to improve the modeling of the UH-60 (Ref. 8).

Recent Experiments

The two recent UH-60 Black Hawk simulations were the first simulation validation experiments on the newly refurbished VMS. The first simulation was done concurrently with a flight test of the UH-60 aircraft at the NASA facility at Crows Landing Naval Auxiliary Landing Field (Calif.). This allowed a back-to-back comparison of flight and simulation, which is desirable when an actual vehicle is being simulated and fidelity assessments are being made.

The recent simulation experiments settled on three primary tasks to be used in assessing simulation fidelity: the bob-up (BU), the sidestep (SS), and the dash/quick-stop (D/QS). The experiments were set up so that the same task could be performed on the simulator as in flight. The selection of the bob-up/bob-down and the sidestep maneuvers allowed the use of a specially designed hover board for the flight tasks (Ref. 9). These boards were duplicated on the DIG-1 image generator used on the VMS simulation to get the one-to-one task performance desired. The boards were placed on a facsimile of the Crows Landing Airfield reproduced on the DIG-1. Figures 16 and 17 show the boards at Crows Landing and in the simulator, respectively. The dash/quick-stop maneuver was performed on the simulator in a setting representative of the task done at Crows Landing. Knowing the limitations of the simulator field of view for the dash/quick-stop, the task was modified to constrain pitch-attitude excursions within those limitations. The HQR results of the subjective evaluations given by the test pilots for the recent flight and two simulation experiments are shown in Fig. 18, along with the corresponding results from the earlier experiments (Fig. 14). The mean ratings for the recent experiments are denoted by the filled symbols and the extremes in ratings are denoted by the solid vertical bars. The earlier results are shown with open symbols and dashed vertical bars.

There has been a significant improvement in the validity of the simulation of the UH-60 for these NOE tasks. The ratings from the current simulation are only 0.5 to 1.5 ratings worse than the flight ratings, whereas in the previous experiments the spread was from 1.5 to 2.5 ratings worse. Pilot commentary provides initial insight into the characteristics of the simulation that still contribute to the differences.

Bob-up and sidestep tasks— Because of the restricted field of view of the CGI scene, the pilots were unable to see the stop point when they initiated the bob-up maneuver. Consequently, they could not lead the task as well as they could in flight, which resulted in higher workload required to mitigate overshoot and bobble when trying to arrest the vehicle at the stop point. In addition, some of the pilots commented that they perceived lighter heave damping in the simulator than in the aircraft. Although considerable progress has been made in improving the mathematical model (Ref. 8), the loader system dynamics, and the visual delay (Ref. 10), other residual visual scene problems may be still contributing to this lack of validity.

Although the hover boards did help in achieving closer agreement with flight by providing improved range and range rate cues, problems still exist with the image. The pilots commented that the reduced resolution and lack of depth perception (Fig. 19) in the simulator detracted from doing precision maneuvering in the simulator. Overall, the pilots said that they tended to perform the task with the same control strategy in the simulator as they did in flight.

Dash/quick-stop task— The mean HQR ratings for the dash/quick-stop task showed the best comparison between simulation and flight, but the pilots noted a difference in the piloting strategy used to accomplish this maneuver. In flight, they relied on the external scene to judge the vehicle's altitude and ground speed, with a cockpit instrument check to verify airspeed and height above the ground. In the simulation, they relied more on aircraft instruments to judge the vehicles attitude, height above the ground, and air speed with a check of the outside CGI scene to verify altitude. They gave two reasons for this change in strategy: first, they could not judge ground speed and altitude from the CGI scene owing to the lack of fine texture; and second, the restricted field of view limited altitude information during pitch changes.

SIMULATOR-INDUCED SICKNESS

An undesirable by-product of ground-based piloted simulation in which the realistic visual scenes available today are used is the phenomenon of simulator-induced sickness. This is a growing international problem (Ref. 11) with the incidence rates appearing to increase as more flight simulators and more complex visual systems are put into use (Ref. 12). In general, increased incidence of simulator sickness is associated with more intensive maneuvering, such as air-to-air combat and NOE flight. It has been hypothesized that simulator-induced sickness is a result of a conflict between the pilots' visual and vestibular systems, that is, actual or cognitively expected motion and visual cues. The consequences of this conflict on the results of simulation, and on the well-being of subject pilots, are key issues that need to be addressed.

An initial joint NASA/Army simulation experiment has been conducted to investigate the causes, symptoms, and measures of simulator-induced sickness and to identify solutions to the problem (reported in detail in Ref. 13.) The large-motion capabilities of the Ames Vertical Motion Simulator provided a unique opportunity to study the effects of visual-motion dis-synchrony on simulator-induced sickness.

The objectives of the experiment were to (1) assess the incidence of simulator sickness under four simulator motion conditions, (2) validate physiological and behavioral measures of pilot performance and well-being, and (3) develop a quantitative measure of conflict between visual and inertial cues for motion sensing. Only the findings regarding the influence of variations in inertial motion cueing on the incidence of simulator sickness are discussed in this paper (refer to Ref. 13 for other details.)

Four simulator motion conditions were tested: (1) fixed-base, (2) VMS nominal, (3) increased lead, and (4) reduced motion bandwidth. The conditions were selected to represent the full range of motion-visual synchronization from the least, in the fixed-base condition, to the highest fidelity that VMS can provide. The specific characteristics of the visual and motion systems are defined in detail in Ref. 13. The intermediate conditions were selected to be representative of motion systems found in current and proposed military flight trainers. The increased-lead condition produced, relative to VMS nominal, exaggerated initial motion inputs in the rotational axes (roll, pitch, and yaw) followed by a more rapid motion washout. The reduced-motion-bandwidth condition was characterized by a decreased motion bandwidth which produced an increased temporal lag in the rotational axes.

Forty-eight Army helicopter pilots participated in the study, each randomly assigned to only one of the four simulator motion conditions. The flight task required each pilot to fly a simplified model of a single-seat UH-60 Blackhawk helicopter while pursuing a target aircraft at a specified interval. The motion of the target aircraft was recorded from prior flights in the VMS. Each pilot flew four 10-min segments distinguished by successively increasing demands on the amount of flight maneuvering required. The first segment involved very gentle maneuvering; the fourth segment was quite aggressive with bank angles frequently exceeding 90°. All four segments were flown at altitudes from 20 to 100 ft above the terrain. Pilots were provided with visual status information which informed them when they were either too close or too far from the target aircraft.

Every 5 min during the simulated flight, pilots were asked by the experimenter to provide a numerical rating, on a scale from 1 to 7, of their level of well being. A rating of 1 signified "I feel fine and symptom-free" and a rating of 7 signified "I am unable to continue and wish to terminate my flight." Pilots were encouraged to terminate their flight at any time if they began to feel uncomfortable or nauseated.

Pilot Discomfort Ratings

Figure 20 presents mean discomfort ratings for pilots grouped by motion condition. The data are presented for all four 10-min sessions, each of which required progressively more maneuvering by the pilot. Because of excessive discomfort, 23.0% of the pilots were unable to complete all four sessions in the increased-lead condition, 18.1% in the fixed-base condition, and 8.3% in both the VMS nominal and reduced-motion-bandwidth conditions.

As indicated in Fig. 20, pilots reported higher levels of discomfort in those conditions that required greater maneuvering. This is particularly evident in the increased-lead condition, in which pilot mean ratings of discomfort increased from 1.5 in low maneuvering to 3.4 in high maneuvering. A less rapid increase in reported discomfort was observed for the other three motion conditions.

The results also suggest an interaction between motion condition and maneuvering intensity. The reduced-motion-bandwidth condition produced greater mean discomfort in the two lowest maneuvering conditions, whereas the increased-lead condition produced more discomfort in the two highest maneuvering conditions. Overall, the VMS nominal condition appeared to be the most benign.

Simulator Side Effects

In general, the measures of simulator side effects corroborate the measures of pilot discomfort discussed above, in that large increases in reported symptoms were observed.

Immediate postflight data revealed increases of 20% or more (over preflight data) in reports of general discomfort, eye strain, salivation increase, sweating, nausea, difficulty concentrating, dizziness, and stomach awareness. One pilot who participated in the fixed-base condition vomited before exiting the simulator.

Data taken 30 min after flight revealed increases of 10% or more (over pretest reports) for general discomfort, eye strain, difficulty focusing, nausea, dizziness, and increased appetite. Across all motion conditions, there were substantial reports of symptoms up to 30 min after exiting the simulator. Prolonged symptoms of general discomfort and nausea appeared with greater frequency in the more attenuated motion conditions (fixed base, increased lead, and reduced motion bandwidth) than in the VMS nominal condition. This appears to follow the prediction of the sensory conflict theory, in that greater discrepancies between visual and inertial cues for motion exist in those three conditions. Long-term aftereffects, from 3 to 48 hr after completion of the simulation session, were found to be negligible.

The results presented above are from the first experiment on the VMS, which was undertaken to gain an understanding of the factors involved and their influence on simulator-induced sickness. The results indicate (1) that phase distortion of motion cues, particularly at high acceleration levels, leads to increased occurrence of symptoms of simulator-induced sickness, and (2) that long-term aftereffects were negligible. Nonetheless, further investigation is required to quantify the degree to which the differences are statistically meaningful and the measures are statistically valid.

CONCLUDING REMARKS

Based on these experiences at Ames in examining the influences of motion and visual fidelity of ground-based piloted simulation, and on the efforts undertaken to properly control these influences, the following concluding comments are offered:

1. It is crucial to satisfactory simulation validity that the piloting tasks be tailored to fit within the motion and visual scene capabilities of the simulator. Conversely, the simulation must designed to provide the cues necessary if the pilot is to perform the task as one would expect him to perform it in flight.

2. High-fidelity motion cues are required to improve task performance for near-Earth or nap-of-the-Earth flight tasks. As the difficulty of the task increases, the effects of motion cueing become more pronounced. Small motion cues, poorly tailored to the task, may degrade performance more than no motion cues (fixed-base).

3. When using a four-window CGI system, phase distortion in motion cueing, particularly at high acceleration levels, leads to increases in simulator-induced sickness. An increase in maneuver level leads to increases in simulation-induced sickness. Long-term aftereffects were found to be negligible.

4. Although the use of carefully controlled tasks can mitigate the effects of limited scene field-of-view, the current fields of view available on the Ames VMS need to be increased further to enable broader nap-of-the-Earth tasks to be flown with acceptable validity.

5. The addition of easily recognizable scaling objects contributes greatly to the pilot's ability to estimate range and range rate.

6. Accurate ground-speed and height sensing, which are crucial to nap-of-the-Earth flight, require fine scene texture.

7. The overall response lags in the simulator visual scene and motion system, and the poor synchrony between these lags, significantly affect pilot acceptability and performance, and the onset of symptoms of simulator sickness. The application of high-speed digital computers, CGI delay compensator techniques, and motion washout adjustment can mitigate these effects.

REFERENCES

1. Bray, Richard S.: Visual and Motion Cueing in Helicopter Simulation. AGARD Conference Proceedings No. 408, AGARD FMP Symposium on Flight Simulation, Cambridge, U.K., 1985.

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

3. Decker, W. A.; Adam, C. F.; and Gerdes, R. M.: Model development and Use of Simulators for Investigation of Autorotation. FAA Conference on Helicopter Simulation Proceedings, Atlanta, Ga., Apr. 1984.

4. Decker, W. A.; Adam, Charles F.; and Gerdes, Ronald M.: Pilot Use of Simulator Cues for Autorotation Landings. 42nd Annual National Forum and Technology Display of the American Helicopter Society, Washington, D.C., June 2-4, 1986.

5. Key, David L.; Hansen, Raymond S.; Cleveland, William B.; and Abbott, William Y.: Helicopter Simulation Validation Using Flight Data. AGARD Flight Mechanics Panel Symposium, Ground/Flight Test Techniques and Correlation, Cesme, Turkey, Oct. 1982; also in AGARD Conference Proceedings No. 339.

6. Clement, Warren F.; Cleveland, William B.; and Key, David L.: Assessment of Simulation Fidelity Using Measurements of Piloting Technique in Flight. AGARD Conference Proceedings No. 359, Monterey, Calif., 1984.

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

8. Ballin, Mark G.; and Dalang-Secrétan, Marie-Alix: Validation of the Dynamic Response of a Blade-Element UH-60 Simulation Model in Hovering Flight. 46th Annual National Forum and Technology Display of the American Helicopter Society, Washington, D.C., May 21-23, 1990.

9. Schroeder, J. A.; Moralez, E.; and Merrick, V. K.: Simulation Evaluation of the Control System Command Monitoring Concept for the NASA V/S TOL Research Aircraft (VSRA). AIAA Paper 87-2255-CP, Monterey, Calif., 1987.

10. McFarland, Richard E.: Transport Delay Compensation for Computer-Generated Imagery Systems. Royal Aeronautical Society Conference, Flight Simulation: Recent Developments in Technology and Use, London, April 12 and 13, 1988.

11. Motion Cues in Flight Simulation and Simulator-Induced Sickness. AGARD Report No. CP-433, 1988.

12. McCauley, M. E.: Research Issues in Simulator Sickness. Proceedings of a Workshop. National Academy Press, Washington, D.C., 1984.

13. McCauley, Michael E.; Cook, Anthony M.; and Hettinger, Lawrence J.: Simulation Sickness. Proceedings of the NASA Steering Committee and a Summary of Recent Research, Royal Aeronautical Society Conference, Progress in Helicopter and V/STOL Aircraft Simulation, London, May 1 and 2, 1990.

ACKNOWLEDGEMENTS

This paper includes the results of the extensive investigative efforts of many people at the NASA Ames Research Center and the U.S. Army's Aeroflightdynamics Laboratory in trying to understand and improve the fidelity and validity of ground-based piloted simulation. The author particularly wants to thank Adolph Atencio of the U.S. Army's Aeroflightdynamics Laboratory for the information on the recent UH-60 investigations.

Table 1.– VMS Motion Specification

Axis	Nominal operational limits		
	Displacement	Velocity	Acceleration
	Performance after upgrade		
Vertical	17 m	5 m/sec	7 m/sec^2
Lateral	12 m	2.5 m/sec	4.5 m/sec^2
Longitudinal	2.4 m	1.2 m/sec	3 m/sec^2
Roll	18°	40°/sec	115°/sec^2
Pitch	18°	40°/sec	115°/sec^2
Yaw	24°	46°/sec	115°/sec^2
	Performance before upgrade		
Vertical	17 m	5 m/sec	7 m/sec^2
Lateral	12 m	2.5 m/sec	4.5 m/sec^2
Longitudinal	0	0	0
Roll	20°	20°/sec	60°/sec^2
Pitch	20°	20°/sec	60°/sec^2
Yaw	20°	20°/sec	60°/sec^2

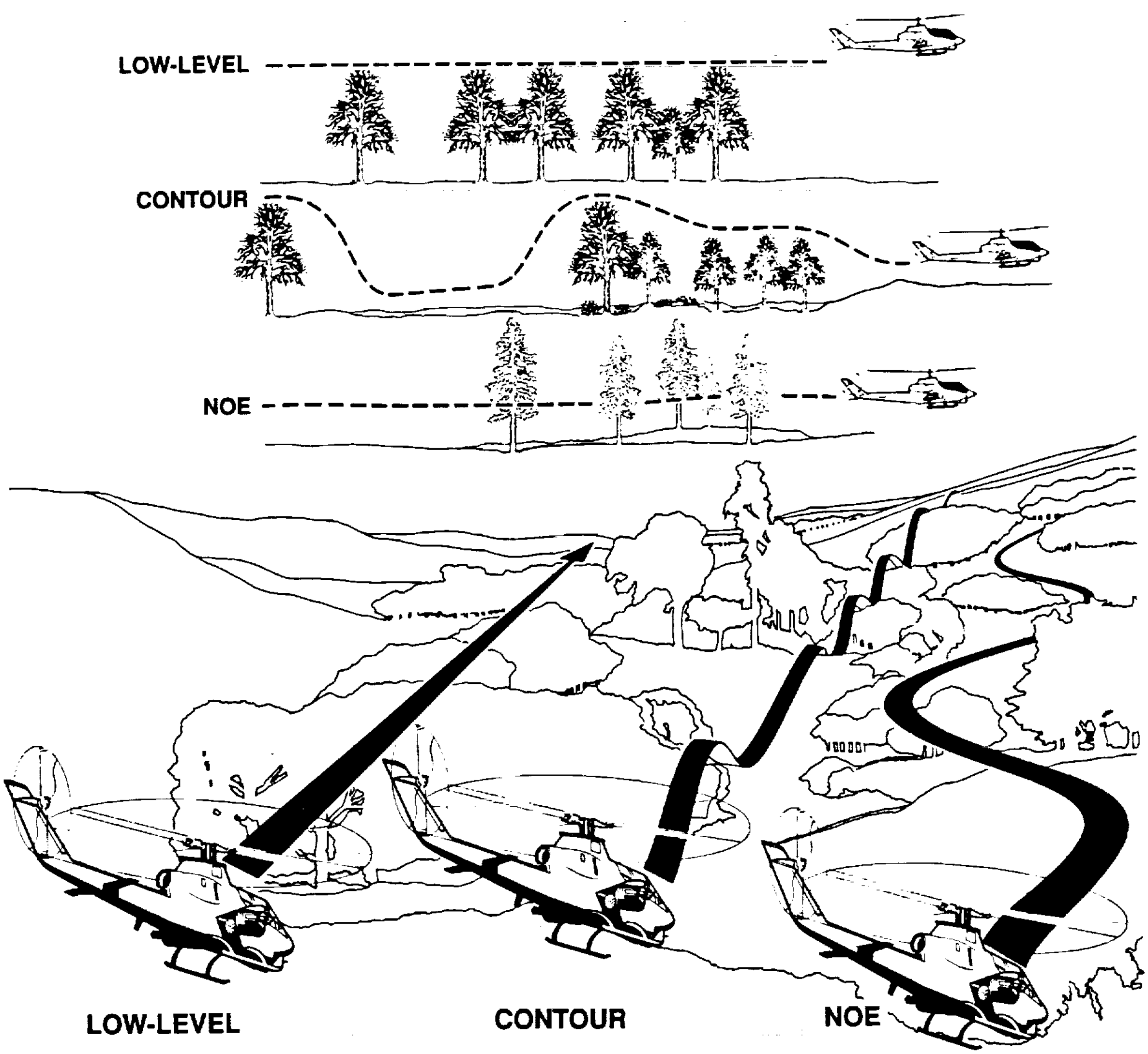


Figure 1.– Modes of helicopter flight near the ground.

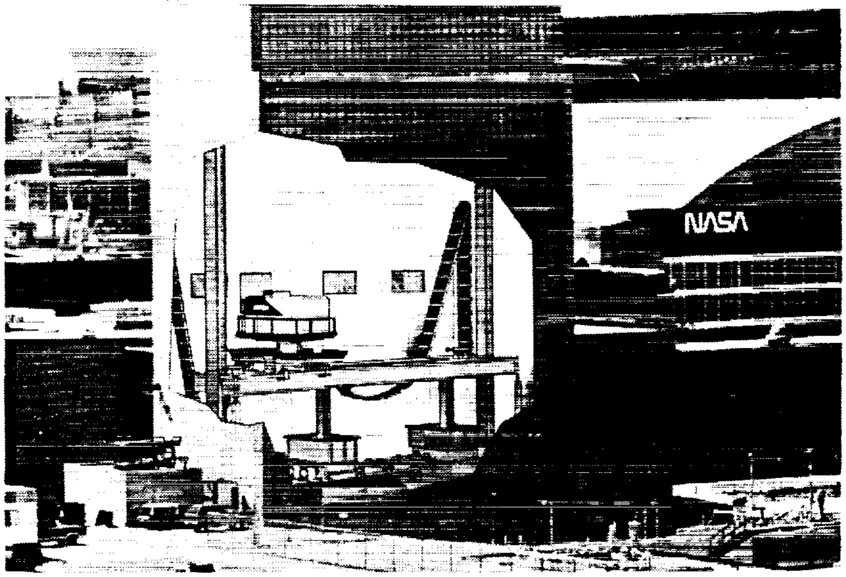


Figure 2.– Vertical Motion Simulator.

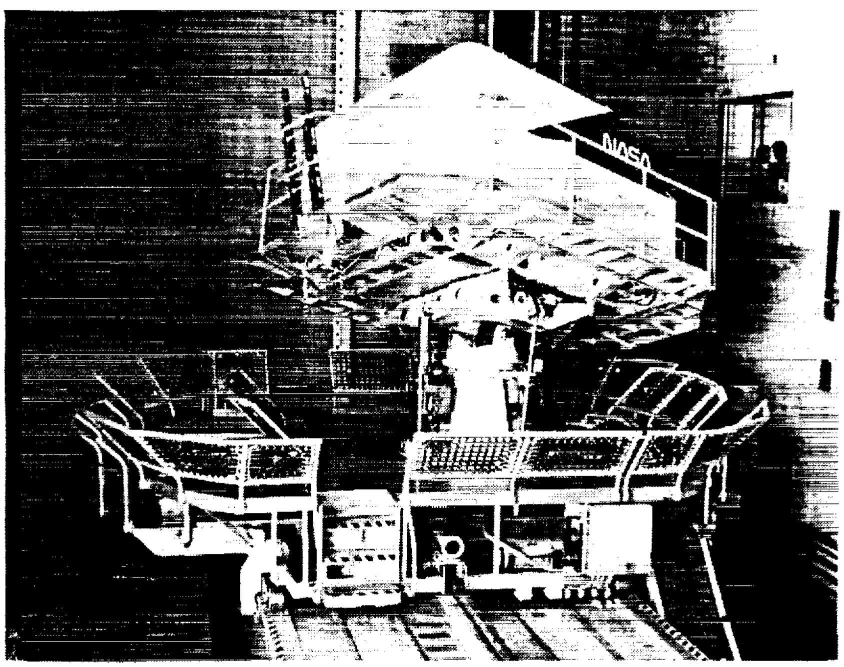


Figure 3.– Interchangeable cab mounted on VMS motion base.

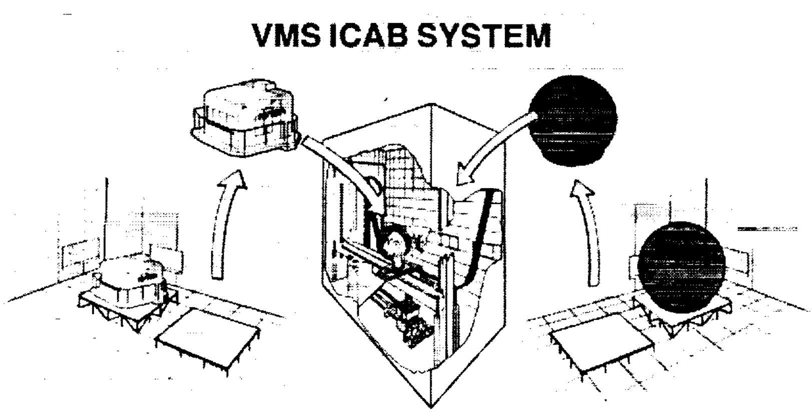
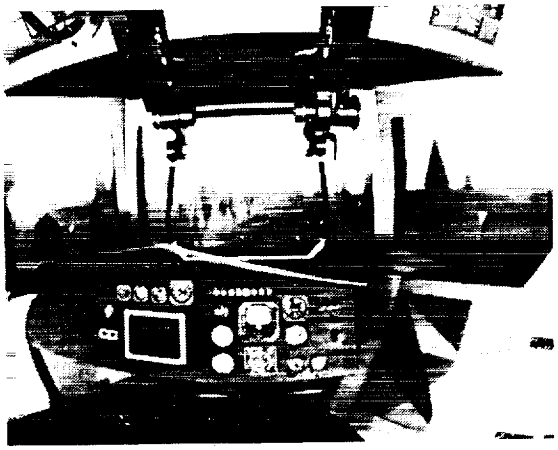
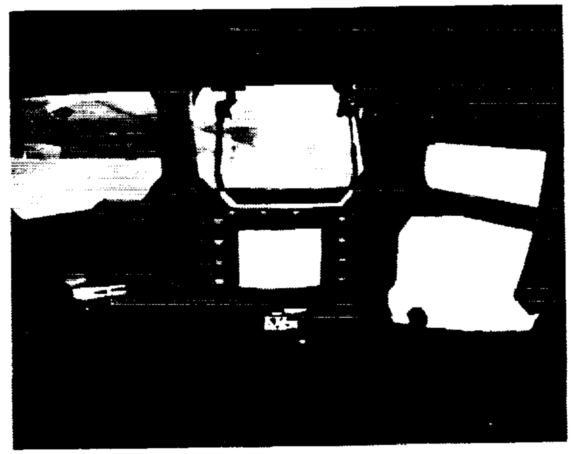


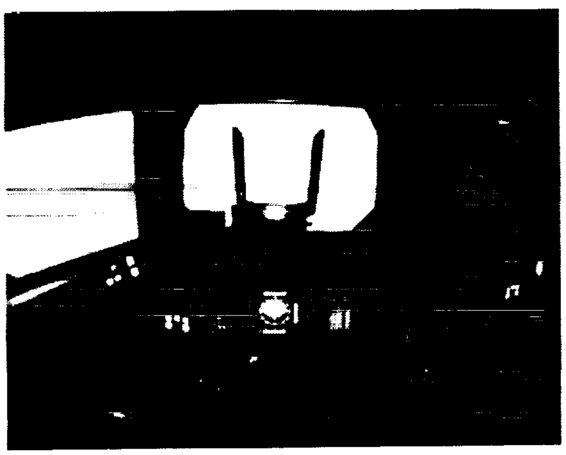
Figure 4.– Interchangeable cab design for VMS.



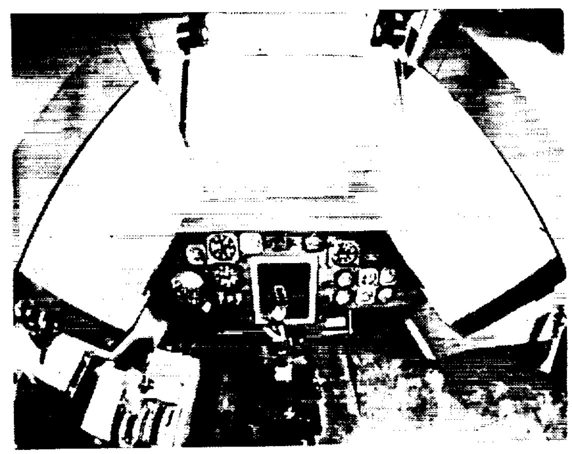
(a) Rotorcraft



(b) Rotorcraft



(c) Transport



(d) Fighter.

Figure 5.– Sample cockpit and visual scene configurations for VMS cabs using CRT monitors.

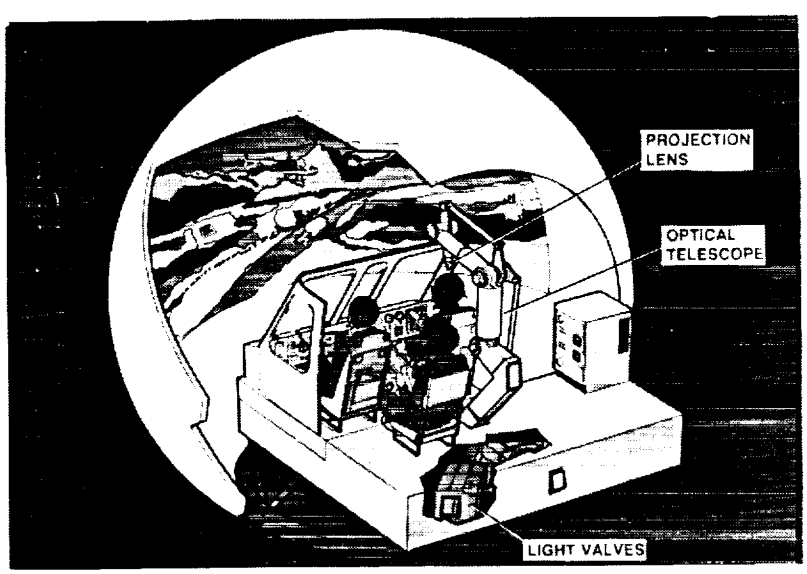


Figure 6.– Dome projection cab for future VMS use.

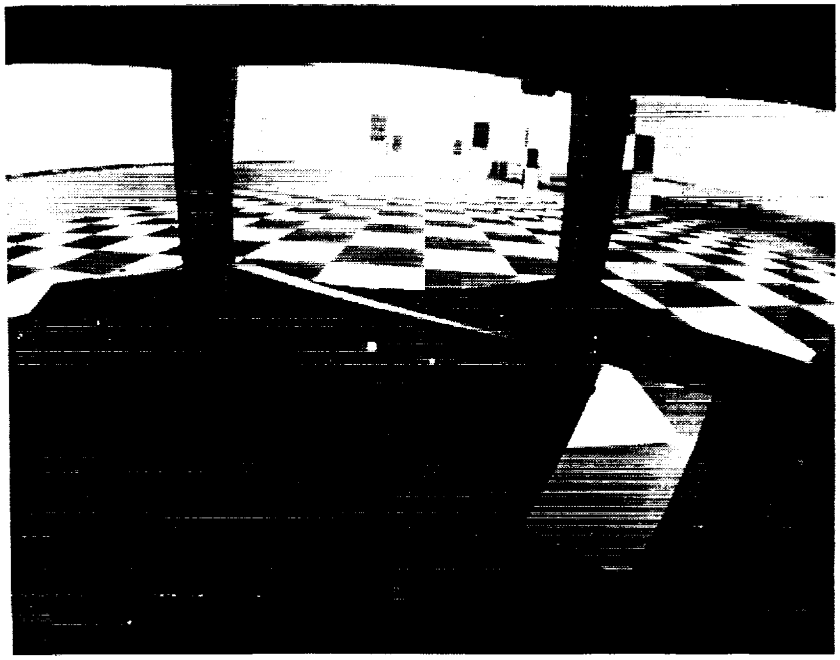


Figure 7.– Computer-generated image view of airfield, with black-and-white checkerboard landing zone, for VMS autorotation experiments.

Figure 8.– Computer-generated image view of airfield, with gray-shaded checkerboard landing zone, for VMS autorotation experiments.

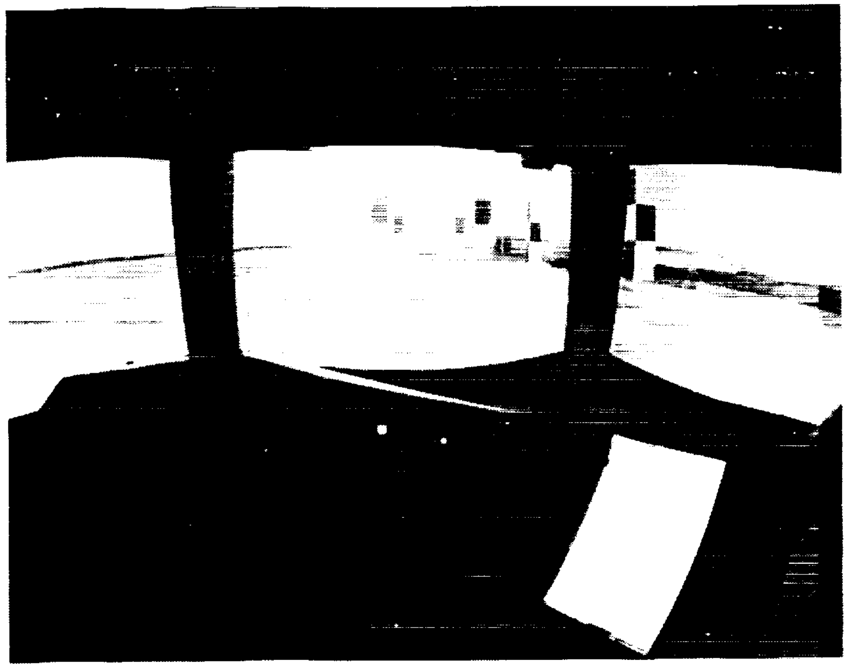


Figure 9.– Computer-generated image view of tree-lined canyon for VMS autorotation experiments.

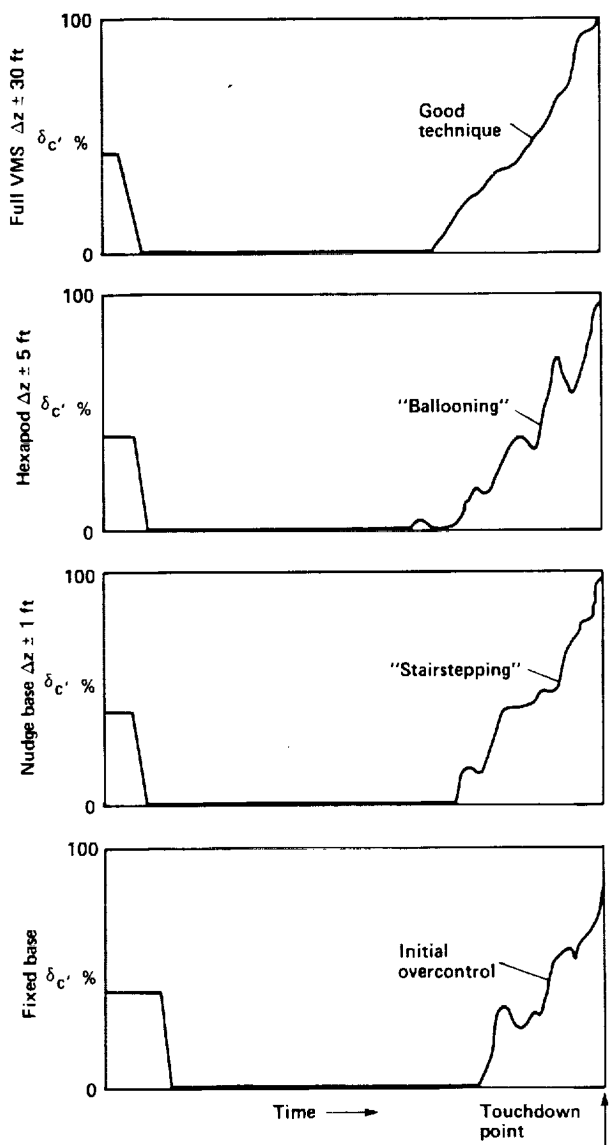


Figure 10.– Time-histories of collective control position during autorotation landings with variations of simulator motion cue levels.

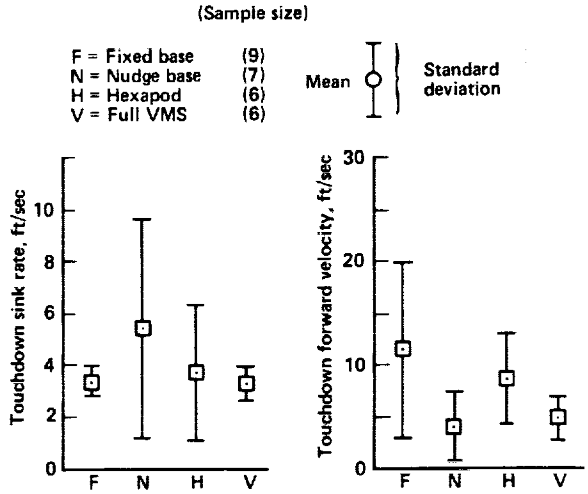


Figure 11.– Autorotation landing performance statistics for VMS experiment: pilot B, 8,000-lb helicopter.

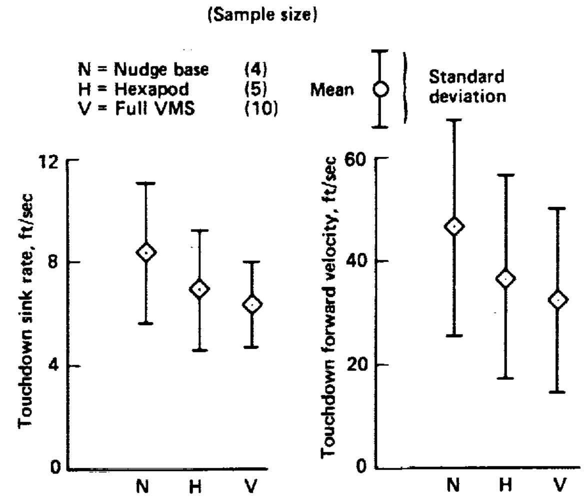


Figure 13.– Autorotation landing performance statistics for VMS experiment: pilot F, 10,000-lb helicopter.

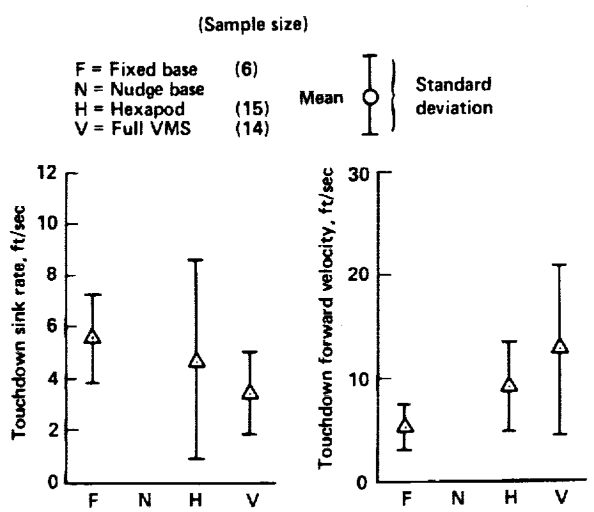


Figure 12.– Autorotation landing performance statistics for VMS experiment: pilot A, 8,000-lb helicopter.

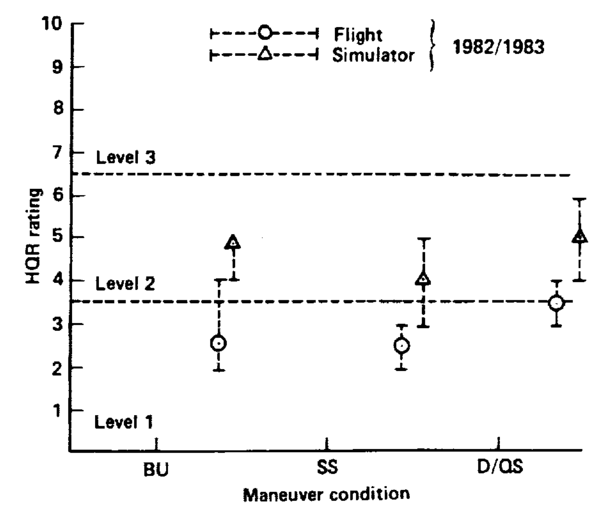
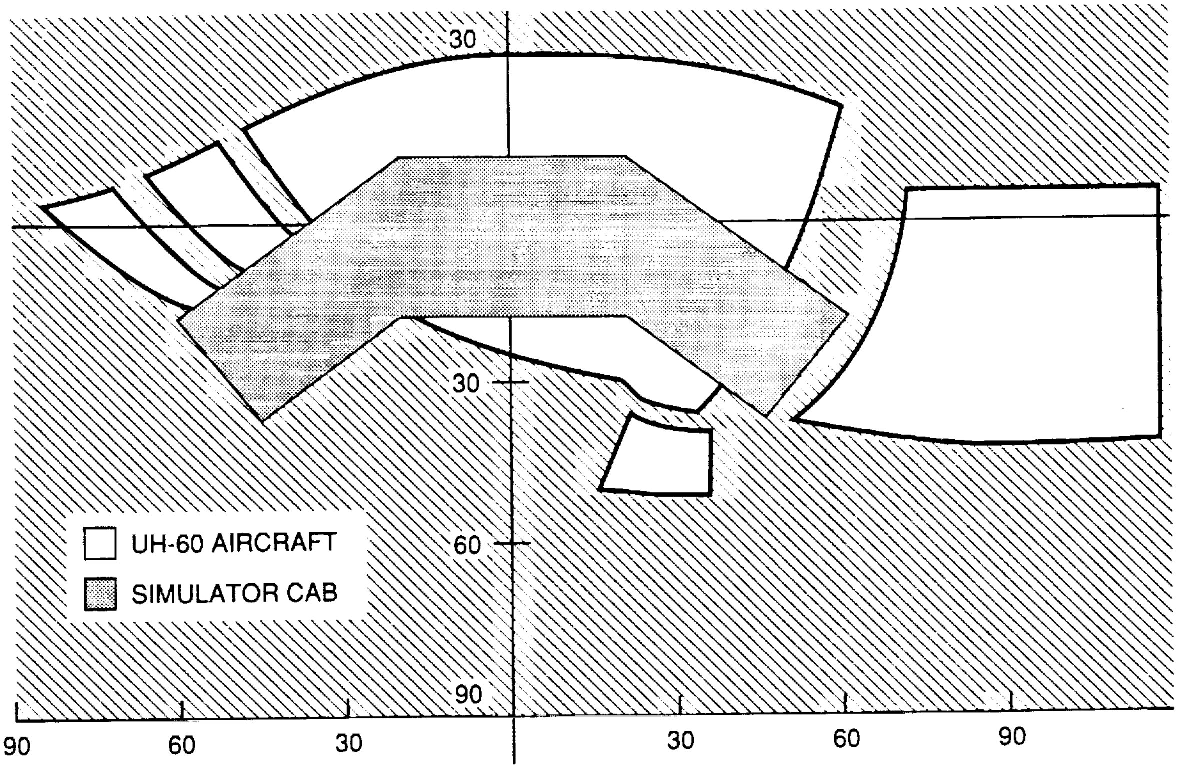
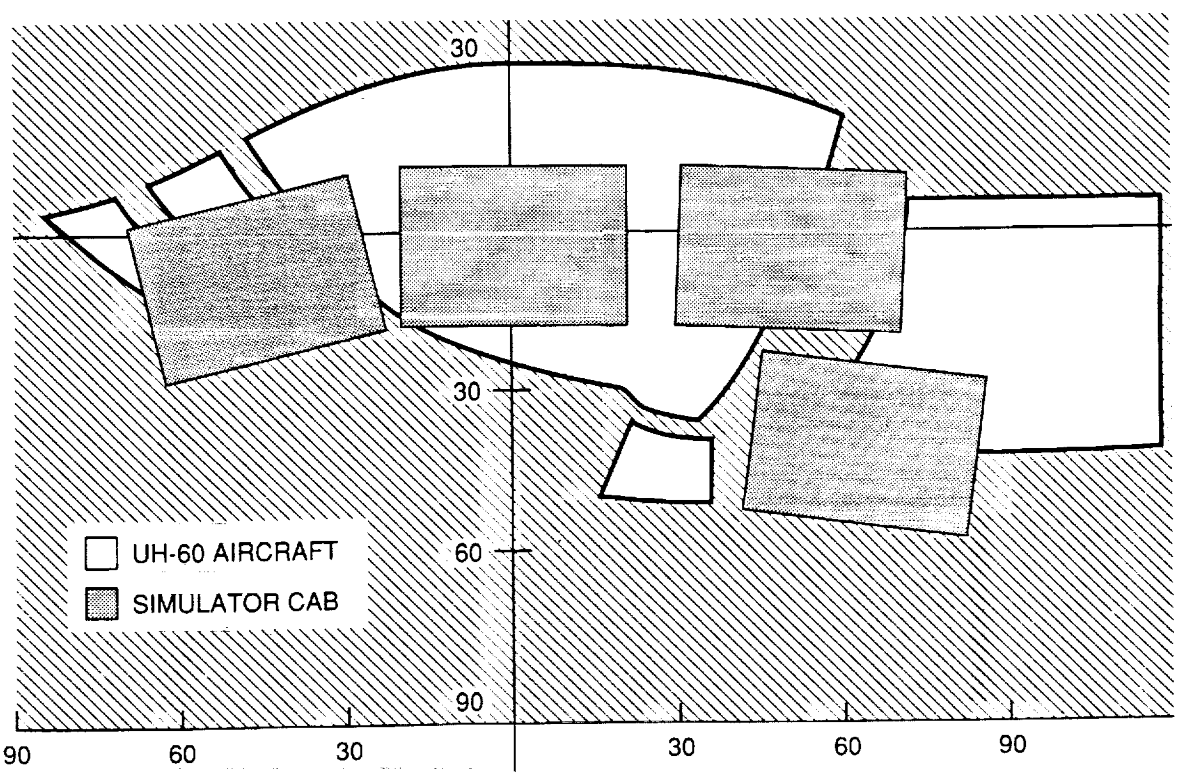


Figure 14.– Comparison of handling-qualities ratings from flight and simulation experiments conducted in 1982/1983, for UH-60 helicopter in three maneuver tasks.



(a) F-Cab (Three window)



(b) N-Cab (Four window)

Figure 15.– Comparison of pilot's field of view between the UH-60 helicopter and two VMS cabs with CRT windows.

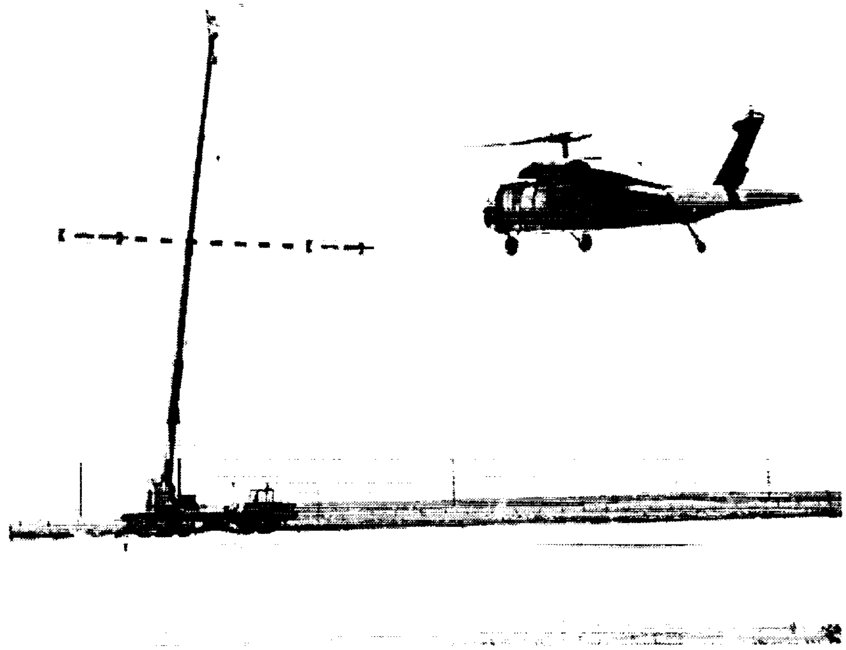


Figure 16.– UH-60 conducting sidestep maneuver against target at Crow's Landing test site.

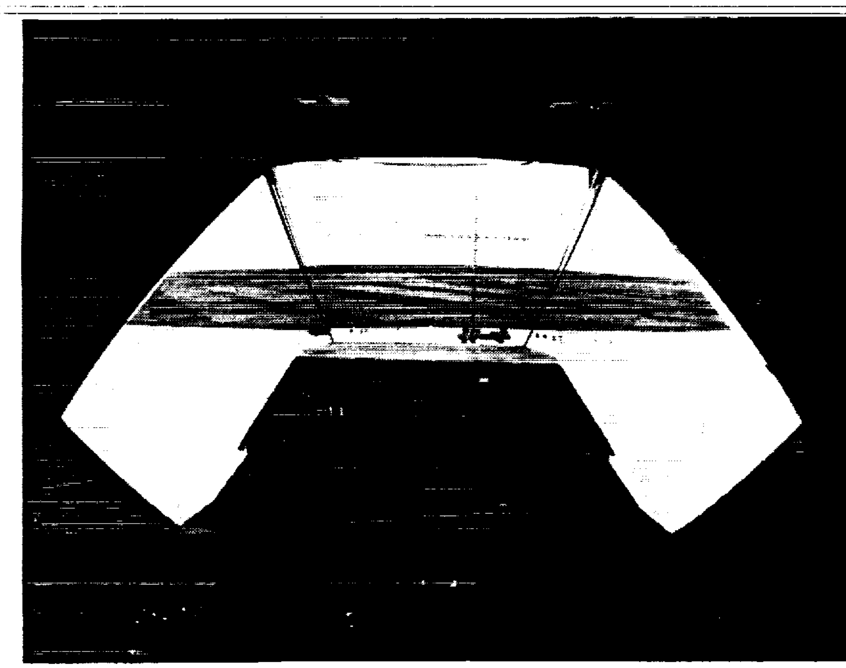


Figure 17.– Pilot view of VMS computer-generated image of sidestep target at Crow's Landing test site.

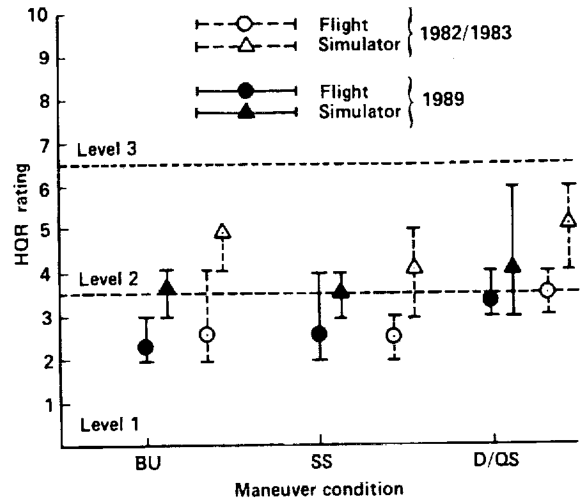


Figure 18.– Comparison of handling-qualities ratings, between flight and simulator experiments conducted in 1982 and 1983, and in 1989, for UH-60 helicopter in three maneuver tasks.

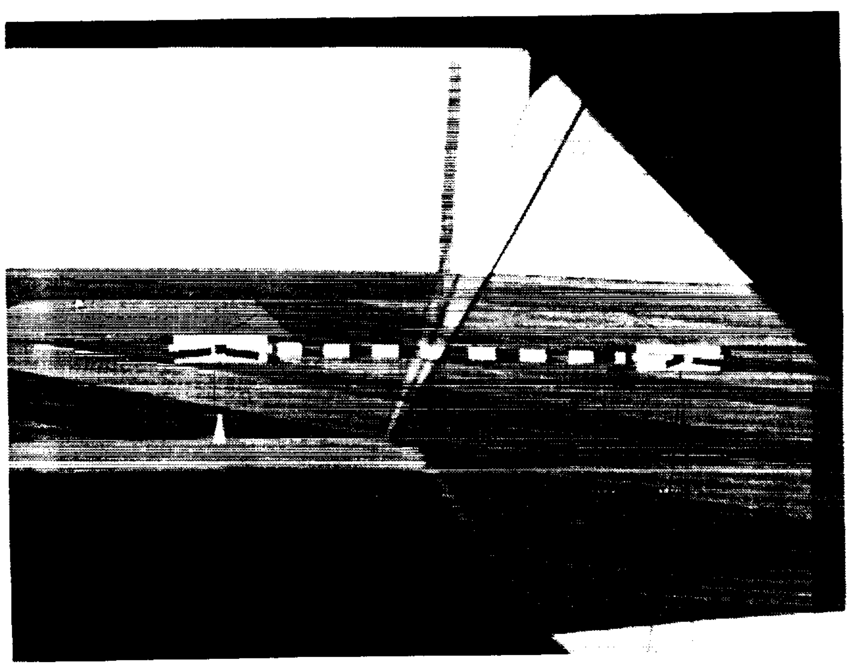
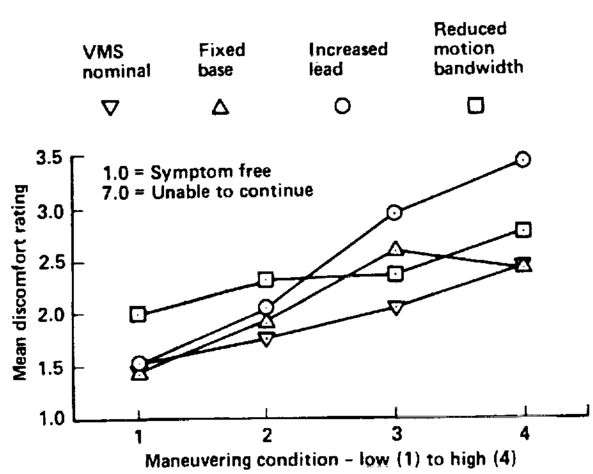


Figure 19.– Close-up view of computer-generated image of target for sidestep maneuver.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH



ORIGINAL PAGE IS
OF POOR QUALITY

Figure 20.– Effects of simulator motion characteristics and aircraft maneuver task on pilot mean discomfort rating.

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-102830		

4. Title and Subtitle	5. Report Date
Simulation of Nap-of-the-Earth Flight in Helicopters	February 1991
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Gregory W. Condon	A-90178
	10. Work Unit No.
	505-66-29
9. Performing Organization Name and Address	11. Contract or Grant No.
Ames Research Center Moffett Field, CA 94035-1000	
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, DC 20546-0001	14. Sponsoring Agency Code

15. Supplementary Notes

Point of Contact: Gregory W. Condon, Ames Research Center, MS 243-1,
Moffett Field, CA 94035-1000; (415) 604-5567 or FTS 464-5567

Presented at AGARD 50th Symposium, Computer Aided System Design and Simulation, Izmir, Turkey, May 22-25, 1990.

16. Abstract

NASA Ames Research Center, in conjunction with the co-located U.S. Army R&T Laboratory's Aeroflightdynamics Directorate, has conducted extensive simulation investigations of rotorcraft in the nap-of-the-Earth (NOE) environment and has developed facility capabilities specifically designed for this flight regime. This paper reports on the experience gained to date in applying these facilities to the NOE flight regime and on the results of specific experimental investigations conducted to understand the influence of both motion and visual scene on the fidelity of NOE simulation. Included are comparisons of results from concurrent piloted simulation and flight research investigations. The results of a recent simulation experiment to investigate simulator sickness in this flight regime are also discussed.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Helicopter Flight simulation Simulation technology	Unclassified-Unlimited Subject Category - 05

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	20	A02

NASA FORM 1626 OCT 86

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