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DEVELOPMENT OF ADOCS CONTROLLERS AND CONTROL LAWS

VOLUME 1 - EXECUTIVE SUMMARY

Kenneth H. Landis
Steven I. Glusman

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United States Army
Aviation Systems
Command
St. Louis, Missouri 63120

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VOLUME 1 - EXECUTIVE SUMMARY

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Prepared for
Aeromechanics Laboratory
U.S. Army Research and Technology
Laboratories (AVSCOM)
under Contract NAS2-10880

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National Aeronautics and
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United States Army
Aviation Systems
Command
St. Louis, Missouri 63120

The Following Three Documents Comprise the ACC/AFCS Final Report:

THIS VOLUME IS **Volume 1 Executive Summary**

Volume 2 Literature Review and Preliminary Analysis

Volume 3 Simulation Results and Recommendations

FOREWORD

This report was prepared by the Boeing Vertol Company for the Aeromechanics Laboratory, U.S. Army Research and Technology Laboratories (AVRADCOM) under NASA-Ames Research Center Contract NAS2-10880 as part of the Army's Advanced Digital/Optical Control System (ADOCS) program managed by the Applied Technology Laboratory, Ft. Eustis, VA. Bruce B. Blake was the project manager and Kenneth H. Landis was the project engineer. Edwin W. Aiken of the U.S. Army Aeromechanics Laboratory at NASA-Ames Moffett Field, CA. supported the program as the contract monitor.

The authors of this report are grateful to the following personnel for their contribution to the success of this program:

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ACRONYMS

AAH	Advanced Attack Helicopter
AC/RA	Acceleration Command/Rate Stabilization
ACC/AFCS	Advanced Cockpit Controls/Advanced Flight Control System
ADOCS	Advanced Digital/Optical Control System
AFCS	Automatic Flight Control System
AFFDL	Air Force Flight Dynamics Laboratory
ASH	Advanced Scout Helicopter
AT/AT	Attitude Command/Attitude Stabilization
AT/LV	Attitude Command/Velocity Stabilization
CGI	Computer Generated Imagery
CHR	Cooper-Harper Rating
CMD/STAB	Command/Stabilization
FLIR	Forward-Looking Infrared
HLH	Heavy Lift Helicopter
HMD	Helmet Mounted Display
HMS	Helmet Mounted Sight
IHADSS	Integrated Helmet and Display Sighting System
IMC	Instrument Meterological Conditions
LV/LV	Velocity Command/Velocity Stabilization
LV/PH	Velocity Command/Position Hold
NOE	Nap-of-the-Earth
PFCS	Primary Flight Control System
PIO	Pilot Induced Oscillations
PNVS	Pilot Night Vision System
RA/AT	Rate Command/Attitude Stabilization

Acronyms (Continued)

RPM	Rotations Per Minute
SCAS	Stability and Control Augmentation System
SSC	Side-Stick Controller
TAGS	Tactical Aircraft Guidance System
VMC	Visual Meterological Conditions
VMS	Vertical Motion Simulator

1.0 SUMMARY

The Advanced Cockpit Controls/Advanced Flight Control System (ACC/AFCS) study was conducted by the Boeing Vertol Company as part of the Army's Advanced Digital/Optical Control System (ADOCS) program. Specifically, the ACC/AFCS investigation was aimed at developing the flight control laws for the ADOCS demonstrator aircraft that will provide satisfactory handling qualities for an attack helicopter mission. The three major elements of design considered during the ACC/AFCS study are summarized as follows:

- o Pilot's Integrated Side-Stick Controller (SSC)--Number of axes controlled; force/displacement characteristics; ergonomic design.

- o Stability and Control Augmentation System (SCAS)--Digital flight control laws for the various mission phases; SCAS mode switching logic.

- o Pilot's Displays--For night/adverse weather conditions, the dynamics of the superimposed symbology presented to the pilot in a format similar to the Advanced Attack Helicopter (AAH) Pilot Night Vision System (PNVS) for each mission phase as a function of SCAS characteristics; display mode switching logic.

Two phases were part of the ACC/AFCS study; Phase 1 included a literature review, preliminary control law analysis, and piloted simulations to evaluate side-stick controller designs and control law requirements for low-speed and low-altitude nap-of-earth flight under IMC. Full-envelope control laws were developed during Phase 2, and piloted simulation was continued to evaluate implementation of high-speed/transition control laws and modified side-stick controller designs developed from the Phase 1 simulations.

Findings from the literature review and the analysis and synthesis of desired control laws are reported in Volume 2. Results of the five piloted simulations conducted at the Boeing Vertol and NASA-Ames simulation facilities are presented in Volume 3. Conclusions drawn from analysis of pilot rating data and commentary were used to formulate recommendations for the ADOCS demonstrator flight control system design. The ACC/AFCS simulation data also provide an extensive data base to aid the development of advanced flight control system designs for future V/STOL aircraft.

2.0 INTRODUCTION

The Advanced Cockpit Controls/Advanced Flight Control System (ACC/AFCS) design study was performed for The Aeromechanics Laboratory, U.S. Army Research and Technology Laboratories (AVRADCOM) under NASA Ames Research Center Contract NAS2-10880. Boeing Vertol was awarded the ACC/AFCS contract in December 1980 as part of the Army's Advanced Digital/Optical Control System (ADOCS) program managed by the Applied Technology Laboratory, Fort Eustis, Va. under Contract DAAK51-82-C-0002.

The ADOCS Program is aimed at developing a battlefield-compatible advanced flight control system which can substantially increase aircraft mission effectiveness in part through decreased pilot workload and improved handling qualities. The objectives of the program are: (1) the development of the technology required for a digital optical flight control system, (2) the integration of the new technology with advanced flight control concepts into a demonstrator aircraft, and (3) the demonstration of the advantages of the system in the areas of: mission effectiveness, handling qualities, flight safety, cost, weight/volume, survivability/vulnerability, and reliability/maintainability. The ADOCS program is divided into two phases: The first involves the development of component technology for a digital optical flight control system while the second is devoted to the development of the ADOCS demonstrator system. The first flight of the demonstrator aircraft, a UH-60A Black Hawk, is scheduled for the fall of 1984.

Figure 2-1 is a schedule which shows major activities of the ACC/AFCS study. Phase 1 consisted of a literature review, preliminary analysis and design, and three piloted simulations. The primary purpose of Phase 1 was to develop a systematic approach to the synthesis of the desired flight control laws for certain critical low-speed, low-altitude portions of the attack helicopter mission for tasks under both visual and instrument meteorological conditions (VMC and IMC, respectively). Variations of the force/deflection characteristics and the number of axes controlled through an integrated side-stick controller (SSC) were investigated. Phase 2 included the synthesis of candidate flight control/display laws for the entire mission including high-speed, transition, and low-speed tasks under both IMC and VMC. An evaluation of automatic control law switching and various selectable mode features was conducted during two simulation phases using the NASA-Ames Vertical Motion Simulator (VMS) Facility.

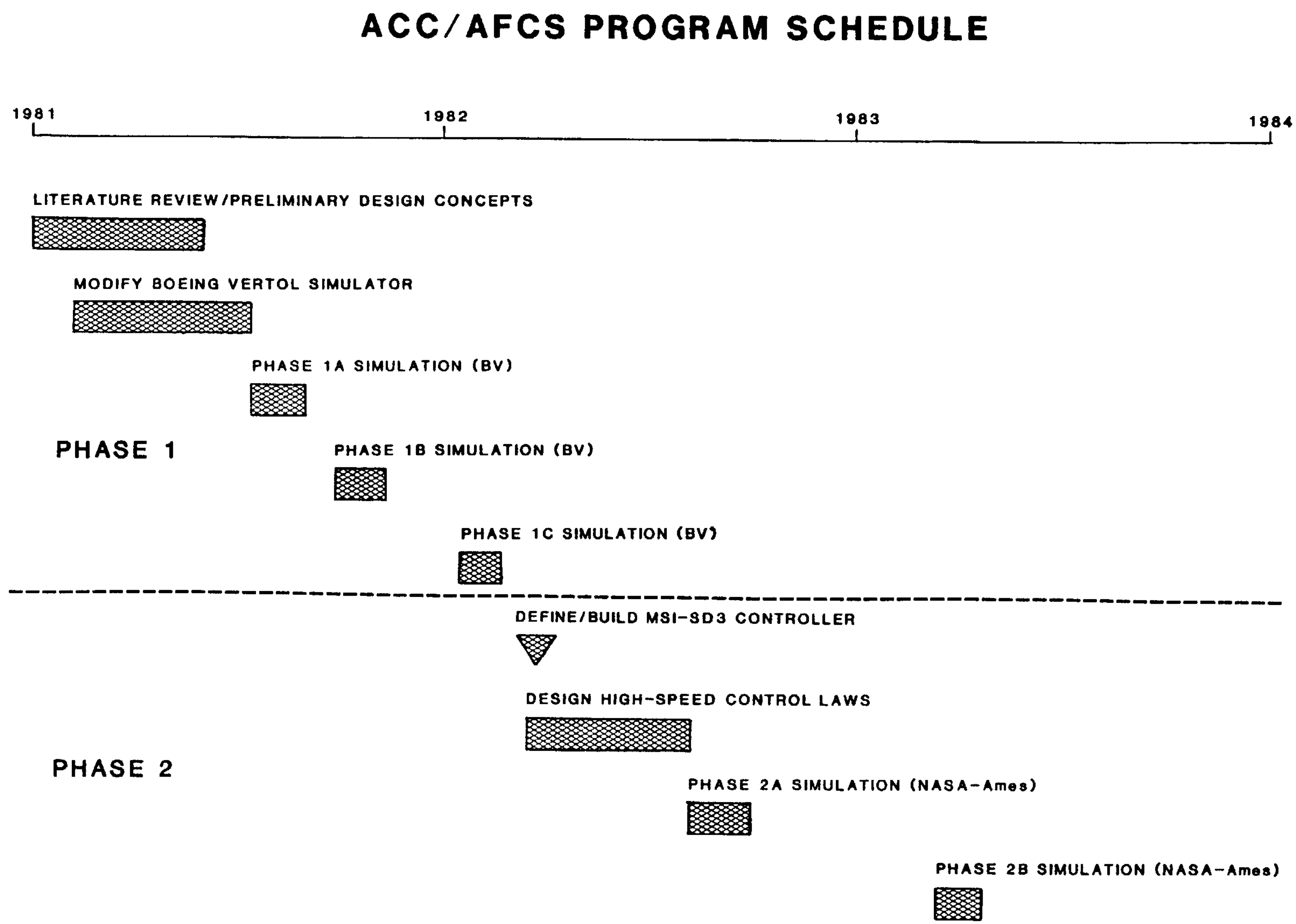

ACC/AFCS PROGRAM SCHEDULE
1981
1982
1983
1984
LITERATURE REVIEW/PRELIMINARY DESIGN CONCEPTS
MODIFY BOEING VERTOL SIMULATOR
PHASE 1A SIMULATION (BV)
PHASE 1
PHASE 1B SIMULATION (BV)
PHASE 1C SIMULATION (BV)
DEFINE/BUILD MSI-SD3 CONTROLLER
DESIGN HIGH-SPEED CONTROL LAWS
PHASE 2
PHASE 2A SIMULATION (NASA-Ames)
PHASE 2B SIMULATION (NASA-Ames)

Figure 2-1

3.0 EXPERIMENT DESIGN

Pilot workload and level of performance achieved during a specific attack helicopter mission task are influenced by combined elements of the helicopter control/display system design. The primary elements considered during this simulation program were:

(1) Side-stick Controller (SSC) Configuration - Stiff or displacement type, and level of integration ranging from a fully-integrated 4-axis side-stick controller to a (2+1+1) arrangement; i.e., a 2-axis side-stick for pitch and roll control with separated directional pedals and a left-hand collective controller.

(2) Stability and Control Augmentation System (SCAS) Characteristics - Several generic types of feedback stabilization and feed-forward command shaping in each of the four control axes (pitch, roll, yaw, and vertical).

(3) Visual Display - Either day VMC with the simulator four-window, wide angle field-of-view visual system, or night IMC using a simulated FLIR image and superimposed YAH-64 Pilot Night Vision System (PNVS) (Reference 1) symbology presented on a helmet-mounted display.

General Approach

The systematic approach to the investigation of these elements is illustrated in Figure 3-1. The overall investigation was directed toward defining those combinations of SSC, SCAS, and display that produce Level 1, 2, and 3 handling qualities ratings (Reference 2).

In applying this general approach to the specific problem, the blocks defined in Figure 3-1 were broken down further into more detailed configuration matrices. For example, each side-stick controller configuration block contains variations in force/displacement relationships as well as ergonomic characteristics. Generic control laws can be mechanized in several different ways with significantly different results. Display symbology involves a myriad of variations in parameters, format, scaling, and logic.

Degraded modes can also be visualized in Figure 3-1. Since the selected controller configuration will be part of the primary flight control system, all allowable degraded modes will lie in the control-law/display-law plane. For example, certain failures such as FLIR loss will affect the display axis only, while loss of a ground velocity signal may affect the system control law and display symbology.

THREE DIMENSIONAL FLIGHT CONTROL SYSTEM DESCRIPTION

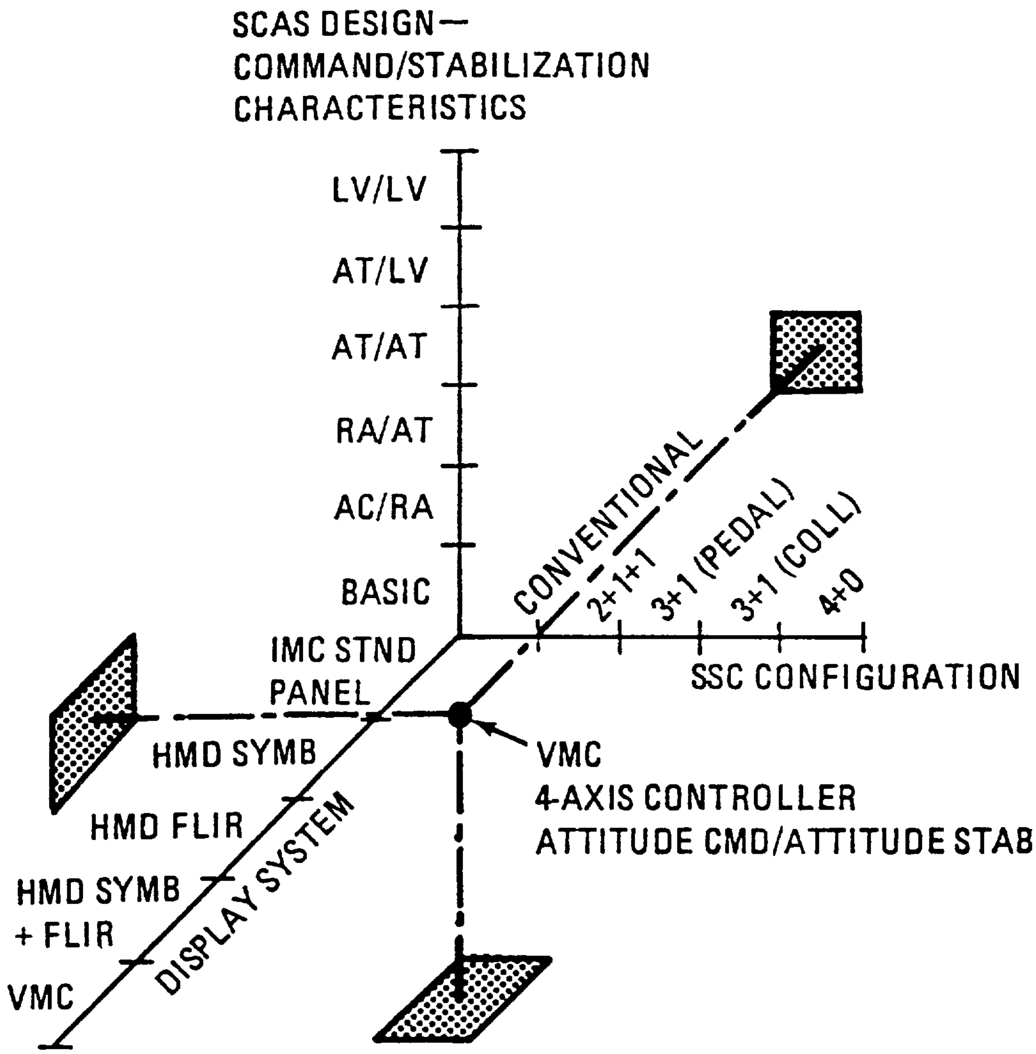


Figure 3-1

By considering the overall system design as a series of matrix levels of increasing detail, the interactive effect on handling qualities of each variation in an element of the system is kept in perspective. A discussion of important issues to be considered within each primary system element follows, including specific details about the controller/SCAS/display characteristics evaluated.

3.1 SIDE-STICK CONTROLLER CONFIGURATION

The experiment was designed to provide a comprehensive evaluation of multi-axis side-stick control for an attack helicopter mission including variations in: (1) the number of axes controlled through the side-stick device, and (2) the force/deflection characteristics of the controller.

The four controller configurations evaluated during Phase 1 are illustrated in Figure 3-2 with the left-hand controller implemented using a conventional collective lever as a force controller. During Phase 2 a side-stick controller replaced the collective lever as the left-hand vertical controller as shown in Figure 3-3. In addition, the (3+1) Pedal configuration was eliminated based on results of Phase 1.

Force/Deflection Characteristics

A definition of acceptable/unacceptable ranges of force/deflection gradient for each controller configuration option (4+0), (3+1), or (2+1+1) was necessary. The determination of desired force/deflection characteristics for the ADOCS demonstrator side-stick controller(s) was performed during the course of this simulation study using seven 4-axis side-stick controllers described in Table 3-1. Force/deflection characteristics for each controller are presented including operating force range, maximum deflection, and force/deflection gradient.

All 4-axis controllers are a base-pivot type for pitch and roll motion. Fore-aft force produces a longitudinal control input and right-left force a lateral control input. Yaw control is obtained by twisting about the grip centerline, and vertical control through application of pure up and down forces.

3.2 STABILITY AND CONTROL AUGMENTATION SYSTEM (SCAS) CHARACTERISTICS

The segments of the attack helicopter mission considered to be critical from a handling qualities point-of-view are those spent in nap-of-the-earth (NOE) flight; those inherently high workload tasks include low-speed point-to-point maneuvering using dash, quick stop, and sideward flight techniques, masked hover in ground effect and unmasked hover out of ground effect including target search, acquisition, and weapon delivery. These simulations were designed to provide a definition of flight control laws and SCAS mode switching logic requirements for the

PHASE 1 CONTROLLER CONFIGURATIONS

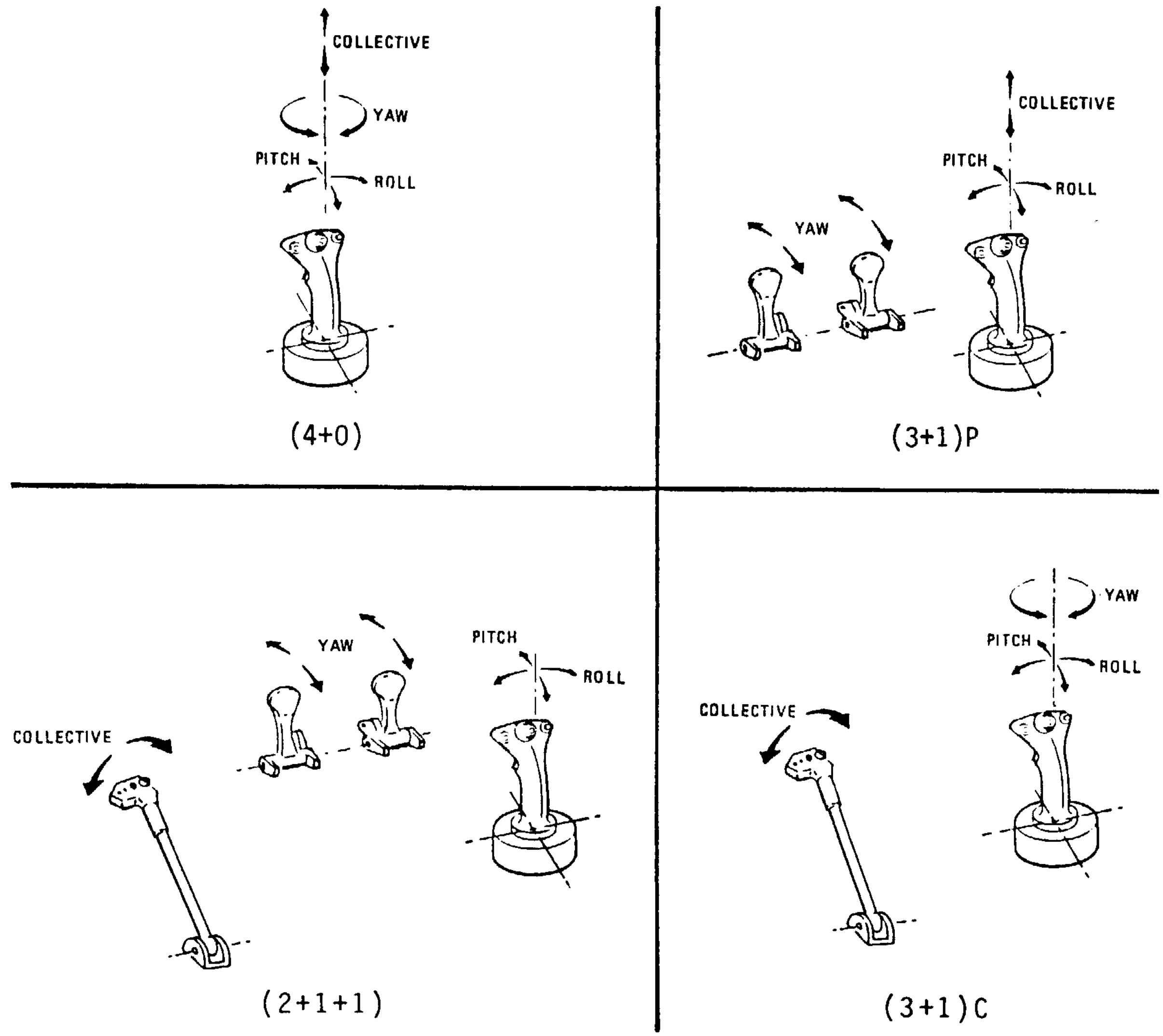


Figure 3-2

PHASE 2 CONTROLLER CONFIGURATIONS

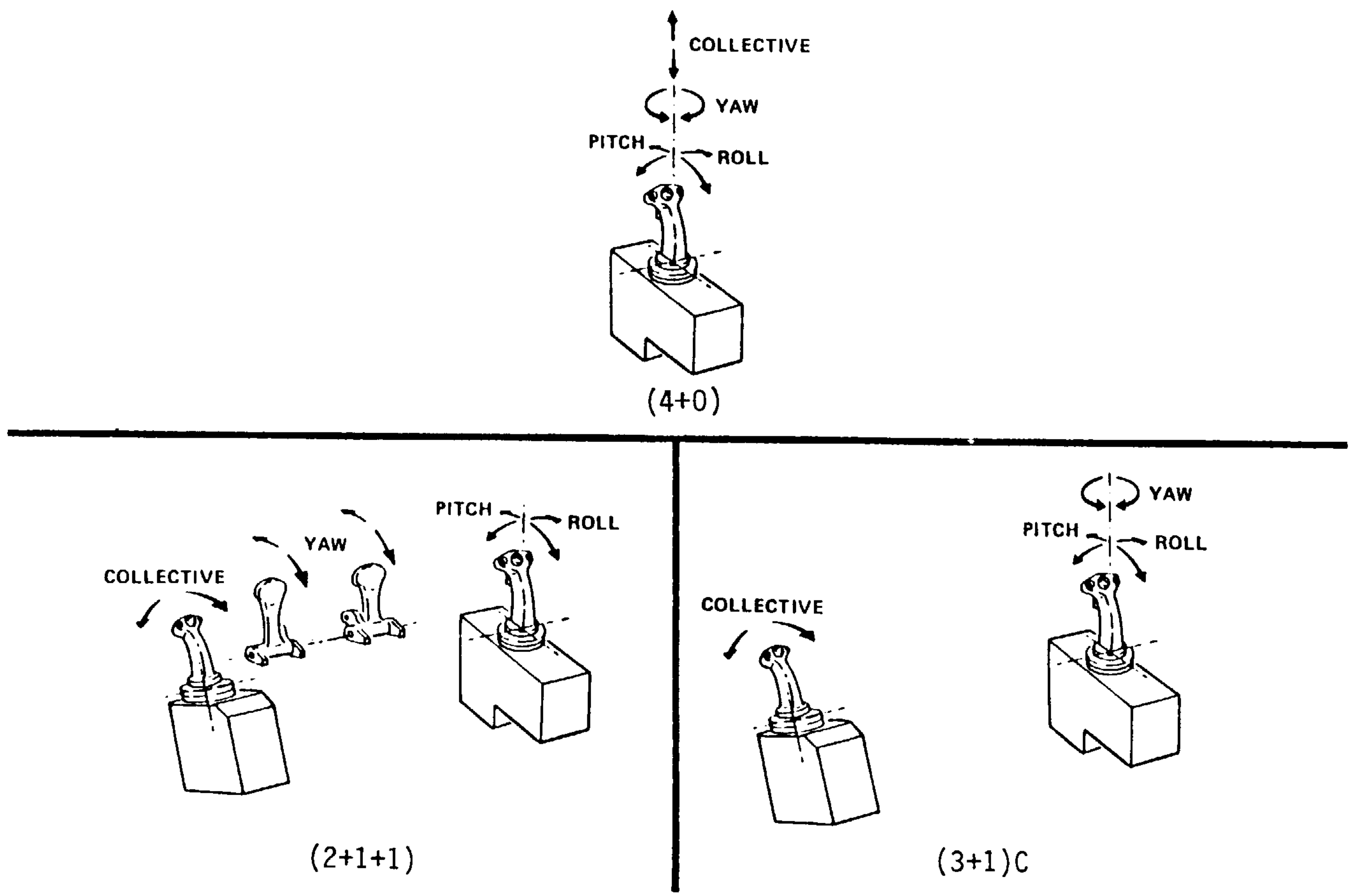


Figure 3-3

4-AXIS CONTROLLER CONFIGURATIONS
FORCE/DEFLECTION CHARACTERISTICS

4-AXIS CONTROLLER CONFIGURATIONS	SIMULATION PHASES		OPERATING FORCE LINEAR RANGE (±)				MAXIMUM DEFLECTION (±)				FORCE/DEFLECTION			
	PHASE 1	PHASE 2	X LONG	Y LAT	Z VERT	ψ YAW	X LONG	Y LAT	Z VERT	ψ YAW	X LONG	Y LAT	Z VERT	ψ YAW
			LBS	LBS	LBS	IN-LBS	DEG	DEG	IN	DEG	LBS/DEG	LBS/DEG	LBS/IN	IN-LBS/DEG
(1) LARGE DEFLECTION - HLH PROTOTYPE	X		—	—	—	—	12.0	12.0	0.5	15.0	0.9	0.6	15.0	0.7
(2) MEDIUM DEFLECTION - HLH PROTOTYPE	X		—	—	—	—	12.0	12.0	0.5	15.0	1.67	1.05	35.0	2.7
(3) SMALL DEFLECTION - (PITCH AND ROLL) MSI-SD1	X		20	20	40	60	5.3	5.3	0.1	4.0	3.05	2.25	400	15.0
(4) STIFF-STICK MSI-SS	X	X	20	20	40	60	0.5	0.5	—	—	40	40	—	—
(5) SMALL DEFLECTION - (PITCH AND ROLL) MSI-SD2	X	X	20	20	40	60	8.3	8.3	0.15	6.0	1.82	1.45	267	10.0
(6) SMALL DEFLECTION - (ALL AXES) MSI-SD3		X	12	12	+24 -21	36	6.6	6.6	.25	10.0	1.82	1.82	+95 -85	3.6
(7) SMALL DEFLECTION - (ALL AXES) LSI - BRASSBOARD		X	15.9	12.8	15.8	35	7.6	7.6	.156	7	2.09	1.67	+95 -85	5.0

Table 3-1

various mission segments. In addition, the effects on both handling qualities and flight safety of reduced levels of stability augmentation were to be determined. The effect of the side-stick controller configuration under degraded SCAS mode conditions is important, since high levels of vehicle stability may mask undesirable characteristics of some controller options. SCAS redundancy requirements also need to be weighed in final selection of a controller configuration. For example, a (3+1) axis controller configuration requiring only rate stabilization may be more cost effective than a 4-axis side-stick controller requiring attitude stabilization to achieve Level 2 handling qualities.

3.2.1 Primary Flight Control System (PFCS) (Figure 3-4)

A quantized controller force-command signal is provided to each PFCS axis. The signal is shaped, adjusted in gain, passed through a derivative rate-limiter, and fed to the AFCS command model and to the primary UH-60A flight-control system through a feed-forward shaping network. Limiting of the AFCS output is also a function of the PFCS, but was not incorporated for this experiment. The specification of force-command signal quantization, nonlinear command shaping, derivative rate-limiter parameters, and forward path lead-lag shaping characteristics are described in detail in Section 4.1 of Volume 2.

3.2.2 Automatic Flight Control System (AFCS)

The AFCS model implemented for the ACC/AFCS simulation was developed in two stages. The original implementation for Phase 1 simulations was designed primarily for hover and low speed flight. Modifications were made for Phase 2 simulations to include additional feedback and feed-forward paths required for forward flight control laws. Specifically, airspeed and lateral acceleration stabilization signals and cross-axis control paths were added for decoupling and automatic turn coordination.

In the longitudinal AFCS, linear velocity stabilization was provided by a longitudinal ground speed signal for airspeeds below 40 knots and by a longitudinal airspeed signal for airspeeds above 45 knots. Switching between the two signals was transient-free.

The lateral AFCS was designed for this experiment to switch between a roll attitude command/lateral velocity stabilization system at low speed and a roll rate command/attitude hold system for higher speed maneuvering flight. This hybrid lateral AFCS was provided as a selectable feature.

The attack helicopter mission dictates precise hover control to maintain horizontal position while executing Precision Hover and Bob-up Tasks. Accordingly, feed-forward and feedback paths were incorporated in the longitudinal and lateral AFCS control laws to provide a pilot-selectable Hover-Hold Mode. The Hover-

ADOCS PFCS DESIGN

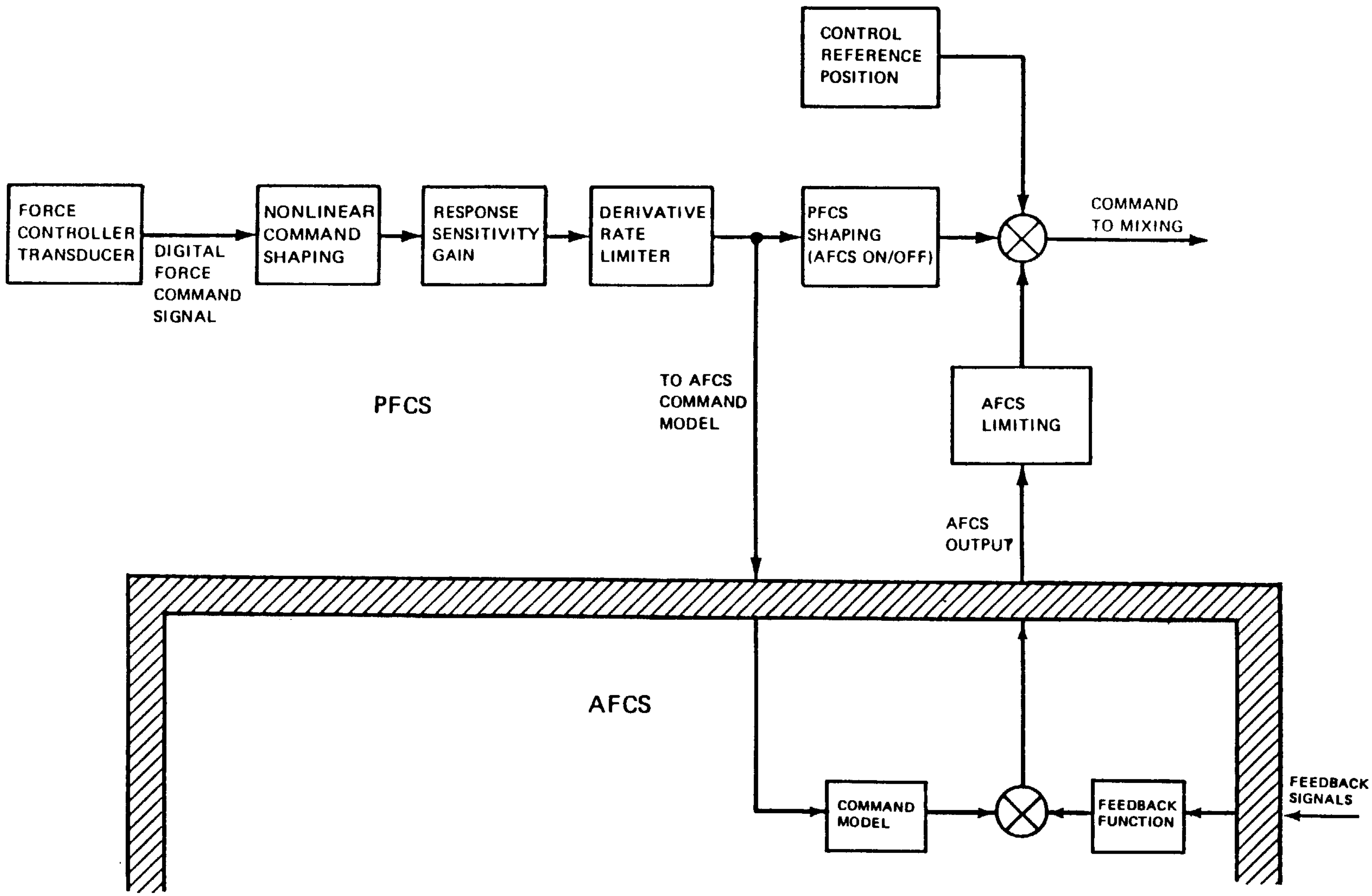


Figure 3-4

Hold Mode provides a velocity-command system with high gain velocity stabilization with or without position feedback. Longitudinal and lateral position reference signals used in the position feedback are derived from groundspeed signals.

The directional AFCS includes yaw rate stabilization with a selectable Heading Hold feature. A cross-axis command path provides an appropriate yaw rate command in forward flight for automatic turn coordination based on airspeed and bank angle. Feed-forward command shaping provides a yaw rate command system if Heading Hold is selected and a yaw acceleration system with the Heading Hold Mode disabled.

The vertical AFCS was implemented with gain scheduling as a function of airspeed for the altitude and altitude rate feedback paths. This was necessary to achieve tight altitude hold for Precision Hover Tasks, while keeping lower stabilization gains to reduce collective control system activity during high speed flight. Command model gains were also altered appropriately to provide the desired vertical response to control inputs at all airspeeds.

3.3 VISUAL DISPLAY SYSTEM

Since the ADOCS mission is to be flown at night or in adverse weather conditions, as well as in VMC, it is necessary to consider not only the effects of the controller and SCAS characteristics, but also the effect on handling qualities of the pilot's night-vision aids. For this experiment, flight under IMC was simulated using the Honeywell Integrated Helmet and Display Sight System (IHADSS). Computer generated symbology, similar to that used with the AH-64 Apache Pilot Night-Vision System (PNVS), was superimposed on a 30° by 40° monochromatic image of the terrain board (Figure 3-5) and presented to the pilot on the helmet-mounted display (HMD). This imagery slaved to the pilot's head movements in azimuth and elevation and driven by aircraft motion parameters, provided the only visual cues available to the evaluation pilot. The pilot's line of sight is tracked with a helmet-mounted sight (HMS) that provides closed-loop command signals to point the terrain-board camera which simulates a turret-mounted night-vision sensor. Since the HMD is coupled to the pilot's head motions, he is able to scan a wide field-of-view without being constrained to a head-down or look-forward position.

A unique feature of this experiment was the capability to easily evaluate and compare the effect of VMC and IMC on pilot ratings and task performance. IHADSS was installed at both simulation facilities for simulation of IMC.

IHADSS HOVER MODE SYMBOLOGY

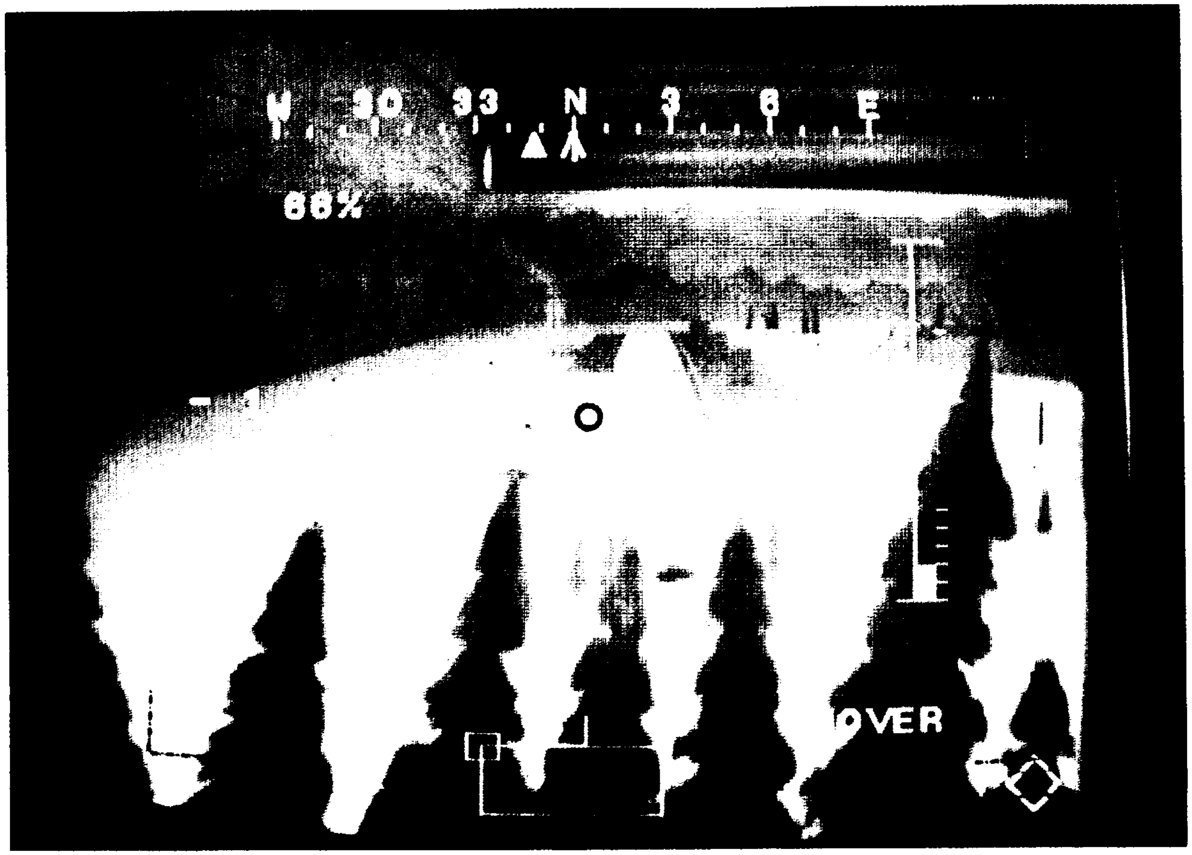


Figure 3-5

4.0 CONDUCT OF EXPERIMENT

4.1 FACILITY DESCRIPTION

Five piloted simulation experiments were conducted as part of the ACC/AFCS study. Three simulations were completed during Phase 1 at the Boeing Vertol Flight Simulator Facility, and two were conducted during Phase 2 at the NASA Ames Vertical Motion Simulator (VMS). The following sections describe these two simulator facilities.

Boeing Vertol Flight Simulation Facility

The major elements of the Boeing Vertol Simulator are shown in Figure 4-1. The cockpit cab is mounted on a six-degree-of-freedom limited-motion base. Both conventional helicopter collective and directional controls were implemented as small-displacement force controllers and adjustable mountings of the various candidate side-stick controllers was provided. A four-camera, wide-angle television visual display system was used to simulate VMC. Figure 4-2 is a photograph which shows a typical scene presented to the simulator pilot on final approach to an airport. The center window video channel was used to provide the IMC image seen with the IHADSS.

Terrain Board

The terrain board developed for the first phase of the simulation is shown in Figure 4-3. The model board is a 200:1 scale model which includes a runway with evenly spaced obstacles for a Slalom Task, a tree-lined river-bed canyon for NOE maneuvers, and various locations for bob-up and lateral jink (sideward) maneuvering.

NASA-Ames Vertical Motion Simulator (VMS)

Ames Research Center's Vertical Motion Simulator (VMS) Facility (Reference 3) has a six-degree-of-freedom moving-base with 60 feet of available vertical travel (Figure 4-4). Modifications, similar to those made on the Boeing cockpit, were also completed on the NASA-Ames cab. In addition to the IHADSS tracking hardware and the right-hand SSC installation, the Ames cockpit was modified to accommodate a left-hand SSC for vertical control. Both SSC mountings were adjustable to provide a comfortable orientation which minimized interaxis cross-coupling of control inputs.

For the VMC portion of the evaluation performed during Phase 2 at NASA Ames, the visual scene was provided using a four-window, color computer generated image (CGI) display system. Two databases were available with the CGI, an NOE course (Figure 4-5) designed as a replica of the terrain board at Boeing Vertol and an airport runway scene (Figure 4-6) utilized to perform Slalom and Approach-to-Hover Tasks.

BOEING VERTOL
SMALL MOTION FLIGHT SIMULATION FACILITY WITH MULTI-WINDOW VISUAL DISPLAY

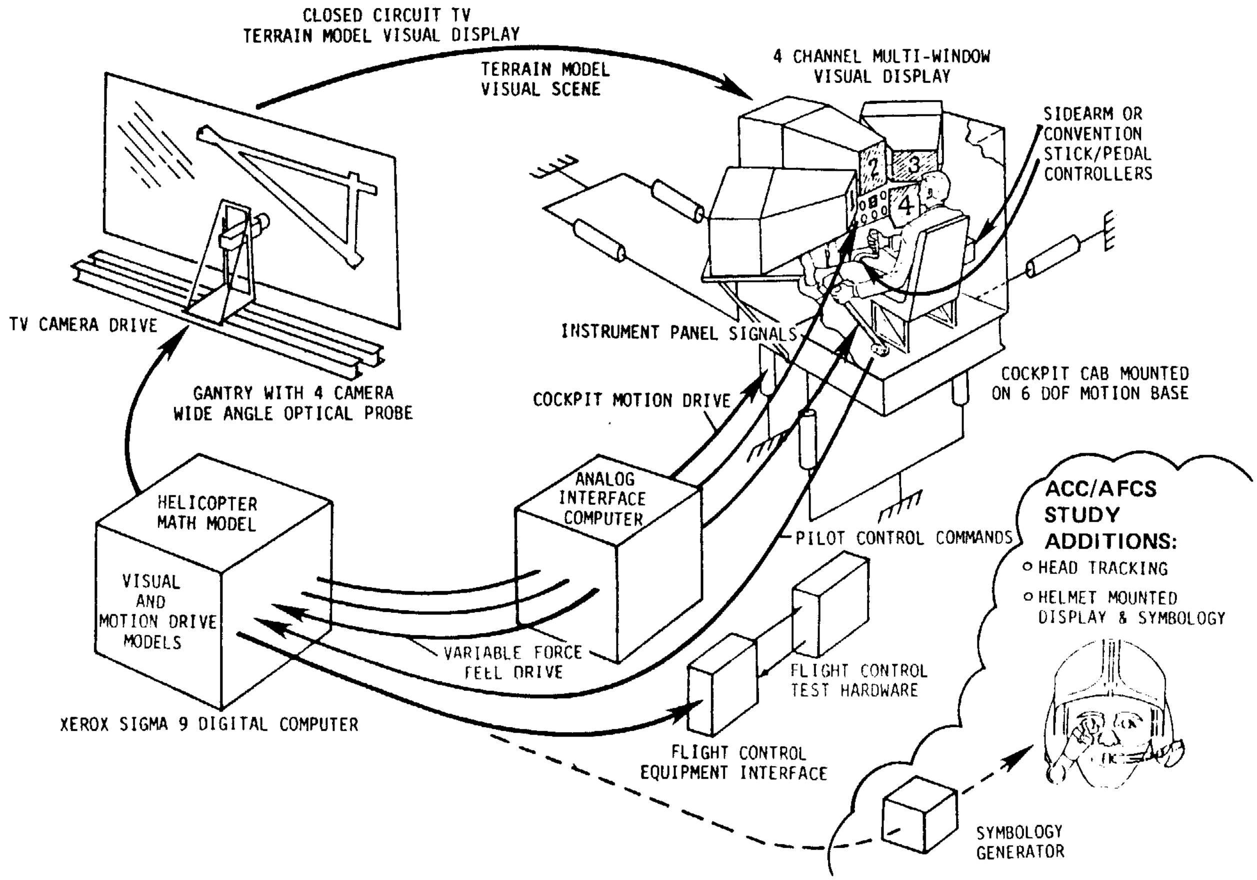
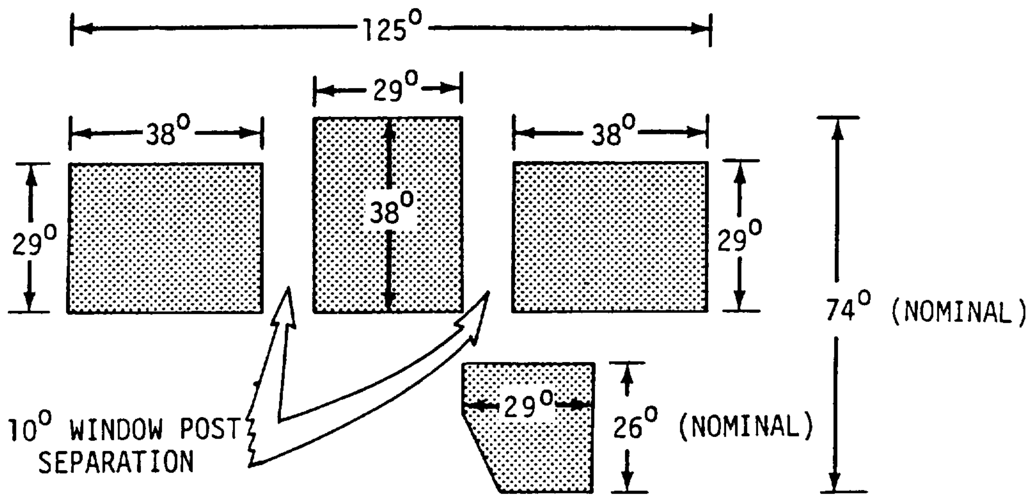


Figure 4-1

APPROACH TO AIRPORT SCENE - B.V. SIMULATOR



COCKPIT WINDOW FIELD OF VIEW

FINAL APPROACH TO AIRPORT

Figure 4-2

ACC/AFCS TERRAIN BOARD

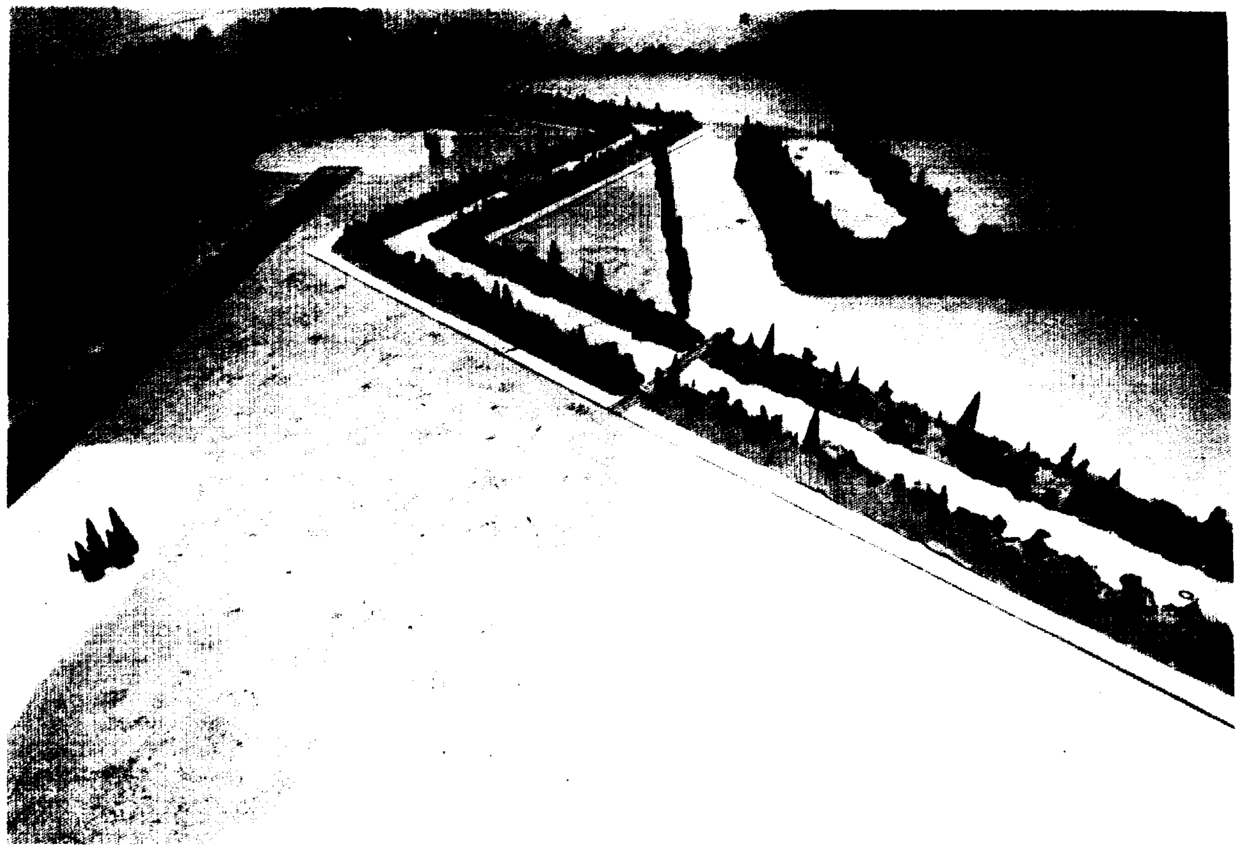


Figure 4-3

NASA-AMES VERTICAL MOTION SIMULATOR

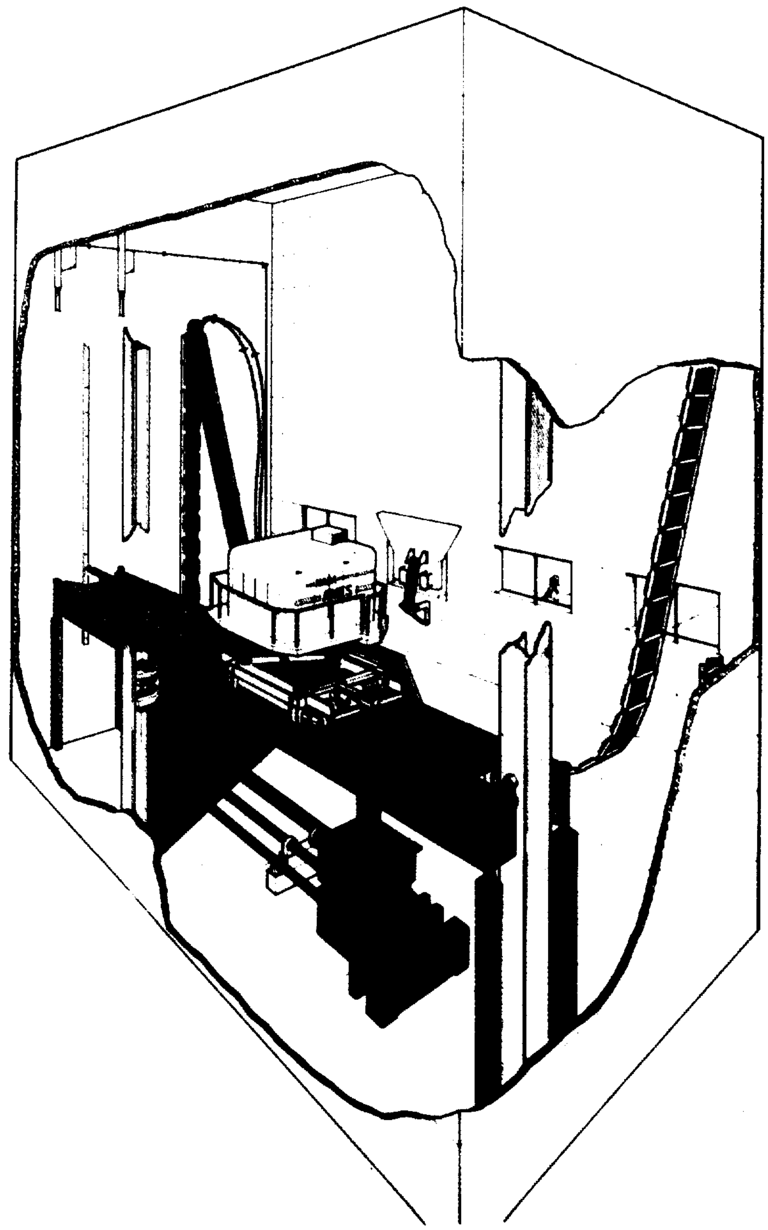


Figure 4-4

CGI DISPLAY — NOE COURSE

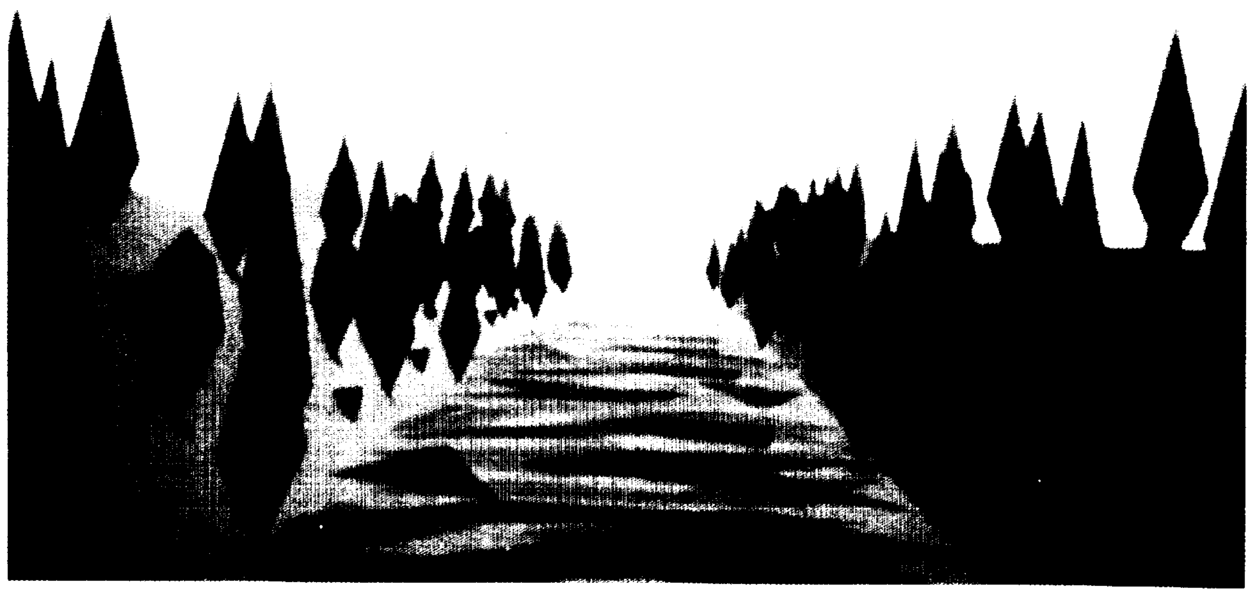


Figure 4-5

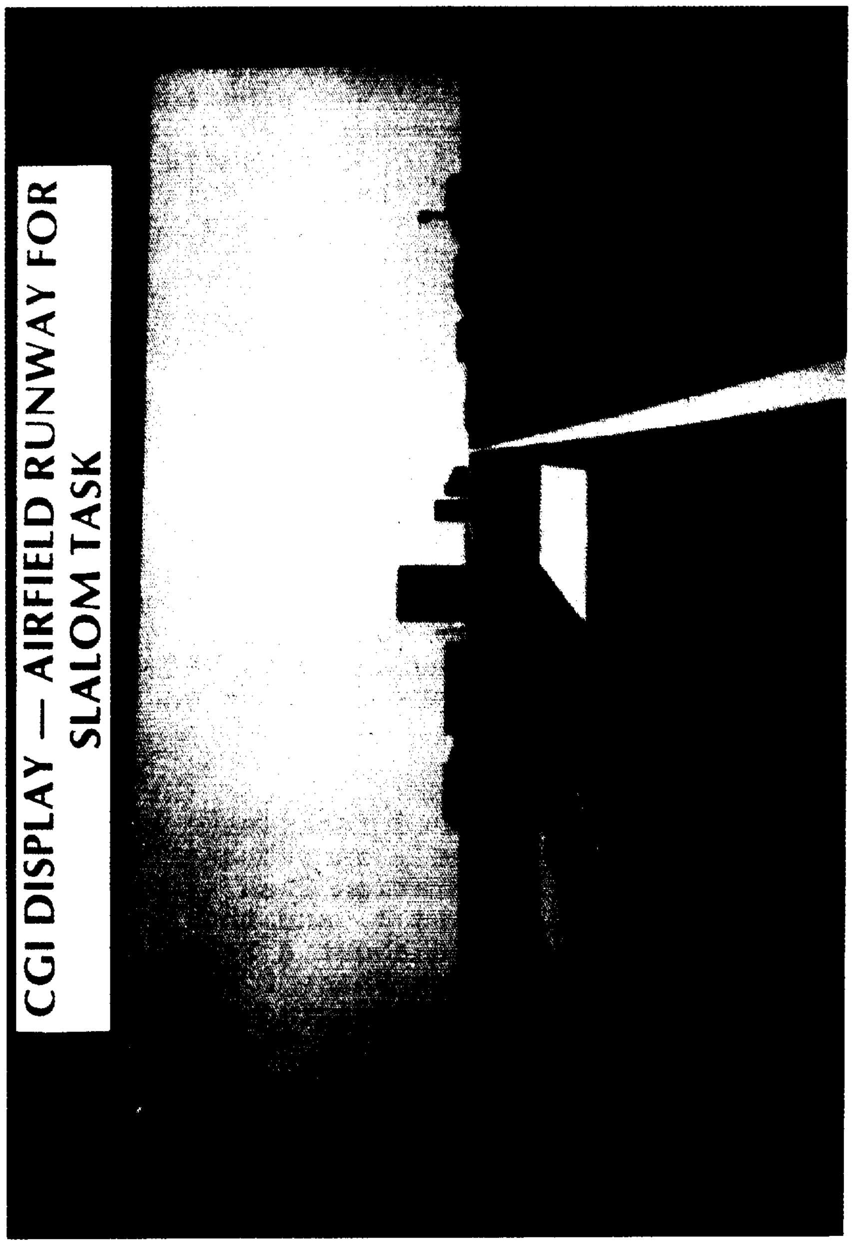


Figure 4-6

During Phase 2B, when handling qualities were evaluated under IMC, the visual scene was simulated using a 300:1 scale terrain board and camera visual system. The same NOE course and airport runway with obstacles were constructed on a model board to perform identical tasks thereby allowing direct comparison of Phase 1 and Phase 2 data.

4.2 AIRCRAFT MATH MODEL

During both phases of the ACC/AFCS study, simulation of the baseline flight vehicle (the UH-60A) was provided by a generic single main rotor helicopter math model. Both simulations included six-degree-of-freedom rigid body dynamics as well as main and tail rotor RPM degrees of freedom configured to represent the Black Hawk helicopter. Also included in both simulations were a canted tail rotor, control mixing, a movable stabilator, and UH-60A fuselage aerodynamics. The NASA Ames model contained three degree-of-freedom tip-path plane dynamics which were not included in the Boeing Vertol model.

4.3 EVALUATION TASKS

Evaluation of total system (pilot, controllers, SCAS, displays) performance was accomplished using a variety of standardized tasks performed under both VMC and IMC. These tasks, are divided up into three main categories: 1) low-speed tasks, 2) high-speed tasks, and 3) transition tasks. During the performance of these tasks, no secondary duties (i.e. armament, communication, or navigation system management) were required of the pilot. The following paragraphs describe each task.

Low-Speed Tasks

Figure 4-7 illustrates the low-speed tasks used for evaluation of handling qualities during Phase 1 and Phase 2 simulation periods. The Acceleration/Deceleration Task along the airport runway was performed only for Phase 1, and the Precision Hover Task where position was maintained about a rock located at the end of the NOE course was added for Phase 2 simulations. Effects of larger motion cues and a simulated gust environment made this task important for defining control response shaping for Precision Hover. The NOE, 30-Knot Slalom, and Bob-up Tasks were performed during both simulation phases. The NOE was a multi-axis task performed in a simulated riverbed. The 30-Knot Slalom involved avoiding evenly spaced obstacles on a runway while maintaining altitude, airspeed, and ground track. The Bob-up Task required a vertical climb, a turn to acquire a target, and a descent; all while maintaining X-Y position.

High-Speed Tasks

In addition to the low speed tasks, high speed Slalom Tasks were defined for the Phase 2 simulation as illustrated in Figure 4-8. The 140-Knot Slalom Task could not be evaluated under

LOW-SPEED EVALUATION TASKS

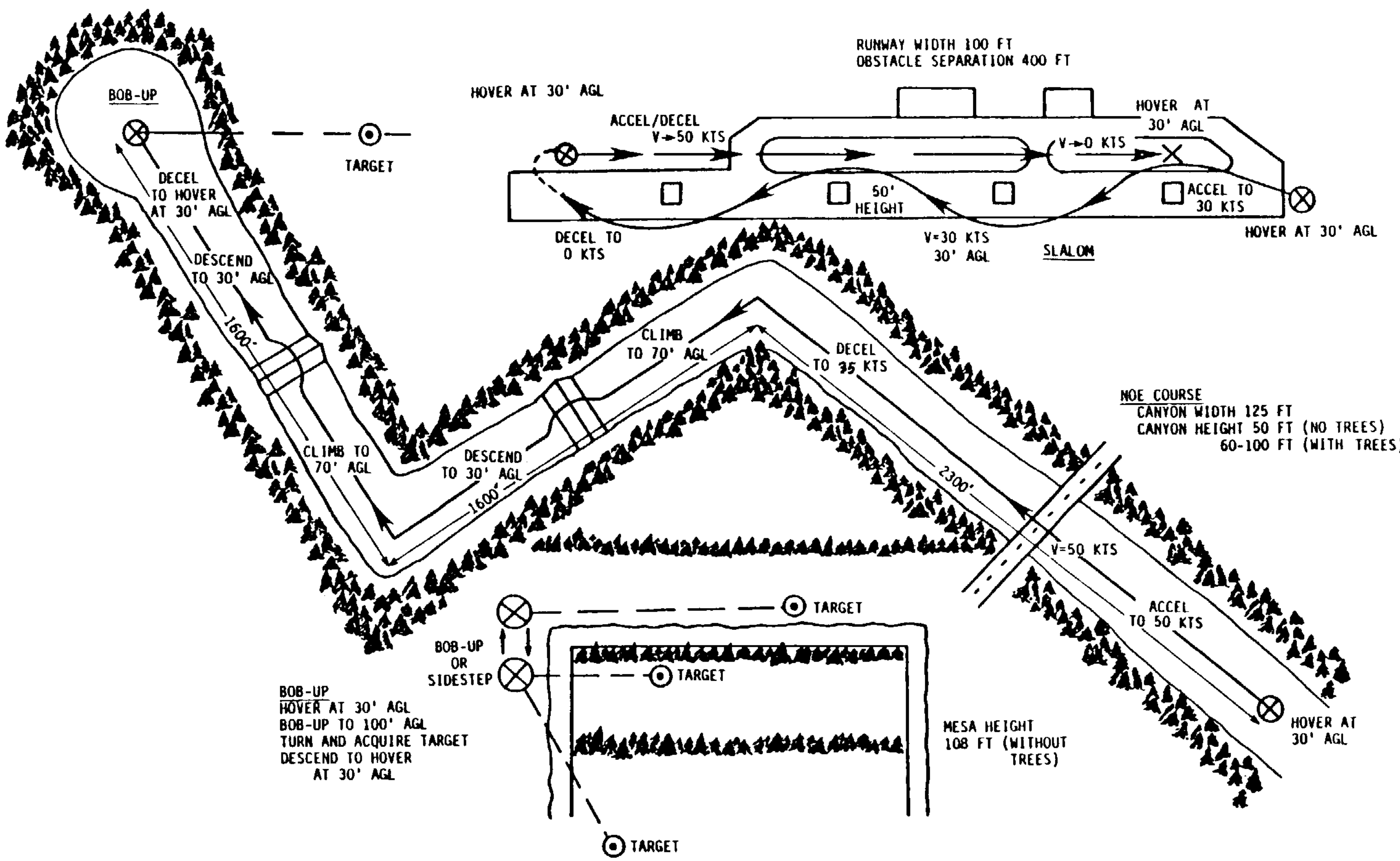


Figure 4-7

HIGH SPEED AND TRANSITION TASKS

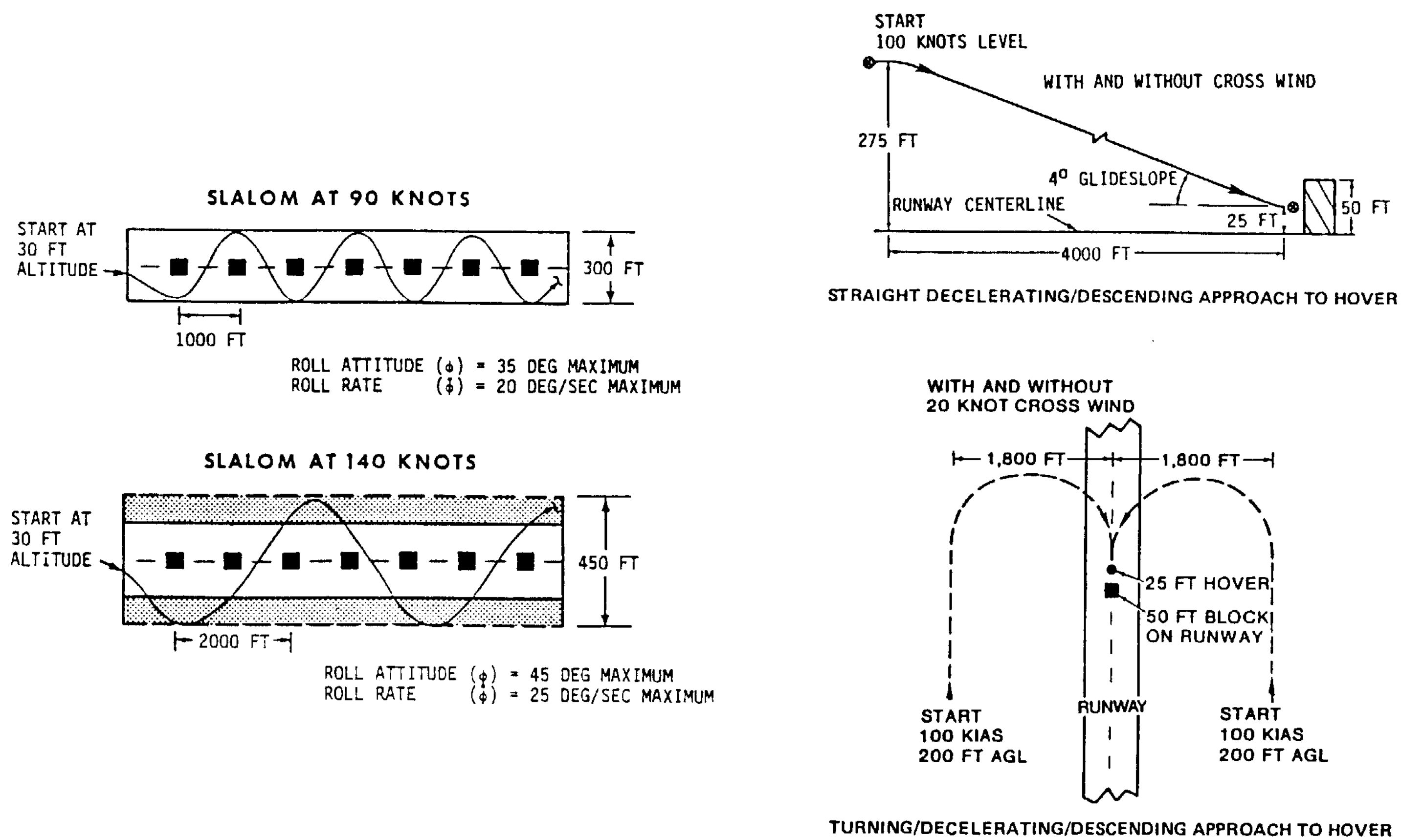


Figure 4-8

IMC during Phase 2B since the maximum velocity of the camera probe was limited.

Transition Tasks

Straight-and-Turning-Decelerating Approach-to-Hover Tasks (Figure 4-8) were performed to evaluate multi-axis maneuvering during transition from forward to low speed flight. These task enabled evaluation of control law switching and ability to precisely arrive at a desired hover location.

4.4 PILOTS' EXPERIENCE SUMMARY

Seven simulation test pilots participated in the ACC/AFCS study. Their background included related simulation or flight test experience with side-stick controllers and/or exposure to IMC visual display systems. Table 4-1 presents the names of all the test pilots, their affiliation and experience, and summarizes their participation in flight hours for each simulation phase. Subsequent to Phase 1A activities, two evaluation pilots were given 3 hours of IHADSS flight training on the PNVS Surrogate Trainer at the U.S. Army Yuma Proving Ground to assess realism of the simulation and improve their proficiency with IHADSS.

4.5 DATA COLLECTION AND ANALYSIS

Both pilot evaluation data and quantitative system performance data were collected. The quantitative system performance data consist of magnetic tape recordings of flight parameters relative to a reference hover position or desired flight path. The pilot evaluation data consist of Cooper-Harper handling qualities ratings (Reference 4) and tape-recorded pilot commentary. At the end of each evaluation run the pilot assigned a single numerical Cooper-Harper rating to the particular controller/ SCAS/task combination under investigation. In addition, the pilot was asked to provide commentary to help identify those aspects of the system that most heavily influenced the rating. Experimental results which follow are based on an analysis of pilot ratings and comments. Averaged pilot ratings are used to summarize general trends and explain pilot qualitative comments.

SUMMARY OF EVALUATION TEST PILOTS' EXPERIENCE

PILOT NAME	AFFILIATION	FLIGHT TIME (HOURS)		RELATED EXPERIENCE		ACC/AFCS SIMULATION HOURS				
						PHASE 1			PHASE 2	
		HELICOPTER FIXED WING	TOTAL	SIDE-STICK CONTROLLER DEVELOPMENT	VISUAL DISPLAYS FOR IMC	1A	1B	1C	2A	2B
A. L. Freisner	Boeing Vertol	3600(H) 2800(F)	6400	X	X*	45:45	32:25	31:00	32:40	3:35
S. Kereliuk	NAE-Canada	950(H) 6450(F)	7400	X	—	—	—	—	13:30	—
R. Merrill	U. S. Army	2500(H) 700(F)	3200	X	X	7:10	—	—	—	—
M. Morgan	NAE-Canada	450(H) 5600(F)	6050	X	—	14:30	10:10	9:00	—	3:35
P. Morris	U. S. Army	1065(H) 2520(F)	3585	X	X	—	13:50	—	5:20	10:50
G. Tucker	NASA-Ames	2745(H) 1200(F)	3945	X	X*	14:05	11:45	15:00	14:05	11:55
J. Tulloch	Boeing Vertol	5000(H) 1000(F)	6000	X	—	—	—	—	—	25:00

*IHADDS TRAINING ON PNVS SURROGATE TRAINER INCLUDED

Table 4-1

5.0 SIDE-STICK CONTROLLER DEVELOPMENT

Fly-by-wire or fly-by-optics flight control systems allow flexibility not only in the synthesis of the control laws but also in the design of the pilot's controllers. The potential benefits of employing an integrated, multi-axis, side-stick controller include: improved visibility, enhanced crashworthiness, easier ingress and egress, a reduction in cockpit space requirements, and an increased potential for single-pilot operations.

5.1 RELATED RESEARCH AND DEVELOPMENT PROGRAMS

Handling qualities research examining the effects of the characteristics of a 2-axis side-stick controller was conducted in support of the development of the F-16 aircraft. In a flight investigation of the effects of variations in force/deflection characteristics for certain fighter aircraft tasks (Reference 5), it was concluded that a small amount of side-stick motion provided improved flying qualities over those achieved with a fixed rigid controller. The results of this and other similar flight experiments were used to develop a guide for the design of two-axis side-stick controllers to be employed in fighter aircraft (Reference 6); included in the design guide are recommendations for stick neutral position, breakout forces, and force-deflection characteristics in both the longitudinal and lateral axes.

Research involving the use of side-stick controllers in Army helicopters began in 1968 with the Tactical Aircraft Guidance System (TAGS) program (Reference 7). The system implemented in a CH-47B aircraft initially included an integrated four-axis large-displacement controller. Because of coupling problems between the longitudinal and vertical axes, a three-axis controller was eventually implemented with vertical control effected through a standard collective lever. On the Heavy Lift Helicopter (HLH) (Reference 8), a 4-axis displacement controller was implemented at the load-controlling crewman's station in conjunction with a ground velocity command and stabilization system.

Side-stick control of single-rotor helicopters has been implemented in a production aircraft - side-stick cyclic control at the copilot's station of the AH-1 series of aircraft. In addition, side-stick controllers have been investigated using both ground- and in-flight simulation. In a three-degree-of-freedom moving-base simulation of the unaugmented Lynx helicopter at RAE Bedford, a 2-axis displacement side-stick was compared to the conventional cyclic controller for eleven different flight tasks (Reference 9). When a suitable control sensitivity was selected, the side-stick compared favorably with the conventional controller and, in fact, was preferred for specific tasks.

A feasibility study of a 4-axis isometric side-stick controller was recently conducted in the Canadian National Aeronautical Establishment Airborne Simulator (a variable stability Bell Model 205A-1) for a wide range of flight tasks (Reference 10). Two primary side-stick configurations, a 4-axis controller and a 3-axis controller with normal pedal control, were evaluated together with three SCAS variations: rate command/attitude hold in roll and pitch with augmented yaw rate damping; augmented roll, pitch and yaw rate damping; and the basic 205 with stabilizer bar removed and horizontal stabilizer fixed. With appropriate gains, shaping, and prefiltering applied to the pilot's force input in each controlled axis, pilot ratings comparable to those obtained with conventional controllers were achieved with both side-stick configurations.

These investigations indicated that a comprehensive evaluation of multi-axis side-stick control for an attack helicopter mission must include variations in: 1) the number of axes controlled through the side-stick device, 2) the force-deflection characteristics of the controller, and 3) the attendant SCAS characteristics.

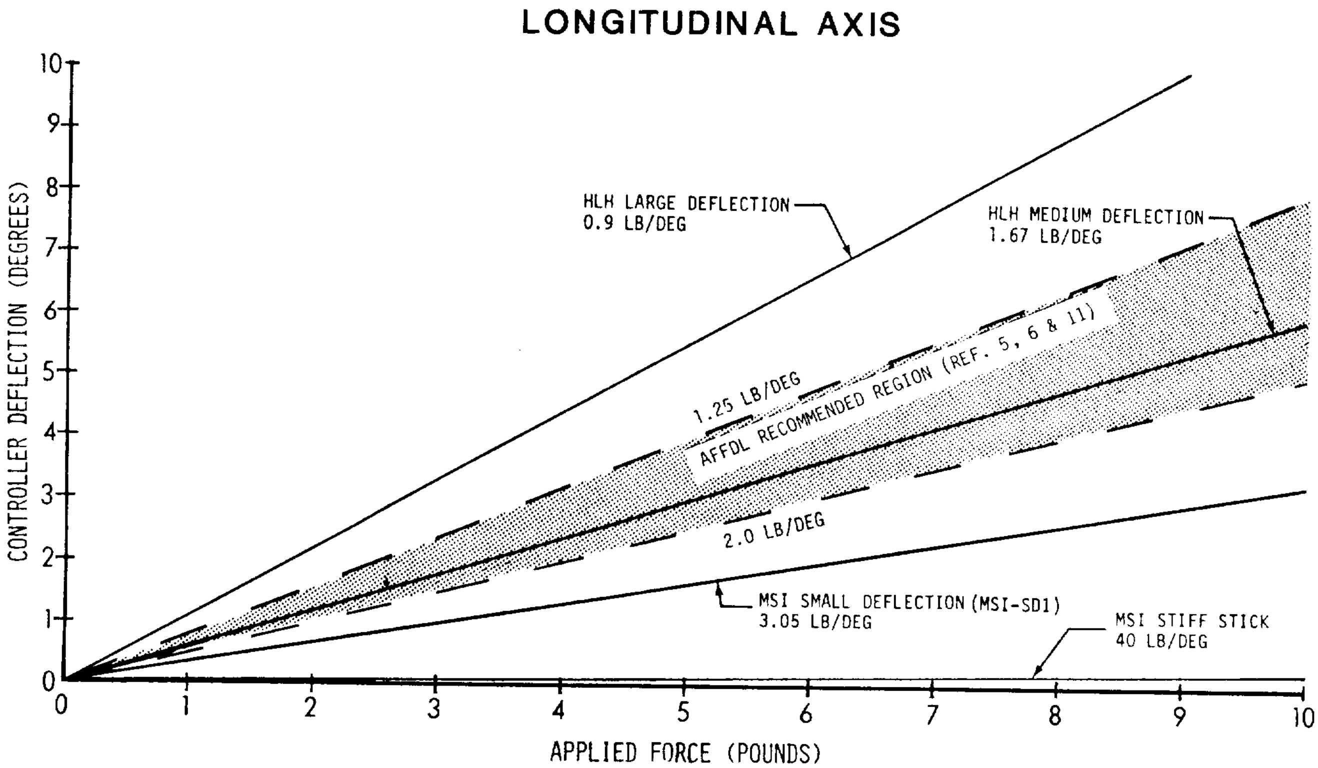
5.2 SIMULATION RESULTS

Force/Deflection Characteristics

The selection of pitch and roll force/deflection gradients was guided by a review of the previously described published data. References 5, 6 and 11 defined preferred regions of longitudinal and lateral force/deflection gradients developed from Air Force flight test evaluation of a 2-axis variable force-deflection side-stick controller. Figure 5-1 shows the recommended force/deflection gradient range, in addition to four specific longitudinal controller force/deflection configurations evaluated during the initial simulation phase of the ACC/AFCS study. The gradients were chosen to cover a range from a "stiff" force gradient with very small deflection to a "soft" force gradient with large deflection (±12 degrees).

Pilot rating data comparing the four selected side-stick controllers are presented in Figure 5-2. Best pilot ratings were achieved with the small-and-medium-deflection side-stick controllers having deflection/force gradients ranging from 0.4 to 0.8 degrees/lb. The large-deflection side-stick controller received the worst overall pilot ratings. Based on these results, two modified side-stick controllers (Figure 5-3) were developed for evaluation. The MSI-SD2 controller had modified force/deflection characteristics in the pitch and roll axes falling between the small-and-medium deflection controllers described above. The MSI-SD3 SSC incorporated small-deflection into all four control axes because of pilot's comments indicating that the lack of control harmony between the pitch/roll axes and the directional/vertical axes was detrimental.

ACC/AFCS CANDIDATE SSC CONTROLLERS FORCE / DEFLECTION CHARACTERISTICS



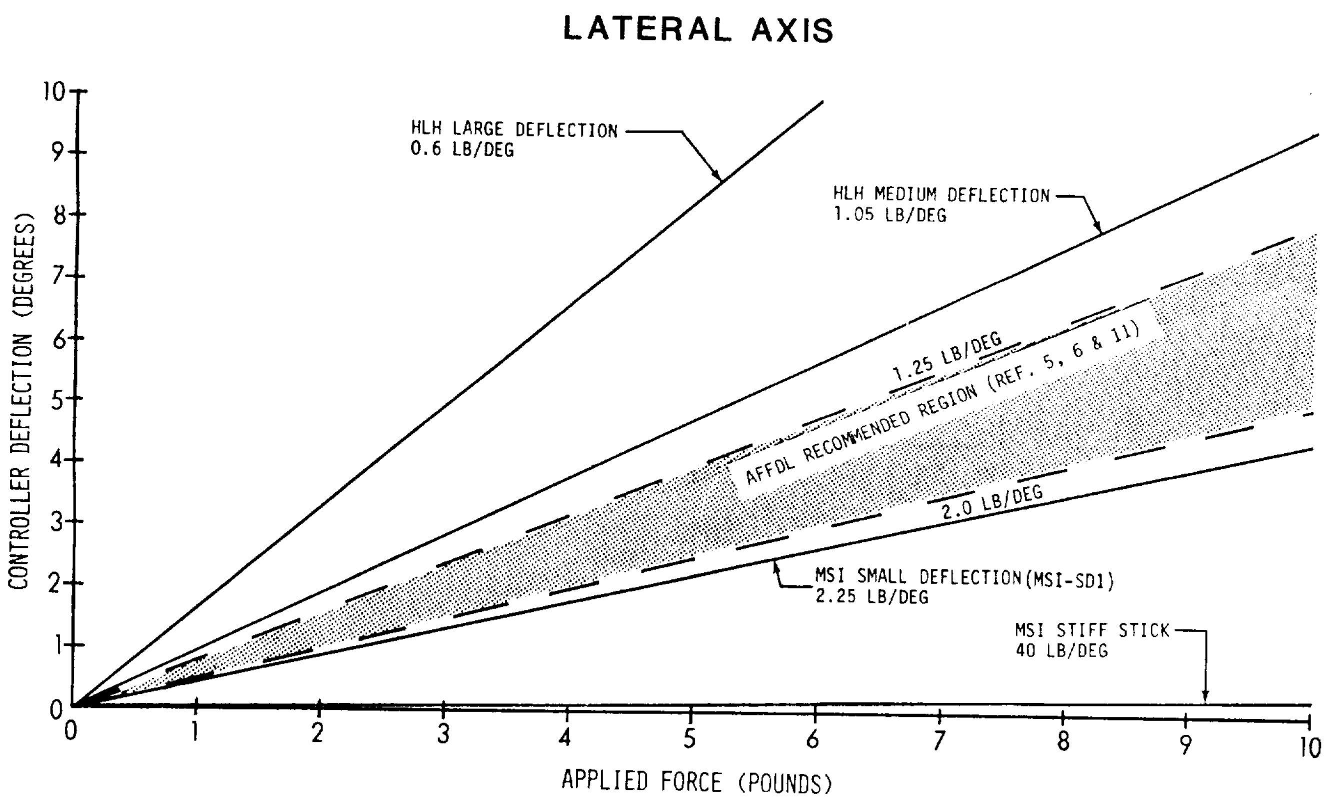


Figure 5-1

EFFECT OF SIDE-STICK CONTROLLER DEFLECTION/FORCE GRADIENT ON PILOT RATINGS

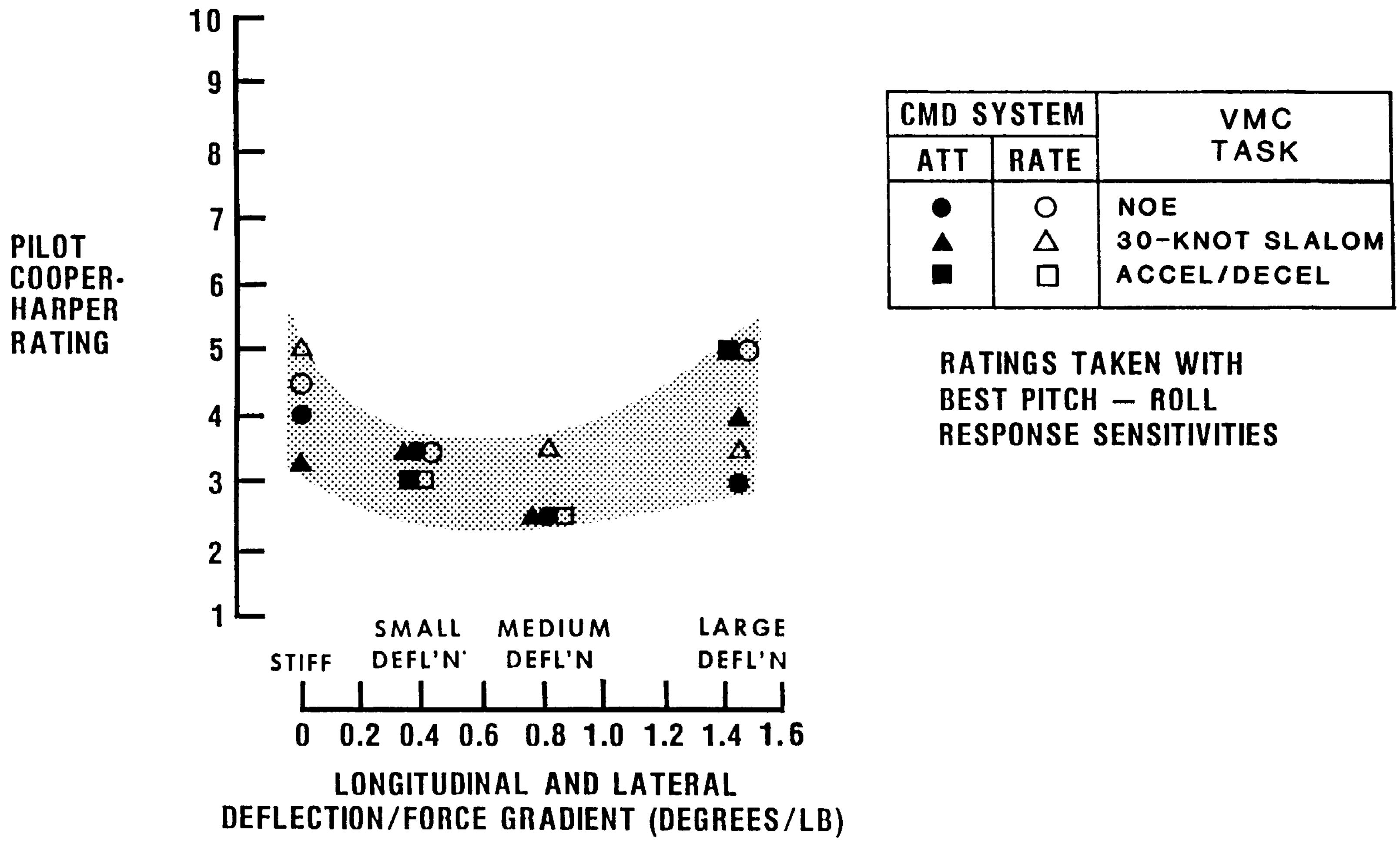
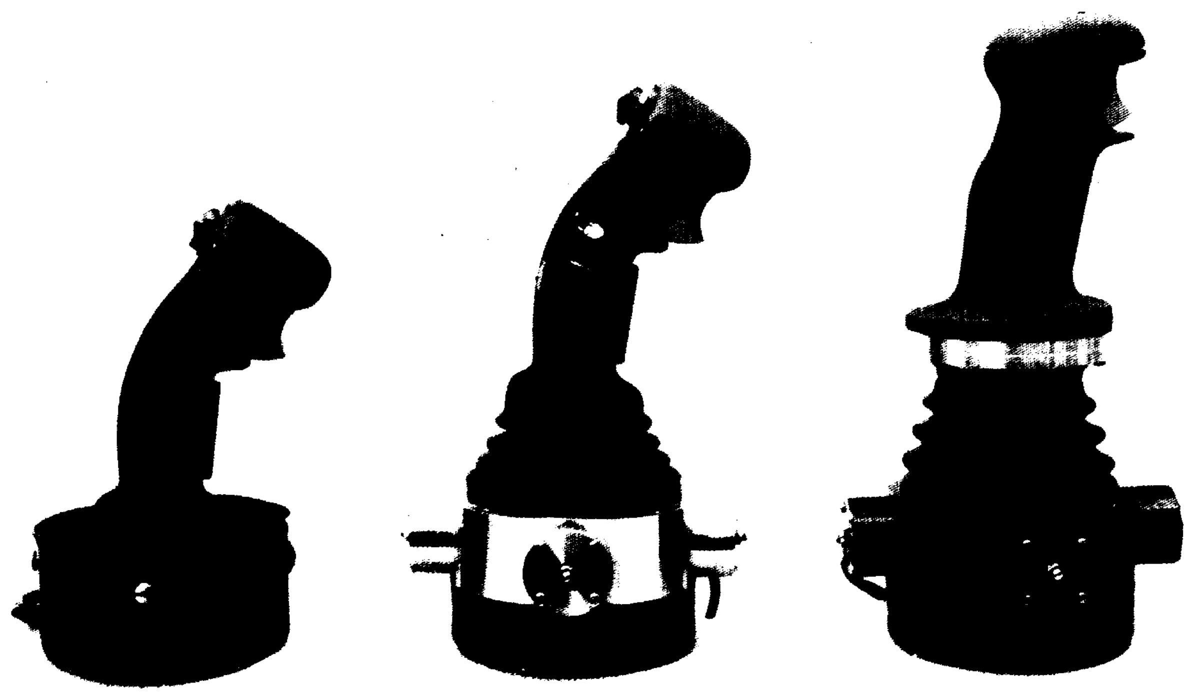


Figure 5-2

PHASE 2 4-AXIS SIDE-STICK CONTROLLERS



STIFF STICK
MSI-SS

SMALL-DEFLECTION
MSI-SD2

SMALL-DEFLECTION
ALL AXES
MSI-SD3

Figure 5-3

Pilot data, obtained during Phase 2A simulations, which compare the three side-stick controllers shown in Figure 5-3 are presented in Figure 5-4. Data shown represent averaged pilot ratings for three low-speed, VMC tasks -- the NOE, Bob-up, and Precision Hover. As indicated, Level 1 pilot ratings were achieved only with the MSI-SD3 SSC having a small amount of deflection in all four axes. All subject pilots felt that deflection in each control axis provided better definition of individual axis commands, reduced the tendency to inadvertly couple control inputs between axes, and allowed precision control tasks to be performed more accurately. The stiff controller (MSI-SS) was felt to provide poor tactile feedback to the pilot and gave the feeling of not being "tight" in the control loop. This controller also exhibited a tendency toward pilot-induced oscillations (PIO) and was less tolerant to variations in response sensitivity changes than the other two controllers.

The MSI-SD2 SSC (Small-deflection in pitch and roll, stiff in directional and collective) was considered an improvement over the stiff controller but exhibited the most degraded pilot ratings. Pilot comments indicate that poor control force harmony resulted from the combination of two stiff and two small-deflection axes on the same controller.

Controller Configuration

Separated controller configurations consistently received better pilot ratings for multi-axis control tasks than did the fully integrated 4-axis controller configuration. Figure 5-5 presents pilot ratings obtained for the VMC and IMC 30-Knot Slalom Task performed during Phase 1. The effect of controller configuration on pilot ratings is evident from this figure. The (2+1+1) and (3+1) Collective configurations received improved ratings compared to the (4+0) and (3+1) Pedal configurations. Pilot comments indicate that a major deficiency with both the (4+0) and (3+1) Pedal configurations was the tendency to cross-couple pitch and roll inputs into the vertical axis. The removal of collective control from the right-hand SSC eliminated this tendency. Yaw control in the SSC was felt to improve directional control, especially for precise heading changes. Pilot ratings for the (2+1+1) and (3+1) Collective configurations were comparable for IMC, whereas under VMC the (3+1) Collective configurations exhibited slightly degraded ratings compared to the (2+1+1) configurations.

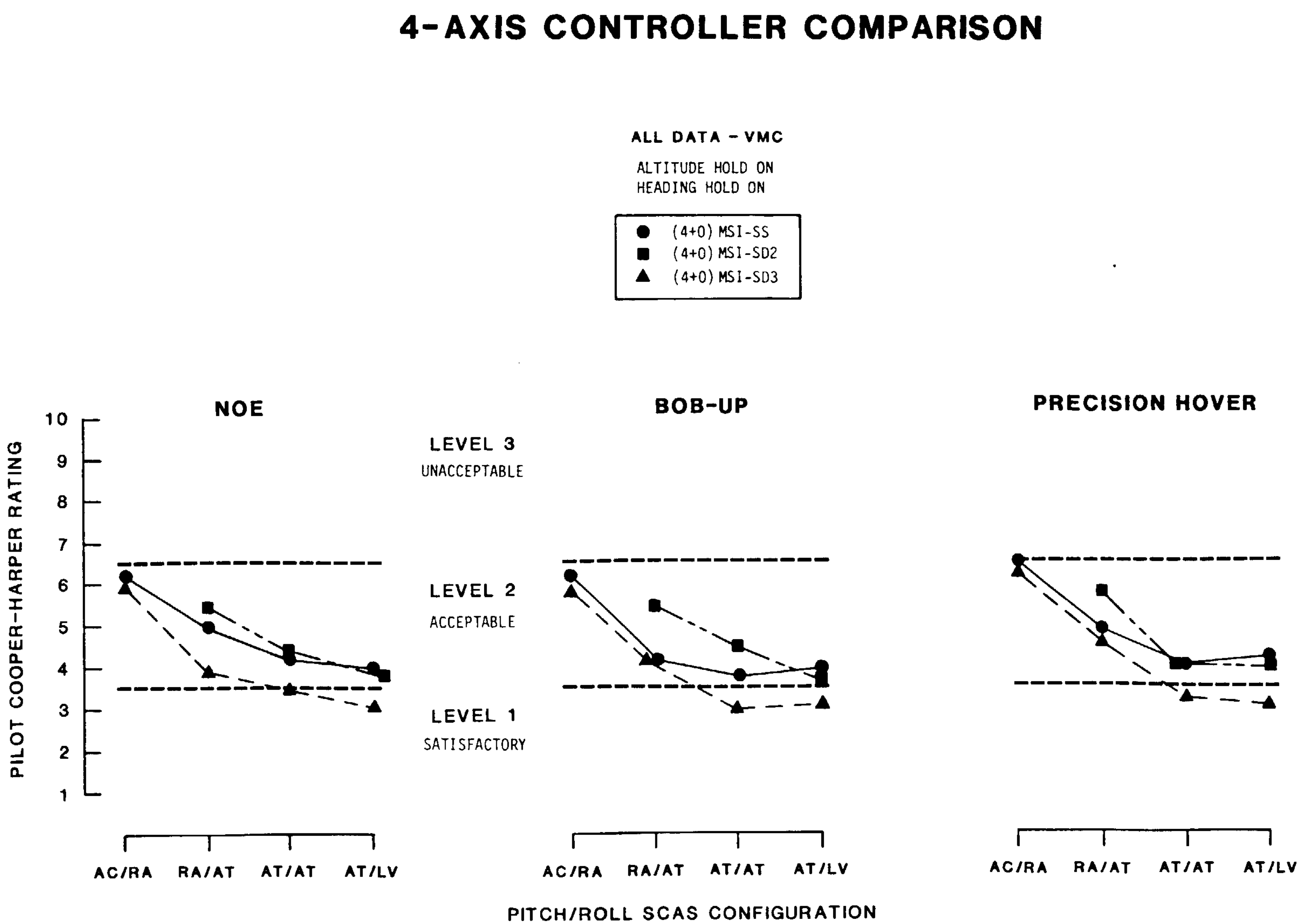

4-AXIS CONTROLLER COMPARISON
ALL DATA - VMC
ALTITUDE HOLD ON
HEADING HOLD ON
(4+0) MSI-SS
(4+0) MSI-SD2
(4+0) MSI-SD3
NOE
BOB-UP
PRECISION HOVER
PILOT COOPER-HARPER RATING
10
9
8
7
6
5
4
3
2
1
LEVEL 3
UNACCEPTABLE
LEVEL 2
ACCEPTABLE
LEVEL 1
SATISFACTORY
AC/RA
RA/AT
AT/AT
AT/LV
PITCH/ROLL SCAS CONFIGURATION

Figure 5-4

PILOT RATINGS - 30-KNOT SLALOM TASK

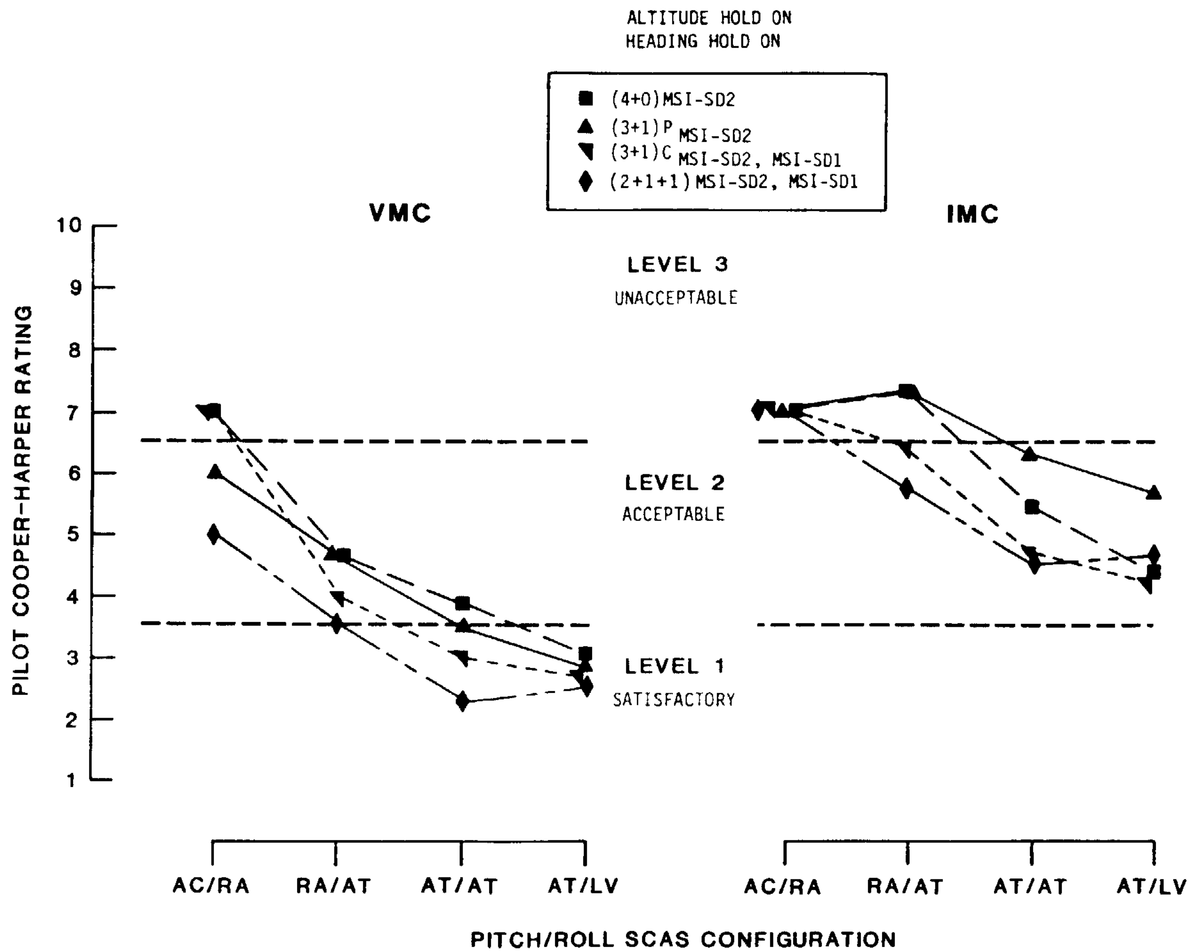


Figure 5-5

6.0 CONTROL LAW DEVELOPMENT

6.1 BASIC CONCEPTS

Figure 6-1 presents a block diagram of the flight control system design concept developed for the ADOCS Demonstrator Program. The use of this system formulation allows for development of handling qualities requirements while still considering aspects of hardware design and redundancy management. Major advantages of this system design concept are:

- Satisfactory unaugmented flight is attained by providing feed-forward command augmentation and shaping as an integral part of the primary flight control system (PFCS). Control mixing and prefiltering are included in the PFCS to reduce pilot workload to an acceptable level for unaugmented flight.

- Stabilization feedback loops are optimized solely for maximum gust and upset rejection. This allows use of high gain full-time stabilization loops required for good attitude or velocity hold during NOE maneuvering or tight position hold for precision hover tasks. Also, aircraft attitude excursions are minimized for improved target acquisition and weapon delivery. No compromise for control response is necessary.

- Use of a control response model provides forward loop commands to tailor the short and long term responses to pilot control inputs as required to achieve satisfactory pilot ratings and performance. Any desired control response can be obtained by appropriate feed-forward shaping regardless of the level of stabilization.

- Pilot display symbology is driven by the same sensor set used for flight control. For some failure modes, redundant signals may be available in the AFCS as backup inputs to the symbology display.

Various control system concepts were formulated to accomplish the attack helicopter low speed/hover maneuvers. The generic SCAS configurations chosen for evaluation are defined in Figure 6-2 in the form of a command response/stabilization matrix. A simple identification code (Figure 6-2) was established. For example, a system with angular rate command and attitude stabilization in pitch and roll was identified with the letter code RA/AT.

The method of SCAS implementation used for the simulation is illustrated in Figure 6-3 for the lateral axis. All control axes were implemented in a similar manner. The stabilization gains shown on the diagram were selected prior to the piloted evaluation phase using the helicopter/stability augmentation system model shown in Figure 6-4. Elements of the model include transfer functions to represent the dynamics of the basic

ADOCS FLIGHT CONTROL SYSTEM CONCEPT

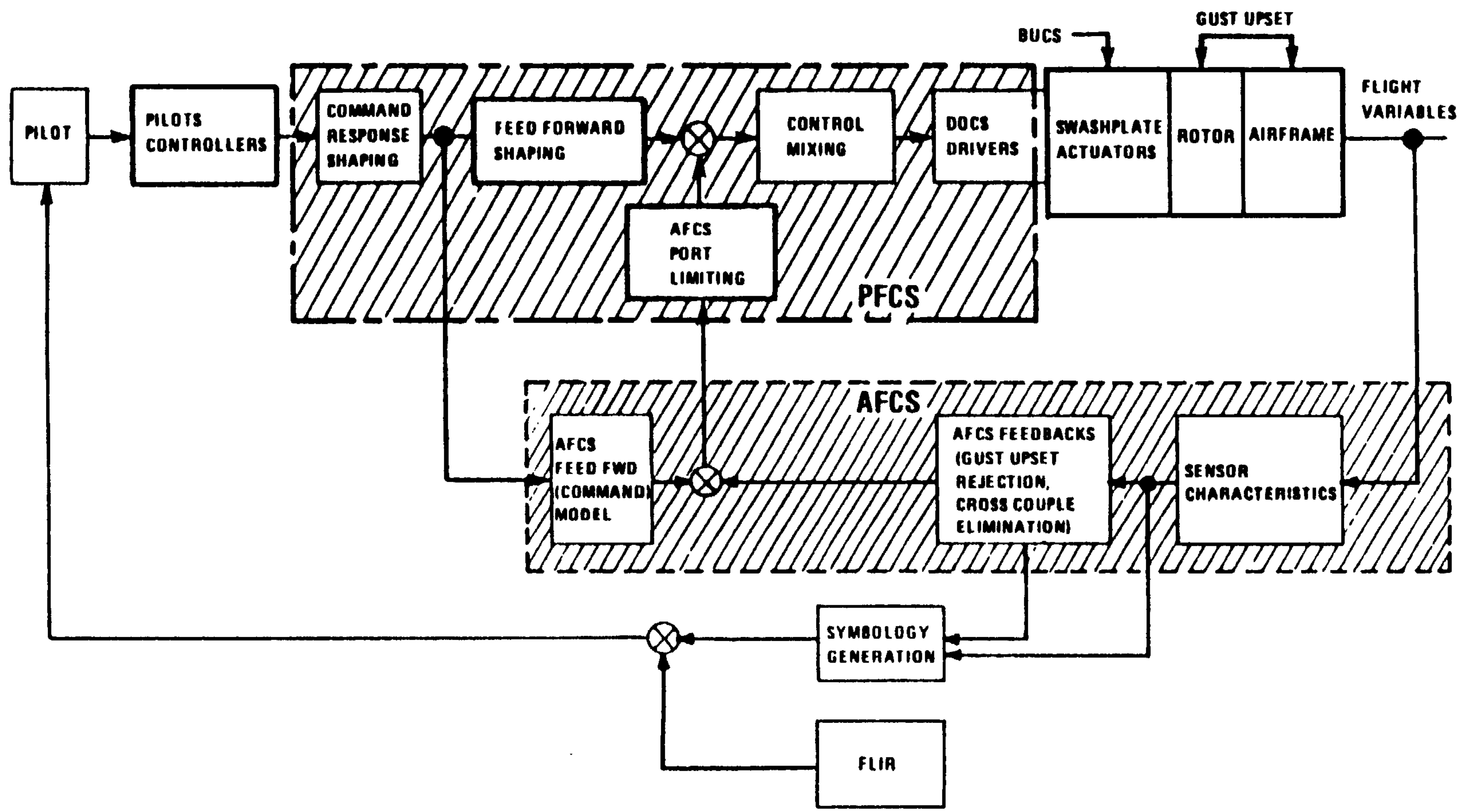


Figure 6-1

GENERIC SCAS CONFIGURATIONS

COMMAND RESPONSE/STABILIZATION MATRIX

RESPONSE COMMAND MODEL	STABILIZATION LEVEL: LONGITUDINAL/LATERAL RA	LONGITUDINAL/LATERAL AT	LONGITUDINAL/LATERAL LV	LONGITUDINAL/LATERAL LP	DIRECTIONAL RA	DIRECTIONAL AT	VERTICAL LV	VERTICAL LP
AC	●				●	●	NA	NA
RA	●	●	●			●	NA	NA
AT		●	●				NA	NA
LA					NA	NA	●	●
LV			●	●	NA	NA		●

IDENTIFICATION CODE

	PITCH/ ROLL	YAW	VERTICAL
ANGULAR ACCELERATION	AC	$\ddot{\psi}$	–
ANGULAR RATE	RA	$\dot{\psi}$	–
ANGULAR ATTITUDE	AT	ψ_H	–
LINEAR ACCELERATION	LA	–	$\ddot{h}$
LINEAR VELOCITY	LV	–	$\dot{h}$
LINEAR POSITION	LP	–	h_H

EXAMPLE: RA/AT

ANGULAR RATE COMMAND/ATTITUDE STABILIZATION

$\dot{\psi}/\psi_H$

YAW RATE COMMAND/HEADING HOLD

Figure 6-2

GENERIC LATERAL SCAS

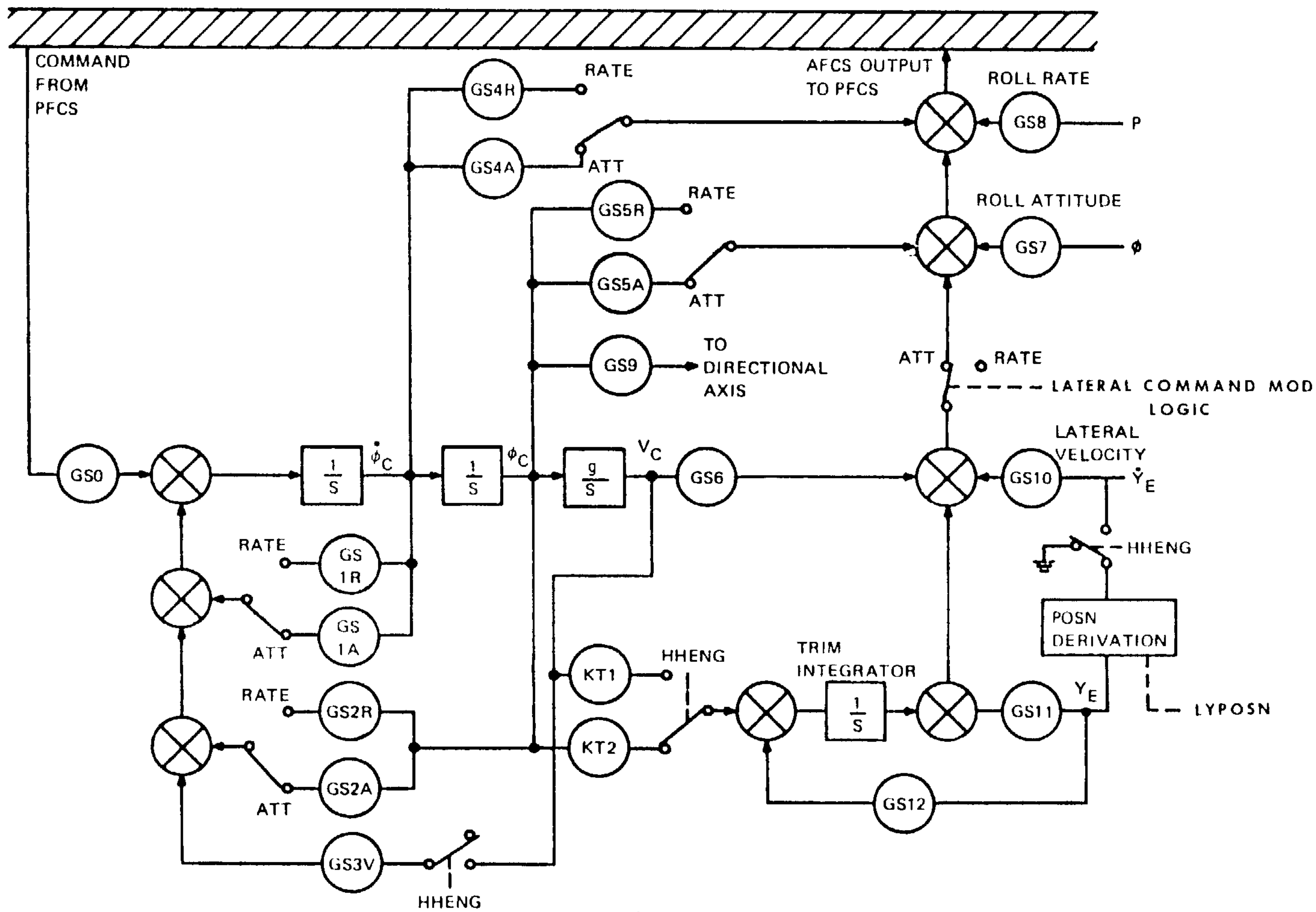


Figure 6-3

UH-60A AIRCRAFT MODEL USED FOR STABILITY ANALYSIS

LONGITUDINAL AXIS

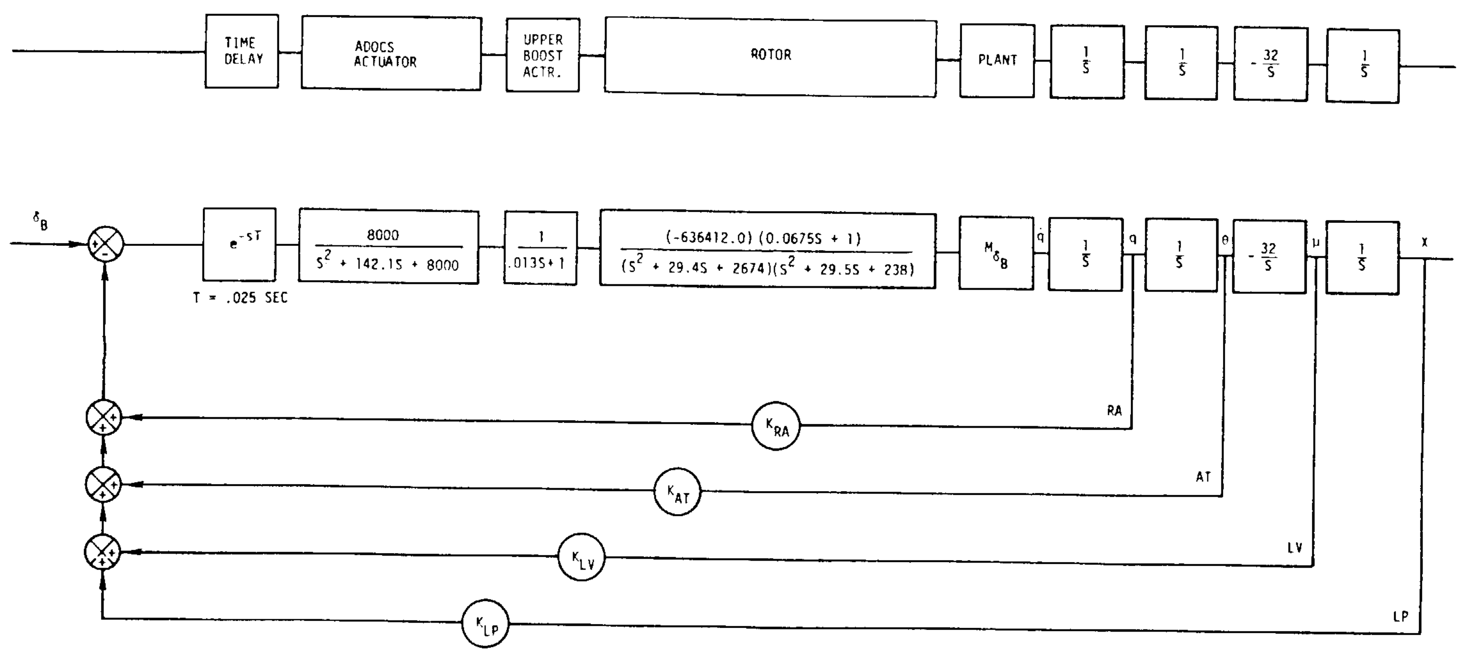


Figure 6-4

helicopter, rotor and actuators as well as a computational time delay. Nichols chart and Root Locus techniques were used to select feedback gains. Multiple feedback paths, each increasing overall level of stability, were closed around the aircraft model one at a time. Gains were determined based on a damping ratio design criteria ($\zeta = 0.7$). The stabilization loop gains derived by this method were similar to gains of previously developed aircraft systems (i.e., TAGS, HLH).

A six degree-of-freedom small-perturbation model of the helicopter was used to develop the command response model for each axis. The analytical study established control response model gains for cancellation of undesirable roots of the vehicle's characteristic equation. Control response model feed-forward parameters were defined for each of the response types previously described. For example, Figure 6-5 shows the lateral response to step force input for an attitude command system with velocity stabilization.

During the preliminary control response design process, information from available literature, as well as related experience, was used to develop design criteria. Quantitative design guidelines for a SCAS intended for low speed and hovering flight is contained in Reference 12 along with VTOL aircraft flying qualities criteria developed from an existing experimental data base. Requirements for generic SCAS designs such as angular rate command, attitude command, and translational rate command are proposed together with suggested vertical augmentation system characteristics. In addition, the use of velocity command system for the Precision Hover Task was flight demonstrated on the HLH Program (References 13 and 14), and the desirability of this control concept was confirmed based on study results published in References 15 and 16.

6.2 SIMULATION RESULTS

A summary of pilot rating data for all tasks and controller configurations combined is shown in Figure 6-6. Under VMC, the "hybrid" command system (e.g. attitude command/velocity hold in hover for pitch and roll, attitude command/airspeed hold (AT/AS) in pitch and rate command/attitude hold (RA/AT) in roll for forward flight) was required for Level 1 handling qualities. The addition of velocity command, with or without position hold, further improved pilot ratings for the Bob-up and Precision Hover Tasks only. Pilot ratings were typically degraded 1.5 pilot rating points under IMC compared to similar VMC tasks. The range of pilot ratings also increased under IMC as indicated by the larger standard deviation shown on Figure 6-6. Under IMC, Level 1 ratings were achieved only for the Precision Hover and Bob-up Tasks with a velocity command/position hold (LV/PH) system.

Studies of directional and vertical SCAS variations showed the benefit of a yaw rate command/heading hold or a altitude rate command/altitude hold system respectively. Figure 6-7

LATERAL AXIS - ATTITUDE SYSTEM RESPONSE

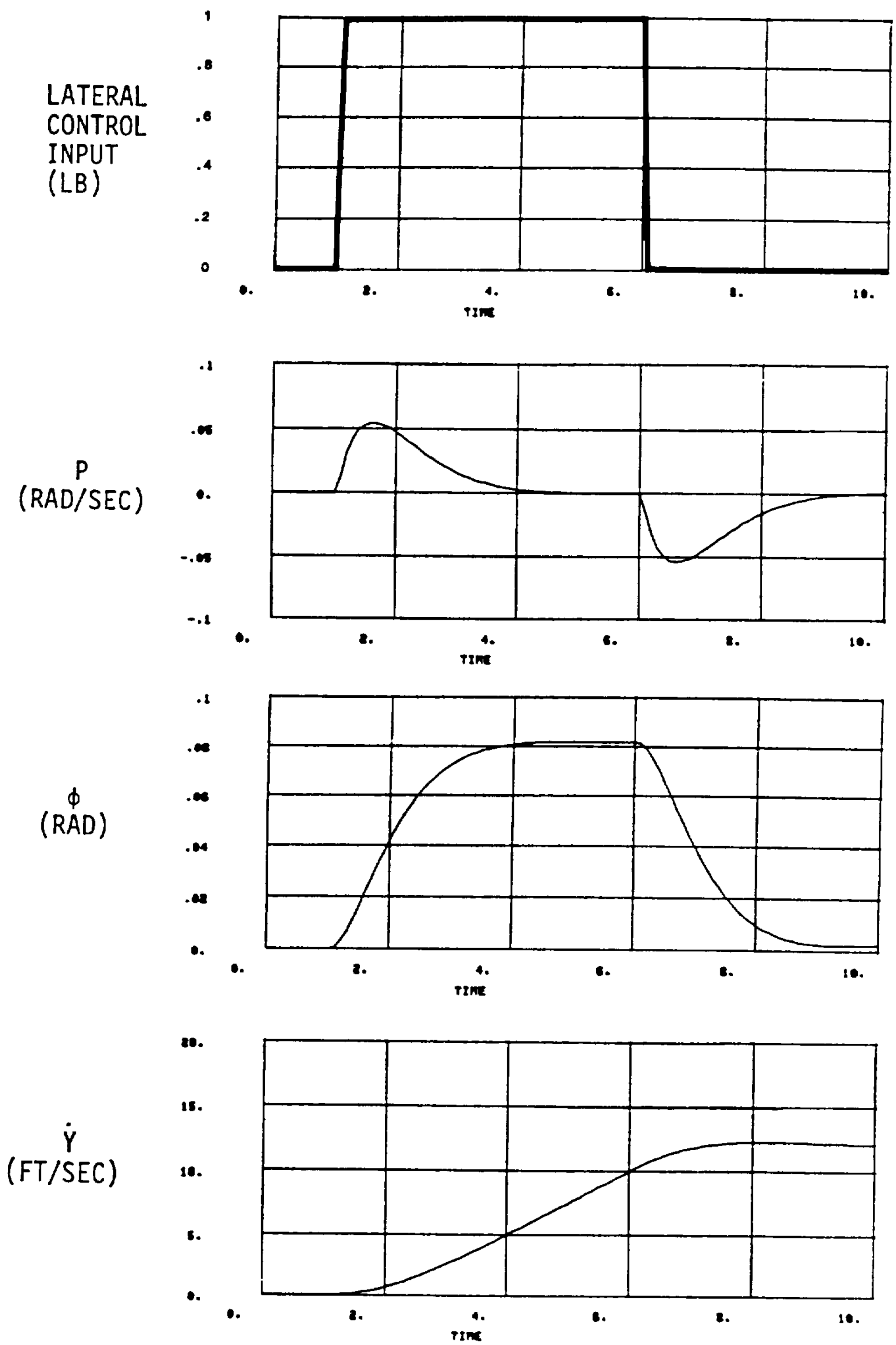


Figure 6-5

SUMMARY OF SCAS MODE EFFECT

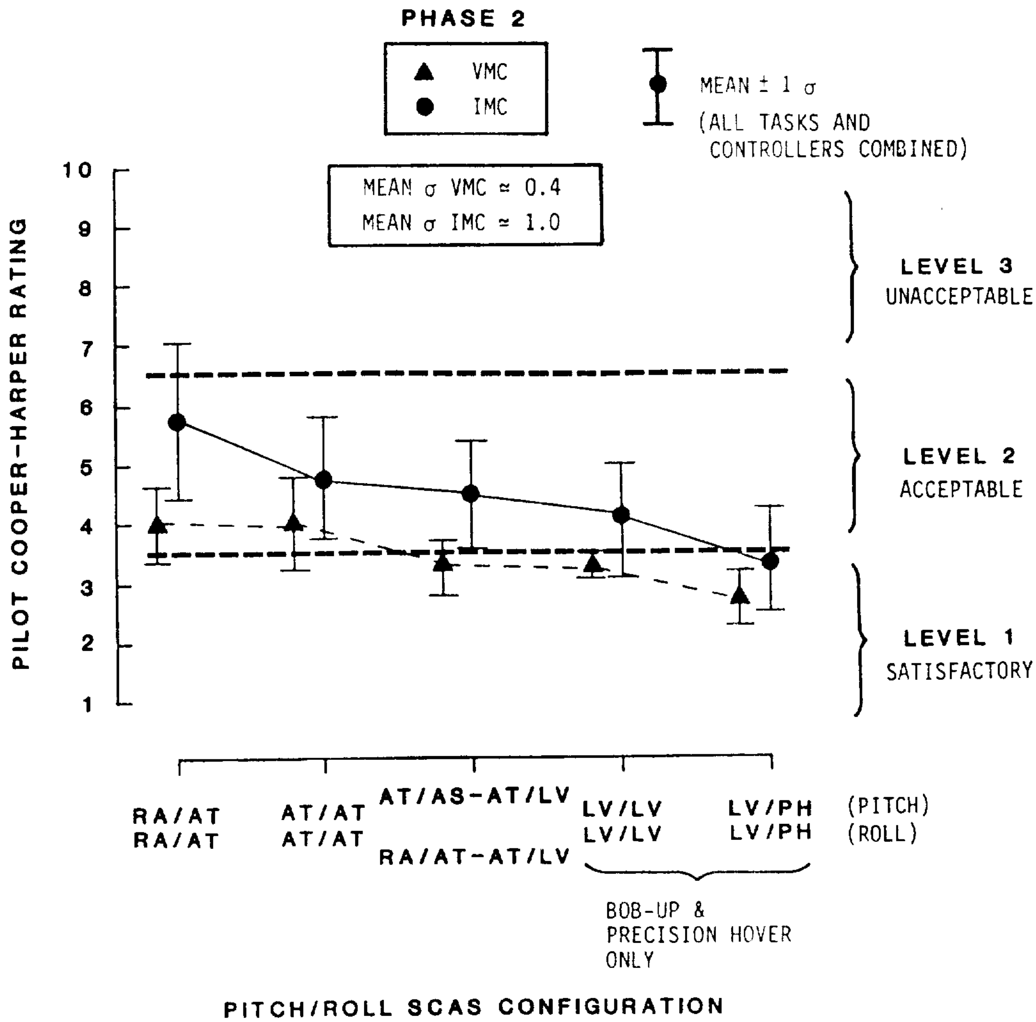


Figure 6-6

illustrates the improvement in pilot ratings achieved with the yaw rate/heading hold system for three low-speed tasks. A degradation in pilot ratings with the yaw acceleration command system was evident as increased precision of yaw control was required. Automatic turn coordination was found to be especially beneficial for forward flight turning maneuvers. Figure 6-8 presents pilot rating data for the 90-Knot Slalom under VMC with and without automatic turn coordination. Pilot ratings were significantly improved from Level 2 to Level 1 with the addition of automatic turn coordination for all controller configurations evaluated.

EFFECT OF DIRECTIONAL SCAS VARIATIONS ON PILOT RATINGS

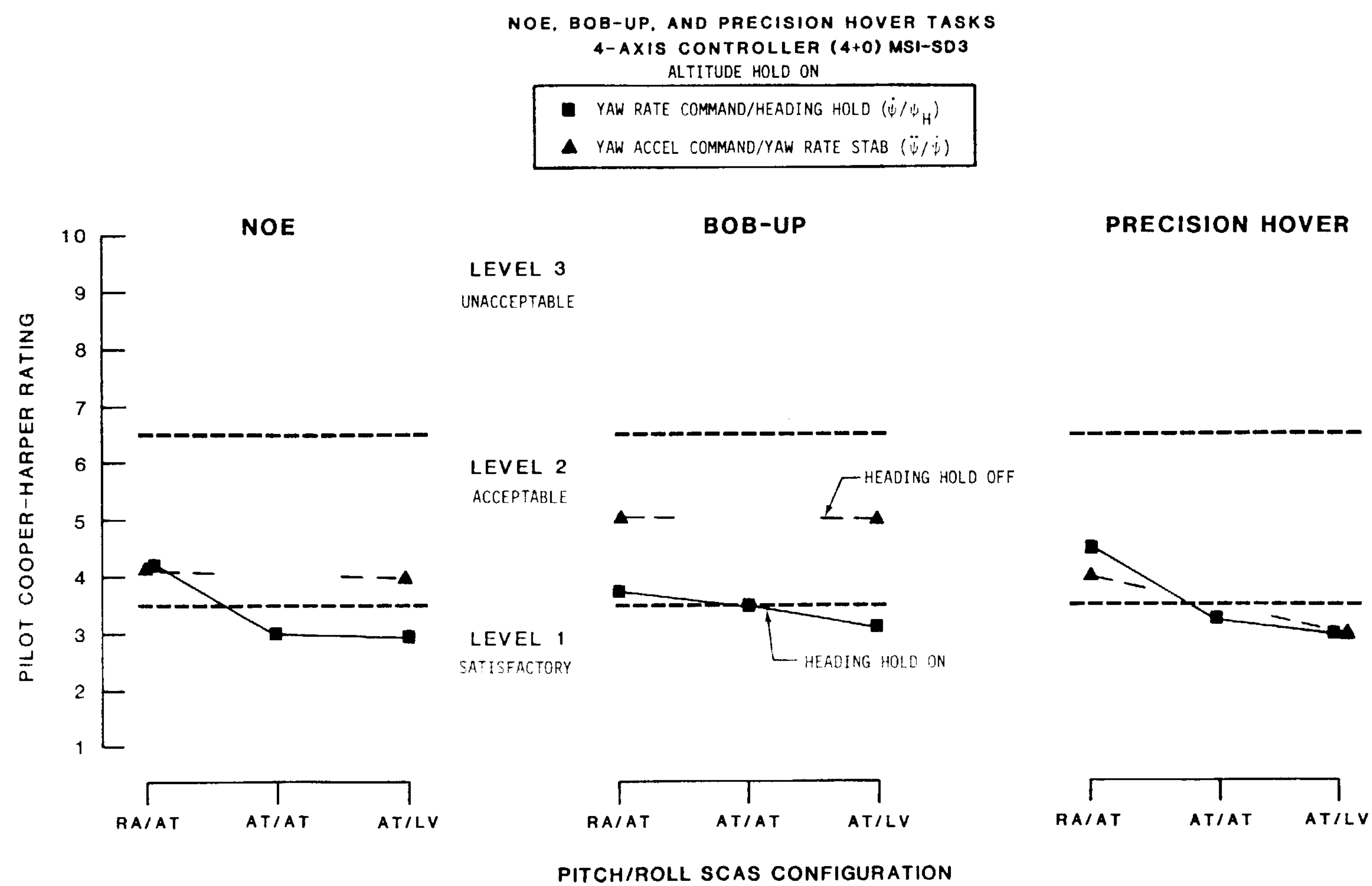


Figure 6-7

EFFECT OF AUTOMATIC TURN COORDINATION ON PILOT RATINGS

90-KNOT SLALOM TASK

ALL DATA - VMC
SCAS CONFIGURATION :
AT/AS (PITCH) ; RA/AT (ROLL)

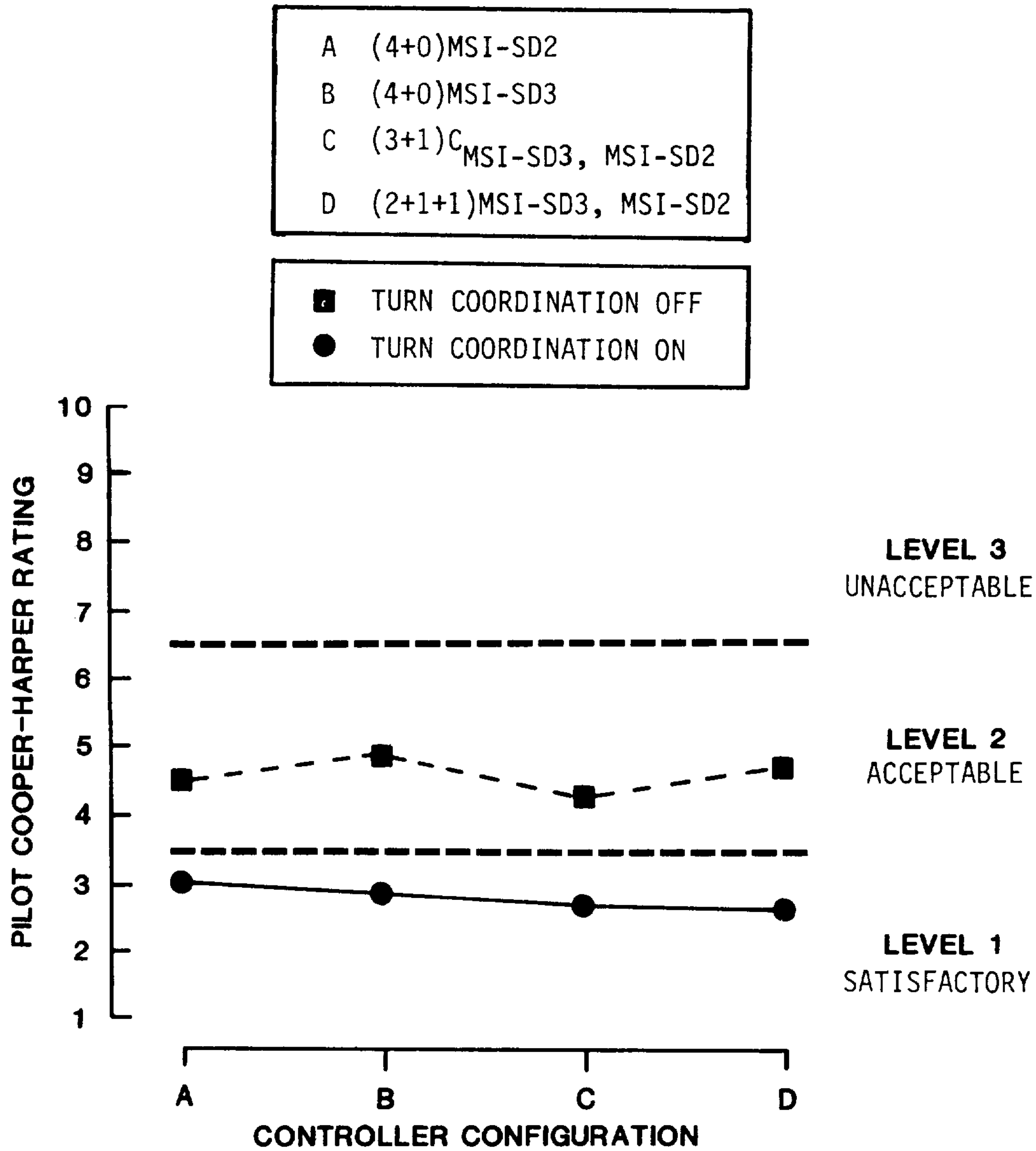


Figure 6-8

7.0 DISPLAY SYSTEM EFFECTS

The importance of superimposed flight control symbology to the enhancement of handling qualities with a limited field of view FLIR image of the outside world has been reported in Reference 17. Baseline display laws and information format used for this investigation were defined based on the AH-64 Pilot Night Vision System (PNVS) (Reference 1). The selectable display modes, which are used to meet the operational requirements for various AAH mission tasks, are:

(1) Cruise: high-speed level flight enroute to the forward edge of the battle area;

(2) Transition: low-speed NOE maneuvers such as dash, quick stop, and sideward flight;

(3) Hover: stable hover with minimum drift; and

(4) Bob-up: unmask, target acquisition, and remask maneuvers over a selected ground position.

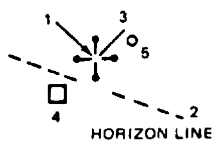
Figure 7-1 presents the display mode symbology divided into three categories - central, peripheral, and weapon delivery/ fire control symbology. The characteristics of each symbol are described and the symbols which appear for the three low-speed mission modes used during this investigation are identified.

In a simulator investigation of a night-time attack helicopter mission which included a head-up display of the PNVS symbology (Reference 15), it was found that the dynamics of the symbology used to aid the pilot in achieving a precision hover at night had a significant effect on the handling qualities of the vehicle. As a result, because of the wide variation in candidate SCAS concepts to be investigated, it was also necessary to ensure compatibility of the symbol dynamics with the varying dynamic characteristics of the augmented helicopter.

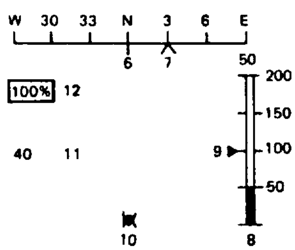
Variations to the baseline AH-64 symbology were made based on Reference 15 as well as a review of reported display system characteristics implemented on the PNVS surrogate trainer flown at the U.S. Army Test Proving Ground, Yuma, Arizona. Changes were incorporated in the programmed symbology primarily to improve low speed maneuvering and hover hold task performance, as well as to reduce pilot workload. These changes, evaluated during the preliminary IHADSS check-out testing, were as follows:

(1) Velocity vector sensitivity was decreased by a factor of two for all modes - from 6 knots to 12 knots full scale in the hover and bob-up modes, and from 60 knots to 120 knots full scale in the transition and cruise modes.

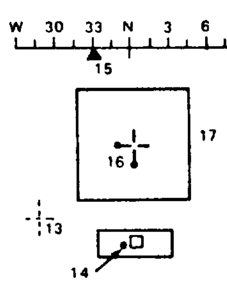
IHADSS SYMBOLOGY



CENTRAL SYMBOL	INFORMATION	MODES CRUISE/TRANS	HOVER	BOB UP
1. Aircraft reference	Fixed reference for horizon line velocity vector, hover position, cyclic director and fire control symbols	X	X	X
2. Horizon line	Pitch and roll attitude with respect to aircraft reference (indicating nose up pitch and left roll)	X	X	X
3. Velocity vector	Horizontal Doppler velocity components (indicating forward and right drift velocities). Sensitivity varies with mode	X	X	X
4. Hover position	Designated hover position with respect to aircraft reference symbol (indicating aircraft forward and to right of desired hover position)		X	X
5. Cyclic director (Acceleration Cue)	Cyclic stick command with respect to hover position symbol (indicating left and aft cyclic stick required to return to designated hover position). Approximated by washed out pitch/roll attitude		X	X



PERIPHERAL SYMBOL	INFORMATION	MODES CRUISE/TRANS	HOVER	BOB UP
6. Aircraft heading	Moving tape indication of heading (indicating North)	X	X	X
7. Heading error	Heading at time bob up mode selected (indicating 030)			X
8. Radar altitude	Height above ground level in both analog and digital form (indicating 50 ft)	X	X	X
9. Rate of Climb	Moving pointer with full scale deflection of ± 1,000 ft/min (indicating 0 ft/min)	X	X	X
10. Lateral acceleration	Inclinometer indication of side force	X	X	X
11. Airspeed	Digital readout in knots	X	X	X
12. Torque	Engine torque in percent	X	X	X



FIRE CONTROL SYMBOL	INFORMATION	MODES CRUISE/TRANS	HOVER	BOB UP
13. Cued line of sight	Overlays designated target positon on background video when target is in display field of view			X
14. Coarse target location	Designated target position with respect to display field of view (inner rectangle) and sensor limits (outer rectangle)			X
15. Target bearing	Designated target bearing (indicating 330° or 30° to left of current heading)			X
16. Target location dots	Illumination of two adjacent dots indicates display quadrant in which designated target is located			X
17. Missile launch constraints	Limits with respect to aircraft reference for successful weapon lock on to designated target			X

Figure 7-1

(2) Hover position sensitivity was decreased for the bob-up mode from a full scale deflection of 44 feet to 88 feet.

(3) A horizon line was included in the symbology format for all modes. The AH-64 has the horizon line in the transition and cruise modes only.

(4) Lateral acceleration was used to drive the "ball" display instead of sideslip angle to augment the simulation turn coordination cues at low speed.

(5) The cyclic director, or longitudinal and lateral acceleration cue, approximated by washed-out pitch and roll attitudes, required different sensitivity and time constant values as a function of the command response system type, i.e., rate, attitude, or velocity. Values were established in the same manner discussed in Reference 15.

In addition, several modifications were made to the IHADSS symbology used in the Phase 1 IMC simulation study. These changes, incorporated during preliminary Phase 2 IHADSS checkout testing, were based on pilot commentary received during the Phase 1 simulation program at Boeing Vertol.

Figure 7-2 compares the formats used during Phase 1 and Phase 2B. As shown in this example, the changes include:

(1) Additional pitch-attitude symbols to provide a more compelling and accurate display of pitch and roll attitude.

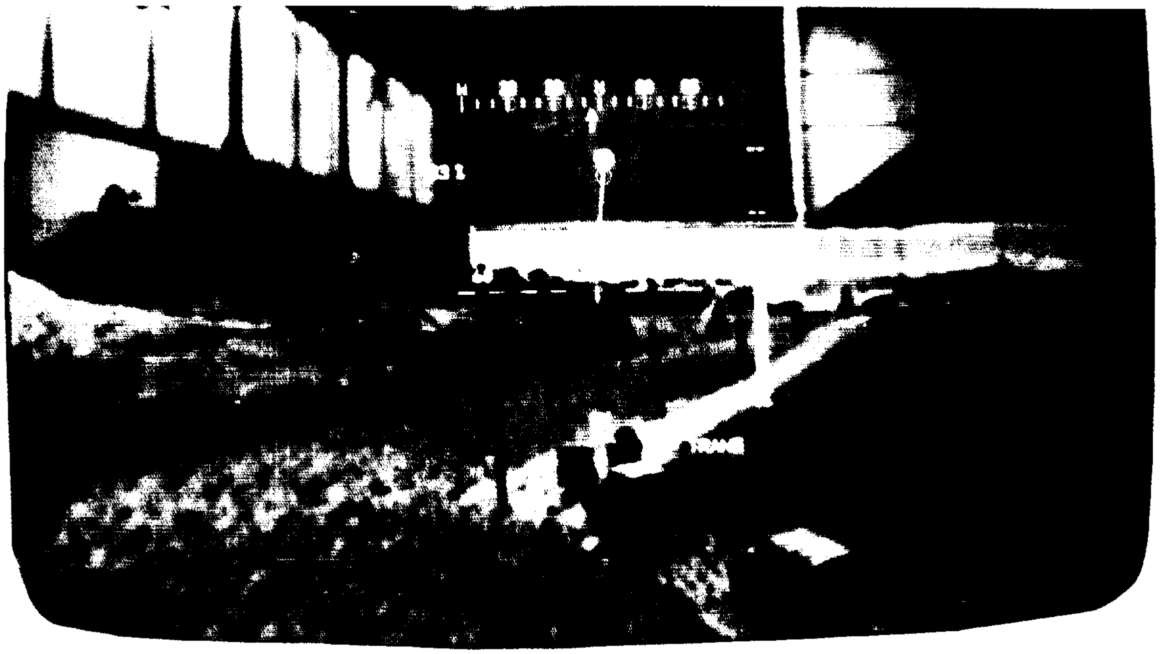
(2) The movement of the heading symbols to the lower center of the display to eliminate the eye muscle strain caused by its usual location well above the display center; the heading scale was also truncated to declutter the display.

(3) The replacement of the diamond-shaped aircraft nose symbol by a cockpit reference display; this symbol provided information concerning aircraft orientation relative to head azimuth and elevation in a format designed to alleviate the disorientation problems experienced in maneuvering flight reported in Phase 1.

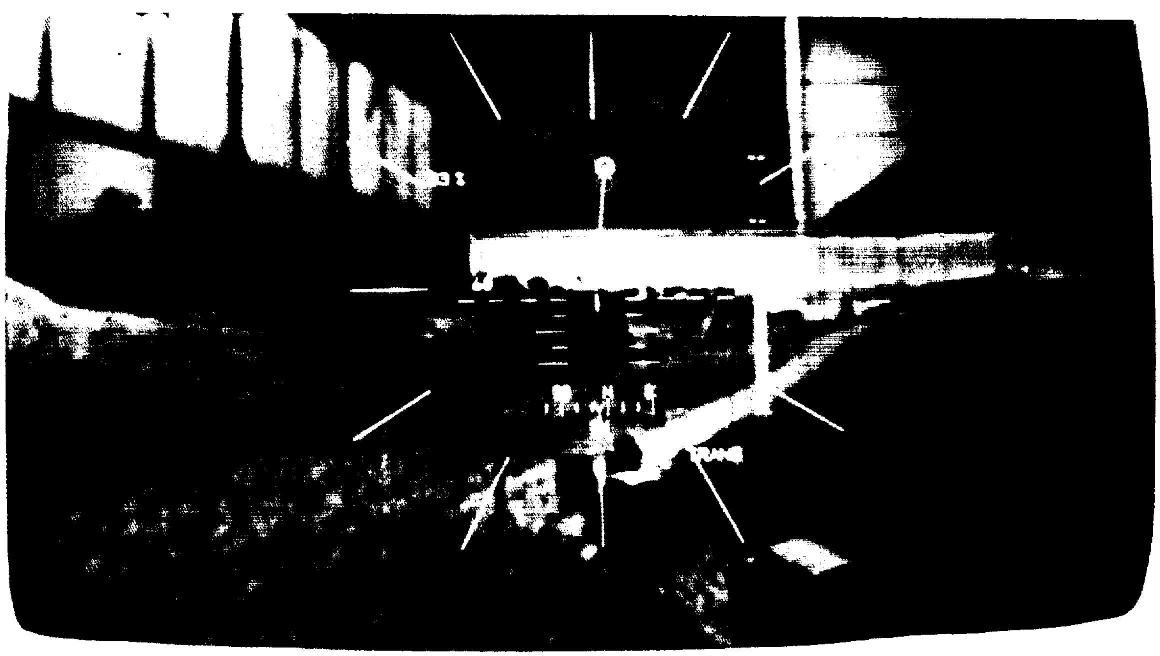
<u>Simulation Results</u>

The degraded visual capabilities provided by IHADSS significantly effected pilot ratings. Figure 7-3 shows the decrement in ratings obtained from pilots who performed identical tasks under both IMC and VMC. Tasks which required more head motion and/or aircraft maneuvering were most adversely effected by IMC

VARIATIONS IN IHADSS SYMBOLOGY



PHASE 1 SYMBOLOGY



PHASE 2 SYMBOLOGY

Figure 7-2

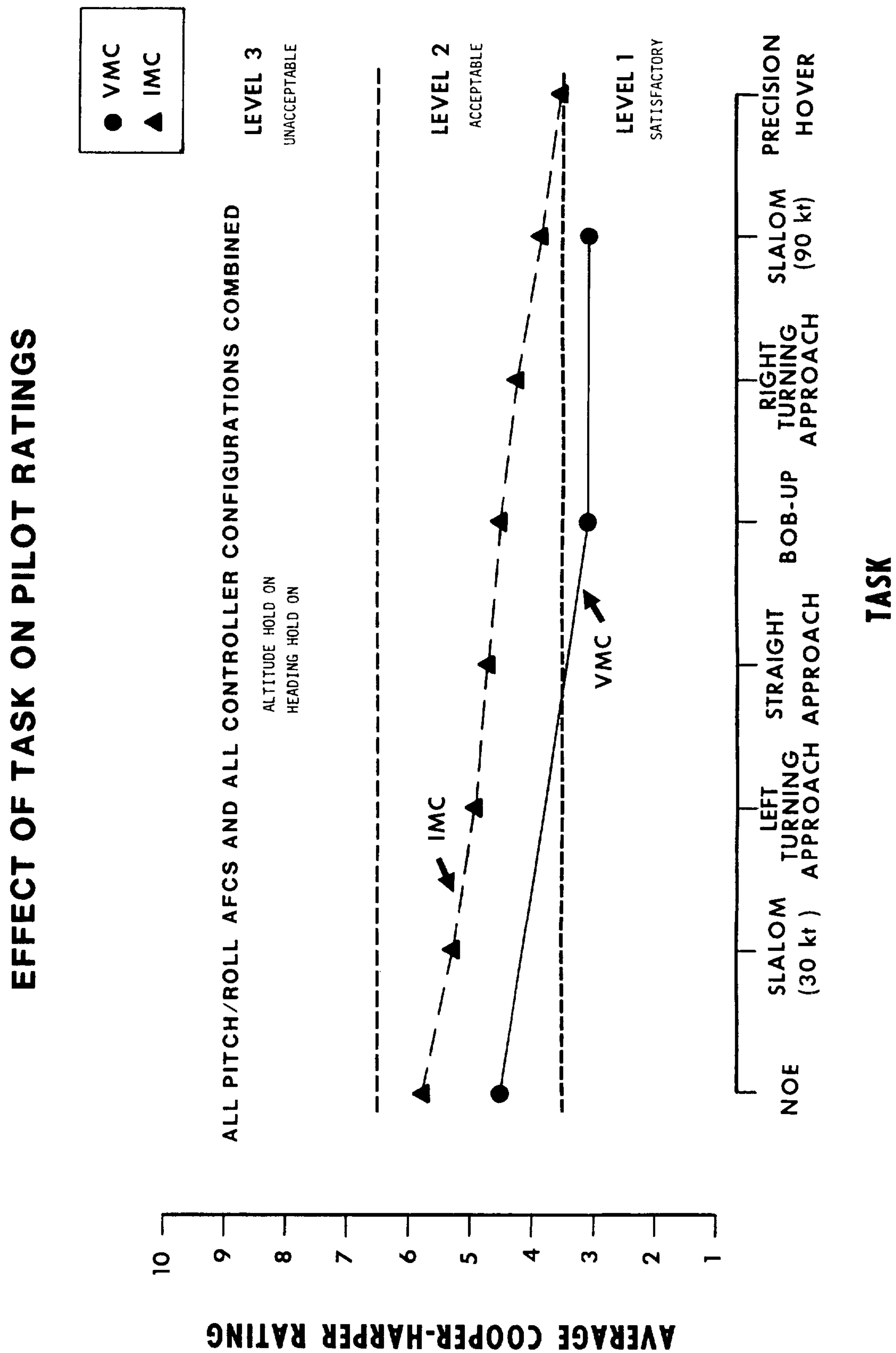

EFFECT OF TASK ON PILOT RATINGS
ALL PITCH/ROLL AFCS AND ALL CONTROLLER CONFIGURATIONS COMBINED
ALTITUDE HOLD ON
HEADING HOLD ON
VMC
IMC
LEVEL 3
UNACCEPTABLE
LEVEL 2
ACCEPTABLE
LEVEL 1
SATISFACTORY
AVERAGE COOPER-HARPER RATING
10
9
8
7
6
5
4
3
2
1
NOE
SLALOM (30 kt)
LEFT TURNING APPROACH
STRAIGHT APPROACH
BOB-UP
RIGHT TURNING APPROACH
SLALOM (90 kt)
PRECISION HOVER
TASK

Figure 7-3

with IHADSS. Pilot ratings for the NOE Task, which was felt to be the most difficult task under both VMC and IMC, degraded an average of 2 points on the Cooper-Harper Scale. Ratings for the Precision Hover and 90 Knot-Slalom Tasks which required little head movement were within half a rating point under both VMC and IMC. As shown on Figure 6-6 previously, Level 1 ratings under IMC were achieved consistently only with the highest level of stabilization, the LV/PH system, and only for the Bob-up and Precision Hover Tasks.

Degradation of task performance under IMC with IHADSS was observed in terms of ground track deviation, velocity hold and control coordination during multi-axis flight maneuvers. For the Bob-up Task, however, task performance as measured by mean radius error was improved under IMC. Figure 7-4 presents averaged performance data for the Bob-up Task under VMC and IMC with and without turbulence. As shown, pilots consistently held X-Y position significantly better under IMC with IHADSS than under VMC. The IHADSS symbology provided an absolute ground position reference which was not available under VMC.

EFFECT OF TURBULENCE ON BOB-UP PERFORMANCE

—IMC AND VMC—

DATA FOR 4-AXIS CONTROLLER CONFIGURATION

ALTITUDE HOLD ON

HEADING HOLD ON

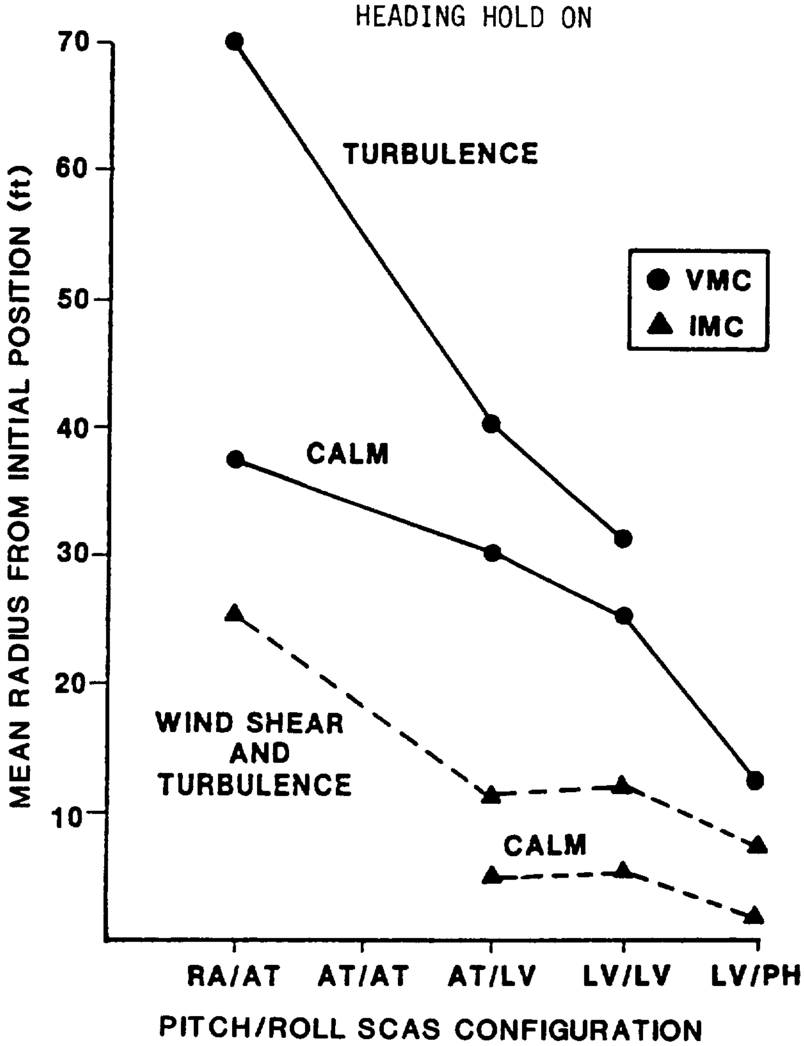


Figure 7-4

8.0 CONCLUSIONS

Piloted simulation investigations were conducted as part of the Advanced Cockpit Controls/Advanced Flight Control System (ACC/AFCS) element of the Army's ADOCS program. The effects of variations in side-stick controller configuration and stability and control augmentation characteristics on scout/attack helicopter handling qualities were evaluated using flight simulation facilities at Boeing Vertol and NASA-Ames. Low speed, transition, and forward flight mission tasks were performed under both day visual meteorological conditions (VMC) and night-time instrument meteorological conditions (IMC) using a visually coupled helmet-mounted display.

Conclusions from these investigations are summarized according to major elements of the simulation study, including side-stick controller design, controller configuration, SCAS design, and IMC display effects.

8.1 SIDE-STICK CONTROLLER DESIGN

A 4-axis controller with small-deflection in all axes was preferred over a 4-axis stiff-stick design, or a design having small-deflection in only the pitch and roll axes. Small-deflection in each axis of the controller improved the pilot's ability to modulate single-axis forces and enhanced control precision for high-gain tasks such as Precision Hover. In high workload situations, there was less tendency with a limited-deflection controller to over-control and/or cross-couple control inputs.

Pilot ratings with a deflection controller are less sensitive to variations in control response/force gradient. As a result, it would be easier to design acceptable control response characteristics for a wider range of pilot preferences if a small-deflection device were implemented.

Controller Orientation

Controller orientation for both the right-hand and left-hand side-stick controller was adjusted to a position acceptable for all test pilot participants. Orientations were chosen to minimize interaxis control inputs as well as to provide a comfortable arm position to reduce fatigue. Figure 8-1 illustrates the final orientation used during the Phase 2B simulation.

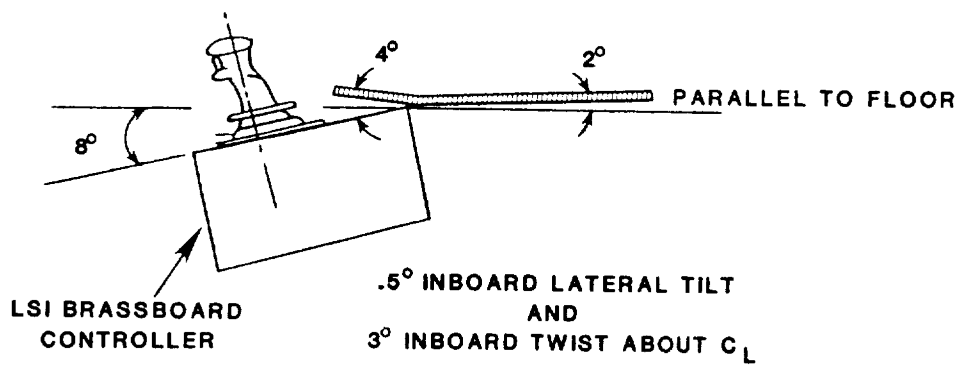
8.2 CONTROLLER CONFIGURATION

4-Axis Controller

With a high level of stability and control augmentation, satisfactory handling qualities were achieved for the low-speed tasks investigated using the preferred small-deflection 4-axis controller i.e., small deflection in all control axes. However,

FINAL CONTROLLER ORIENTATION

RIGHT HAND CONTROLLER MOUNTING



LEFT HAND CONTROLLER MOUNTING

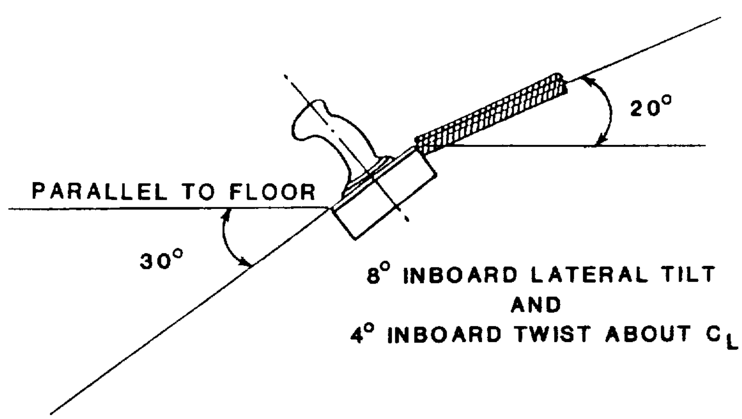


Figure 8-1

the 4-axis configuration exhibited degraded pilot ratings compared to separated controller configurations for:

- o Multi-axis control tasks, such as the Precision Hover, Decelerating Turning Approach-to-Hover, and the High-Speed Slalom
- o Reduced levels of stability and control augmentation

Separated Controller Configurations

The separated vertical controller configurations -- (3+1) Collective and (2+1+1) -- achieved similar overall pilot ratings which were generally improved compared to the integrated 4-axis controller configurations for the lower levels of stability and control augmentation investigated. Either separated vertical controller configuration was preferred for the high speed slalom maneuver and the descending decelerating approach-to-hover task. Separation of the vertical controller provided the following significant advantages for VMC or IMC terrain flight:

- o Elimination of unintentional cross-axis coupling, especially vertical-to-pitch/roll coupling.
- o Reduction of pilot workload for multi-axis tasks due to the separation of any required steady vertical or directional control forces from continuously modulated pitch and roll forces.

Directional control on the side-stick -- (4+0) and (3+1) Collective configurations -- provides more precise heading control than the pedals. There is a tendency to inadvertently couple yaw control to roll; however, all pilots adjusted easily to eliminate or minimize this characteristic. The (3+1) Pedal configuration evaluated during Phase 1 significantly degraded pilot ratings for IMC tasks because of poor yaw controllability. The limited field-of-view helmet-mounted display had a strong effect on lateral-directional control. The use of separated pedals for VMC tasks was not a problem. With good peripheral visual cues, directional control became a less demanding task.

8.3 SCAS DESIGN

The level of handling qualities attainable by various generic SCAS configurations was defined as follows:

Pitch and Roll SCAS

For low-speed maneuvering and Precision Hover Tasks under VMC, an attitude command/velocity stabilization system (AT/LV) provided satisfactory handling qualities for all controller configurations.

In forward flight satisfactory ratings under VMC were achieved with a hybrid combination of control laws consisting of pitch attitude command/airspeed stabilization (AT/AS) in the longitudinal axis and roll rate command/attitude stabilization (RA/AT) in the lateral axis.

Satisfactory handling qualities were not achieved for any combination of controller and AFCS investigated for the low-speed IMC maneuvering tasks. Satisfactory ratings were obtained under IMC for both the Bob-up and Precision Hover Tasks when performed in calm air with a longitudinal and lateral velocity command/velocity stabilization system. With wind and turbulence, the addition of a position hold feature was required to maintain satisfactory ratings for the Bob-up Task.

Yaw and Vertical SCAS

Heading and altitude stabilization were beneficial for all tasks. Yaw rate and vertical velocity command systems were preferred for all tasks and controller configurations. However, with a pitch and roll rate command system, there exists a preference for side-stick yaw acceleration and vertical acceleration command systems to eliminate the requirement to hold steady forces during multi-axis maneuvers.

Control Law Mode Switching

To achieve the desirable low speed and forward flight handling qualities without pilot selection, the control laws required automatic switching during transition as follows:

- Longitudinal - Pitch attitude command/groundspeed stabilization for low speed and pitch attitude command/airspeed stabilization at high speed.

- Lateral - Roll attitude command/groundspeed stabilization for low speed and roll rate command/attitude stabilization at high speed.

- Directional - Full-time heading hold for low speed and turn coordination in forward flight.

The method developed to switch control laws felt natural to the pilot. No undesirable effects on handling qualities were evident during transition maneuvers as control low switching was prevented until rates and attitudes were below predefined thresholds.

Automatic Control Force Trimming

For stiff-stick or small-deflection controllers, elimination of steady forces for steady-state helicopter trim must be automatic through design of the primary control system and/or SCAS control response laws. The build-up of long-term steady forces is unacceptable.

8.4 IMC DISPLAY EFFECTS

The reduction in quality of visual cues and occasional disorientation experienced when looking off the aircraft centerline with the visually coupled helmet-mounted display caused significant degradations in handling qualities for certain IMC tasks relative to the identical tasks conducted under VMC. This degradation was especially severe for the low-speed NOE maneuvering task which required a significant amount of pilot head motion to acquire the required visual information. Significant improvements in hover position hold performance occurred for the IMC tasks compared with the VMC tasks because of the pilots' use of the displayed superimposed symbols which included explicit inertial velocity and position error information.

9.0 RECOMMENDATIONS

The recommendations presented herein are based on the results of the previously described simulation studies. As Boeing Vertol was awarded both contracts -- the ACC/AFCS element of the ADOCS program contract and the ADOCS flight demonstrator program -- the recommendations presented in this section have been incorporated into the demonstrator control system design.

9.1 CONTROLLER DESIGN

The definition of a multiaxis side-stick controller (SSC) design for use in the ADOCS demonstrator aircraft was a primary objective of the ACC/AFCS simulation study. Force-deflection characteristics were defined and the effect of the number of axes controlled by the SSC was investigated.

Recommended design characteristics for the various controllers to be manufactured by Lear Siegler Inc. are based on the ACC/AFCS simulation results. Design characteristics for the 4-axis, right-hand SSC are given in Table 9-1 for each control axis. Force/displacement characteristics for separated controllers, including a left-hand single-axis collective controller and small-deflection force pedals, are defined in Table 9-2. The Lear Siegler ADOCS brassboard 4-axis controller with the characteristics outlined in Table 9-1 was evaluated during the final piloted simulation phase at NASA-Ames. The results from this simulation demonstrated that an acceptable hardware design was achieved.

In addition to the 4-axis configuration, the simulation studies investigated alternate controller configurations (See Figures 3-2 and 3-3). Because the separated controller configurations (e.g. the (3+1) Collective and the (2+1+1) configurations) received improved pilot ratings for certain tasks, the demonstrator aircraft will contain provisions for flight evaluation of these configurations as well as the 4-axis configuration.

9.2 CONTROL LAW DESIGN

The control laws developed during the ACC/AFCS program were designed to provide the handling qualities required to accomplish the attack/scout helicopter mission. The control laws were implemented in a manner that facilitates the evaluation of various SCAS command/stabilization systems during flight testing of the demonstrator aircraft. The recommended PFCS design provides control shaping for both AFCS ON and OFF operation and includes a force trim method that eliminates the requirement for open loop integrators which are undesirable due to redundancy management constraints.

RECOMMENDED 4-AXIS CONTROLLER
FORCE/DISPLACEMENT CHARACTERISTICS

AXIS	GRADIENT	MAXIMUM DISPLACEMENT	MAXIMUM FORCE	BREAKOUT
Longitudinal	2.09 lb/deg.	$\pm$ 7.6 degrees or $\pm$ 0.8 inch at 6 inch radius	$\pm$ 15.9 lbs	0.0 lb
Lateral	1.67 lb./deg.	$\pm$ 7.6 degrees or $\pm$ 0.8 inch at 6 inch radius	$\pm$ 12.8 lbs	0.0 lb
Directional	5.0 in-lb/deg.	$\pm$ 7.0 degrees	$\pm$ 35 in-lbs	0.0 lb
Vertical	95. lb/inch (up) 85. lb/inch (down)	$\pm$ .156 inches	15.82 lb (up) 13.86 lb (down)	1.0 lb (up) 0.6 lb (down)

Table 9-1

RECOMMENDED ALTERNATE CONTROLLER FORCE/DISPLACEMENT CHARACTERISTICS

CONTROLLER	GRADIENT	MAXIMUM DISPLACEMENT	MAXIMUM FORCE	BREAKOUT
Single-axis collective (left-hand)	2.19 lb/deg	$\pm$ 6.10 degrees or $\pm$ .64 inch at 6 inch radius	$\pm$ 16.5 lbs	$\pm$ 0.5 lbs
Pedals	50.0 lb/inch	$\pm$ .78 inches	$\pm$ 45.0 lbs	$\pm$ 6.0 lbs.

Table 9-2

ADOCS PFCS DESIGN

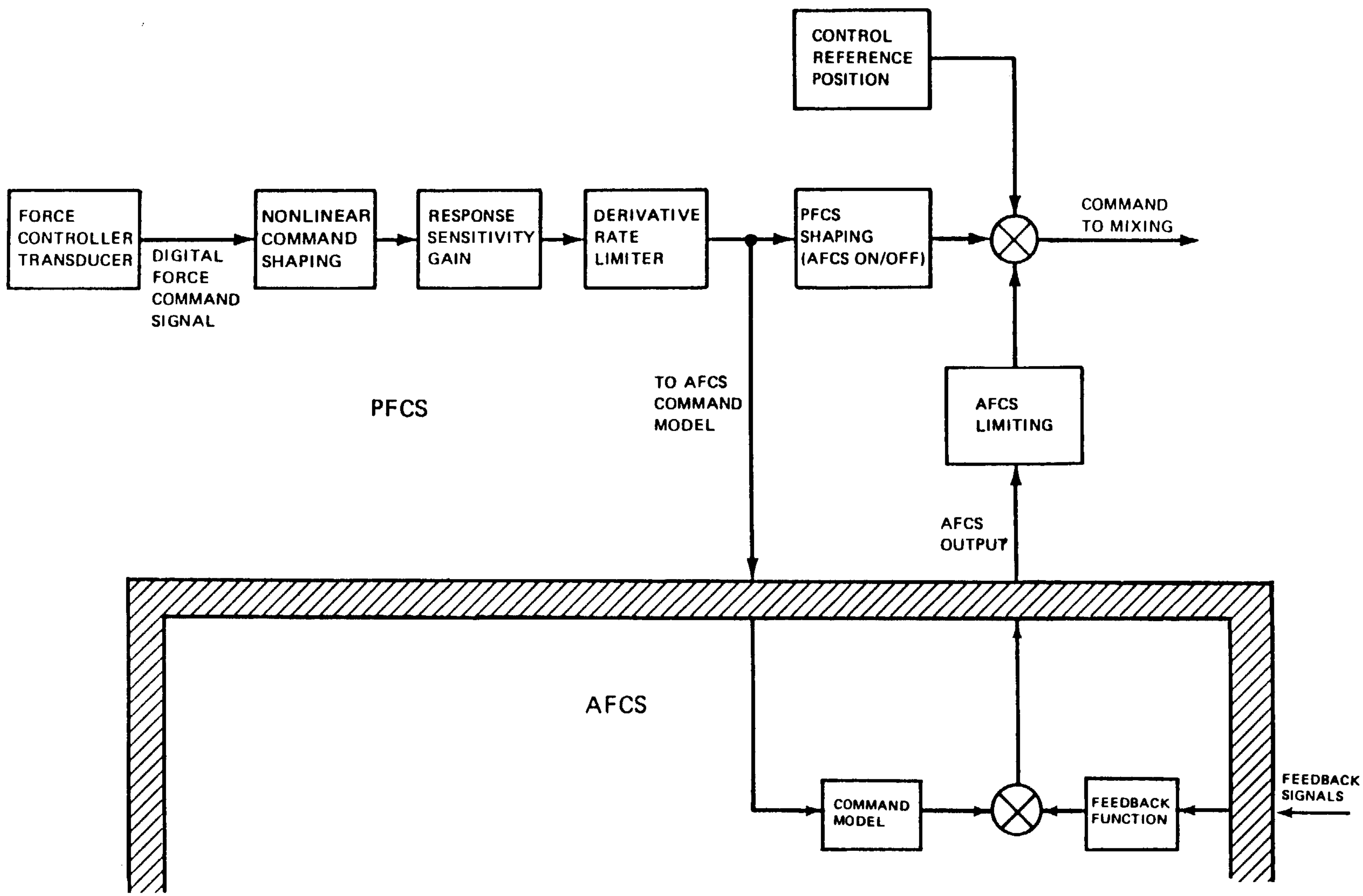


Figure 9-1

PFCS Design

Significant features of the recommended PFCS design (Figure 9-1) are briefly described as follows:

Force Transducer Quantization - 8-bit signal quantization is required to provide acceptable response resolution in each axis.

Nonlinear Command Response Sensitivity - To provide acceptable response characteristics for both small precision control tasks and large maneuvers, nonlinear command shaping is required.

Derivative Rate Limiter - A derivative rate limiter is required in each axis to limit the magnitude of initial acceleration response during rapid maneuvers when using a force controller.

Command Signal Shaping - Forward path lead-lag shaping is included in the PFCS full time for augmented flight conditions. Lead-lag time constants are selected to properly match the desired command model and basic helicopter response characteristics in order to achieve a balanced or small AFCS output during dynamic maneuvers. During AFCS OFF operation, a parallel high-gain lag path with a long time constant is included to automatically reduce steady-state control trim forces to an acceptably low level.

SCAS Design

The stability and control law features recommended for the ADOCS demonstrator design are summarized in Tables 9-3 and 9-4. These design features for SCAS ON flight evolved from the extensive ACC/AFCS simulation studies. Low-speed and forward flight control laws are defined in Table 9-3 for the basic SCAS configuration. Table 9-4 identifies the selectable modes that provide the handling qualities to meet attack helicopter IMC or VMC mission requirements for precision hover capability and for tight flight path control during low-speed NOE maneuvers.

9.3 DISPLAY SYSTEM

The selectable display modes used to meet attack helicopter operational requirements for various mission tasks are:

> Cruise - high-speed level flight enroute to the forward edge of the battle area;
>
> Transition - low-speed NOE maneuvers such as dash, quick stop, and side-ward flight;
>
> Hover - stable hover with minimum drift; and
>
> Bob-Up - unmask, target acquisition, and remask maneuvers over a selected ground position.

BASIC SCAS MODES

AXIS	HOVER/LOW SPEED		FORWARD FLIGHT	
	COMMAND	STABILITY	COMMAND	STABILITY
LONGITUDINAL	PITCH ATTITUDE	LONGITUDINAL GROUNDSPEED (LOW GAIN)	PITCH ATTITUDE	AIRSPEED HOLD
LATERAL	ROLL ATTITUDE	LATERAL GROUNDSPEED (LOW GAIN)	ROLL RATE & YAW RATE (TURN COORD)	ROLL ATTITUDE HOLD
DIRECTIONAL	YAW ACCELERATION	YAW RATE	YAW ACCELERATION	YAW RATE & LAT ACCEL (TURN COORD)
VERTICAL	VERTICAL ACCELERATION	VERTICAL VELOCITY	VERTICAL ACCELERATION	VERTICAL VELOCITY

Table 9-3

SELECTABLE SCAS MODES

AXIS	HEADING HOLD		VELOCITY STABILITY GROUNDSPEED < 40 KNOTS		HOVER HOLD		ALTITUDE HOLD (RADAR OR BARO)	
	COMMAND	STABILITY	COMMAND	STABILITY	COMMAND	STABILITY	COMMAND	STABILITY
LONGITUDINAL	–	–	PITCH ATTITUDE	LONGITUDINAL GROUNDSPEED (HIGH GAIN)	LONGITUDINAL GROUNDSPEED	LONGITUDINAL GROUNDSPEED OR POSITION HOLD	– –	–
LATERAL	–	–	ROLL ATTITUDE	LATERAL GROUNDSPEED (HIGH GAIN)	LATERAL GROUNDSPEED	LATERAL GROUNDSPEED OR POSITION HOLD	–	
DIRECTIONAL	YAW RATE	FULL TIME HEADING HOLD AS $<$ 40(kts) ------ HEADING HOLD $\phi \leq 3^{\circ}$ $\dot{\phi} \leq 1^{\circ}$/SEC AS $>$ 40(kts)	–	–	YAW RATE	HEADING HOLD	–	–
VERTICAL	–	–	–	–	VERTICAL VELOCITY	ALTITUDE HOLD (RADAR)	VERTICAL VELOCITY	ALTITUDE HOLD -- BARO OR RADAR $<$ 1000 (ft)

Table 9-4

A three-position (center off) mode select switch is required to sequence through the four modes in either the forward direction (i.e. Bob-Up, Hover, Transition, Cruise) or reverse direction. This switch must be accessible to the pilot's left-hand, either mounted on the left-hand side-stick controller or on the control panel. If mounted on the controller, the breakout force required to activate the switch must be minimal (i.e. less than 50% of the SSC breakout force).

The symbology dynamics used to aid the pilot under IMC with IHADSS have a significant effect on aircraft handling qualities. The compatibility of the symbol dynamics for the various modes and varying dynamic characteristics of the SCAS configuration must be ensured. Therefore, the display mode logic must automatically change the symbology format/sensitivities as a function of control laws, to reduce pilot workload and improve low speed maneuvering and hover hold task performance.

For instance, selection of the Bob-up display mode will also automatically engage the SCAS Hover Hold Mode providing a velocity command system. Logic to automatically enable/disable display modes should be considered. For instance, the Bob-Up and Hover display modes could be restricted to low speed flight less than 25 knots while the Cruise mode might only be used for high speed flight at airspeeds greater than 50 knots.

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15. Supplementary Notes

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16. Abstract

The Advanced Cockpit Controls/Advanced Flight Control System (ACC/AFCS) study was conducted by the Boeing Vertol Company as part of the Army's Advanced Digital/Optical Control System (ADOCS) program. Specifically, the ACC/AFCS investigation was aimed at developing the flight control laws for the ADOCS demonstrator aircraft that will provide satisfactory handling qualities for an attack helicopter mission. The three major elements of design considered during the ACC/AFCS study are summarized as follows: Pilot's Integrated Side-Stick Controller (SSC) -- Number of axes controlled; force/displacement characteristics; ergonomic design. Stability and Control Augmentation System (SCAS)--Digital flight control laws for the various mission phases; SCAS mode switching logic. Pilot's Displays--For night/adverse weather conditions, the dynamics of the superimposed symbology presented to the pilot in a format similar to the Advanced Attack Helicopter (AAH) Pilot Night Vision System (PNVS) for each mission phase as a function of SCAS characteristics; display mode switching logic. Volume I is an Executive Summary of the study. Findings from the literature review and the analysis and synthesis of desired control laws are reported in Volume 2. Results of the five piloted simulations conducted at the Boeing Vertol and NASA-Ames simulation facilities are presented in Volume 3. Conclusions drawn from analysis of pilot rating data and commentary were used to formulate recommendations for the ADOCS demonstrator flight control system design. The ACC/AFCS simulation data also provide an extensive data base to aid the development of advanced flight control system design for future V/STOL aircraft.

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