An Assessment of Various Side-Stick Controller/Stability
and Control Augmentation Systems for Night Nap-of-Earth Flight
Using Piloted Simulation

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ABSTRACT

A series of piloted simulator experiments was conducted to assess the interactive effects of side-stick controller characteristics and level of stability and control augmentation on attack helicopter handling qualities. Several night nap-of-the-earth mission tasks were evaluated using a helmet-mounted display which provided a limited field-of-view image with superimposed flight control symbology. A wide range of stability and control augmentation designs was investigated. Variations in controller force-deflection characteristics and the number of axes controlled through an integrated side-stick controller were studied. In general, a small displacement controller was preferred over a stiff-stick controller particularly for maneuvering flight. Higher levels of stability augmentation were required for IMC tasks to provide handling qualities comparable to those achieved for the same tasks conducted under simulated visual flight conditions.

NOTATION

AAH	Advanced Attack Helicopter
ACC/AFCS	Advanced Cockpit Controls/ Advanced Flight Control System
ADOCS	Advanced Digital/Optical Control System
BUCS	Back Up Control System
DOCS	Digital Optical Control System
FLIR	Forward-Looking Infrared
HLH	Heavy Lift Helicopter
IHADSS	Integrated Helmet and Display Sighting System
IMC	Instrument Meteorological Conditions
NOE	Nap-of-the-Earth
PFCS	Primary Flight Control System
PNVS	Pilot Night Vision System
SCAS	Stability and Control Augmentation System
SSC	Side-Stick Controller
VMC	Visual Meteorological Conditions

INTRODUCTION

The Army's Advanced Digital/Optical Control System (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 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.

This paper presents the results of a conceptual design and piloted simulation study of the cockpit controller configuration, flight control laws, and display logic required to achieve satisfactory handling qualities for the mission defined for the ADOCS demonstrator aircraft: an attack helicopter mission conducted under both day and night/adverse weather conditions. The simulation, as part of the Advanced Cockpit Controls/ Advanced Flight Control System (ACC/AFCS) element of the ADOCS program was conducted using the Boeing Vertol Flight Simulation Facility. Although both day VMC and night IMC missions were simulated, this paper emphasizes the low-speed night NOE segments of the ADOCS mission and assesses the interactive effects on

handling qualities of the integrated side-stick controller characteristics, flight control laws, and helmet-mounted display symbol dynamics.

EXPERIMENT DESIGN

Pilot workload and the 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 four-axis side-stick controller to a 2+1+1 arrangement; i.e., a two-axis side-stick for pitch and roll control with small-displacement directional pedals and collective lever.

(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)[1] symbology presented on a helmet-mounted display.

GENERAL APPROACH

The approach to the systematic investigation of these elements is illustrated in Figure 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[2].

In applying this general approach to the specific problem, the blocks defined in Figure 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 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 seriously affect the system control law and display symbology.

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.
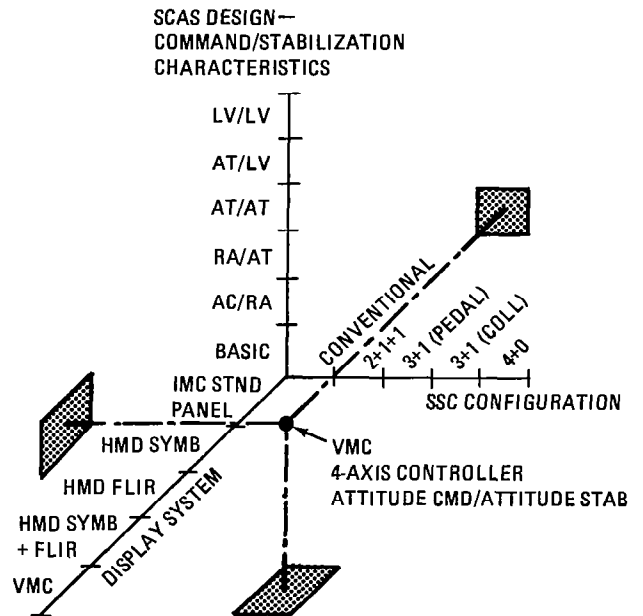

Figure 1   Three-Dimensional Flight Control System Description

INTEGRATED SIDE-STICK CONTROLLER

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.

Related Research and Development Programs

Handling qualities research examining the effects of the characteristics of a two-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[3], it was concluded that a small amount of side-stick motion provided improved flying qualities over those achieved with a fixed controller. The results of this and other similar flight experiments were incorporated in a design guide for two-axis side-stick controllers used in fighter aircraft[4]; included in the 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 con-
trollers in Army helicopters began in 1968 with
the Tactical Aircraft Guidance System (TAGS)
program[5]. The system implemented in a CH-47B
aircraft initially included an integrated four-axis
large-displacement controller. Because of cou-
pling problems between the longitudinal and
vertical axes, a three-axis controller was even-
tually implemented with vertical control effected
through a standard collective lever. On the
Heavy Lift Helicopter (HLH)[6], a four-axis dis-
placement controller was implemented at the
load-controlling crewman's station in conjunction
with a ground velocity command and stabiliza-
tion 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 - and investigated
using both ground- and in-flight simulation. In
a three-degree-of-freedom moving-base simula-
tion of the unaugmented Lynx helicopter at RAE
Bedford, a two-axis displacement side-stick was
compared to the conventional cyclic controller
for eleven different flight tasks[7]. When a suit-
able control sensitivity was selected, the side-
stick compared favorably with the conventional
controller and, in fact, was preferred for cer-
tain of the tasks.

A feasibility study of a four-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[8].
Two primary side-stick configurations, a four-
axis controller and a three-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 by both primary side-stick con-
figurations.

These investigations indicate that a comprehen-
sive 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-de-
flection characteristics of the controller, and
3) the attendant SCAS characteristics.

Level of Integration (Number of Axes)

Four variations in controller configuration rep-
resenting different levels of controller integra-
tion were investigated. Figure 2 shows the
controller configurations including:

(1) 4+0: All control axes (pitch, roll, yaw,

and vertical) on the side-stick con-
troller,

(2) 3+1 (Collective): Three-axis side-stick for
pitch, roll and yaw control, and a
separate collective lever for vertical
control,

(3) 3+1 (Pedal): Three-axis side-stick for
pitch, roll and vertical control, and
pedals for directional control, and

(4) 2+1+1: Two-axis side-stick for pitch and
roll control, with separate collective
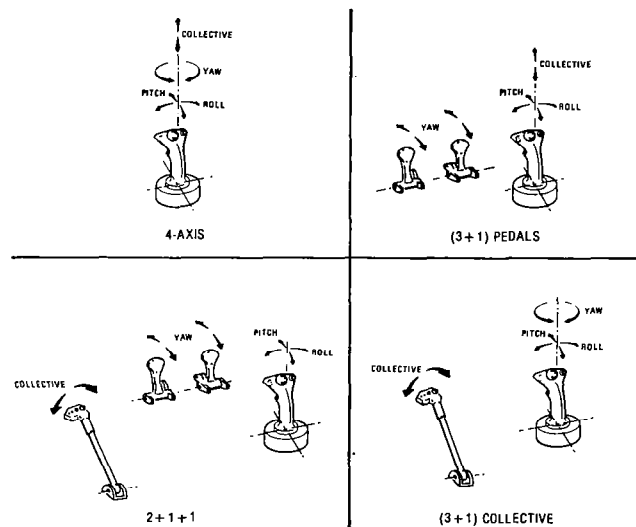lever for vertical control, and pedals
for directional control.

Figure 2   Controller Configurations

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 force-deflec-
tion characteristics was performed using three
4-axis side-stick controllers:

(1) A stiff-stick force controller,

(2) A small-deflection controller with two force/
deflection gradient configurations, and

(3) A large-deflection controller with an as-
sortment of springs which provided inde-
pendent adjustment of force/deflection
gradients and breakout forces in each
axis. This controller is a modified load-
controlling crewman's controller used
during the HLH program.

All controllers are a base-pivot type for pitch
and roll motion. Fore-aft force produces longi-

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tudinal 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. Figure 3 shows the three controllers.
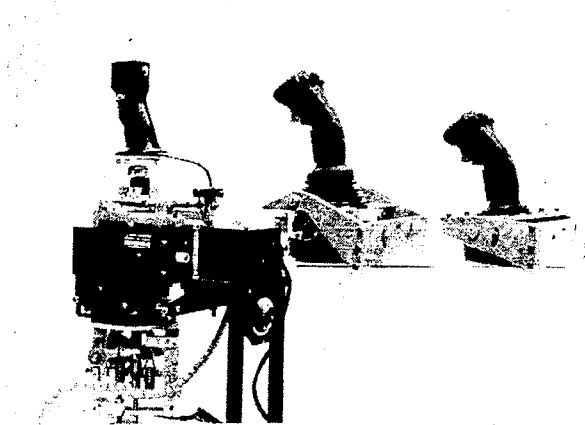

Figure 3 Four-Axis Side-Stick Controllers

The selection of pitch and roll force/deflection gradients was guided by a review of previously described published data. References 4 and 9 defined preferred regions of longitudinal and lateral force/deflection gradient developed from Air Force flight test evaluation of a two-axis variable force-deflection side-stick controller. Figure 4 shows the recommended force/deflection gradient range, in addition to five specific longitudinal controller force/deflection configurations evaluated during this 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). The F-16 side-stick controller design is also shown for comparison.

Complete force/deflection characteristics for the five 4-axis controller configurations utilized during this simulation are presented in Table 1. Operating force range, maximum deflection, and force/deflection gradient are given for the four control axes. Yaw and vertical controller compliance for both small-deflection configurations were relatively "stiff" compared to the pitch and roll axes. In contrast, the medium- and large-deflection configurations were evaluated with lighter yaw and vertical force/deflection gradients for harmony with pitch and roll.

Evaluation of the (3+1) collective, (3+1) pedal, and 2+1+1 controller configurations was performed using a conventional collective lever and directional pedal controls. The simulator variable force-feel collective lever was implemented as a "stiff" force controller with small deflection. A pedal force control system was configured using a mechanical spring capsule attached directly to the pedals. The directional pedal configuration selected had a force/deflection gradient of 40 lbs/inch with a force breakout of 6.0 lbs.
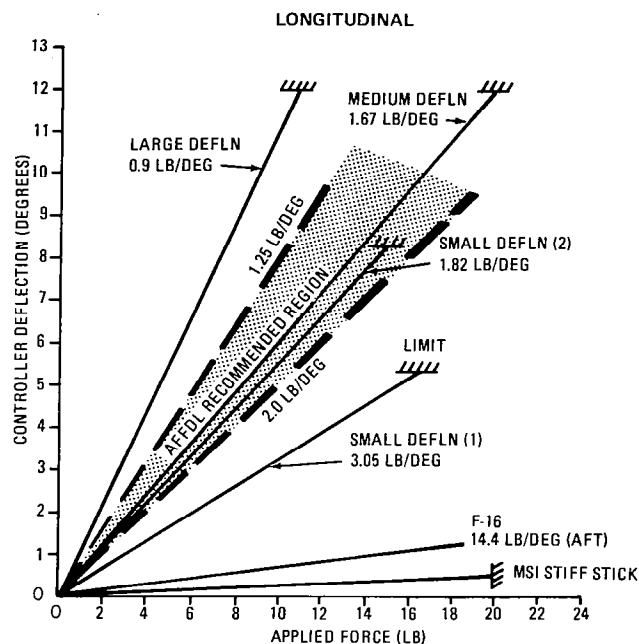

Figure 4 Longitudinal Axis Force-Deflection Characteristics

4 AXIS CONTROLLER CONFIGURATIONS	OPERATING FORCE LINEAR RANGE (±)				MAXIMUM DEFLECTION (±)				FORCE/DEFLECTION			
	X LONG LB/DEG	Y LAT LB	Z VERT LB	ψ YAW IN LB	X LONG DEG	Y LAT DEG	Z VERT IN	ψ YAW DEG	X LONG LB	Y LAT LB/DEG	Z VERT LB/IN	ψ YAW IN LB/DEG
(1) STIFF STICK - MEASUREMENT SYSTEMS, INC PHASES 1 AND 2	20	20	40	60	0.5	0.5	–	–	40	40	–	–
(2) SMALL DEFLECTION - CONFIG NO. 1 MEASUREMENT SYSTEMS, INC PHASE 1	18	12	40	60	5.3	5.3	0.1	4.0	3.05	2.25	400.0	15.0
(3) SMALL DEFLECTION - CONFIG NO 2 MEASUREMENT SYSTEMS, INC. PHASE 2	15	12	40	60	8.3	8.3	0.15	6.0	1.82	1.45	267.0	10.0
(4) MEDIUM DEFLECTION - HLH PROTOTYPE PHASE 1	20	12.6	17.5	40	12.0	12.0	0.5	15.0	1.67	1.05	35.0	2.7
(5) LARGE DEFLECTION - HLH PROTOTYPE PHASE 1	10.8	7.2	7.5	22	12.0	12.0	0.5	15.0	0.9	0.6	15.0	0.7

Table 1 Four-Axis Controller Force-Deflection Characteristics

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. This simulation was designed to provide a preliminary definition of flight control laws and SCAS mode switching logic requirements for the various mission phases. In addition, the effects on both handling qualities and flight safety of degraded SCAS modes were to be determined. The effect of the side-stick controller configuration under degraded SCAS mode

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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.

Results presented herein are for the first of two scheduled simulation phases, which concentrated on the low speed portion of the NOE mission, that is, airspeeds below approximately 50 knots. High speed control laws and transition requirements will be evaluated during the second simulation phase.

Figure 5 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:

o 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.

o Stabilization feedback loops are optimized solely for maximum gust and upset rejection. This allows use of high full-time stabilization gains 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.

o 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.

o 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.
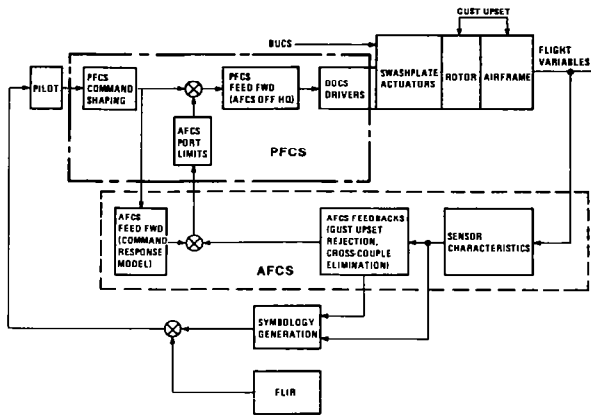

Figure 5   ADOCS Demonstrator-Flight
Control System Concept

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

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

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   Generic SCAS Configurations-Command Response/Stabilization Matrix

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the letter code RA/AT. It should be noted that the longitudinal and lateral control axes were always evaluated with the same command response and stabilization system.

The method of SCAS implementation used for the simulation is illustrated in Figure 7 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 8. Elements of the model include transfer functions to represent the dynamics of the basic helicopter, rotor and actuators as well as a computational time delay. Nichols chart techniques were used to select feedback gains. Multiple feedback paths, each increasing overall stability, were closed around the model based on a damping ratio design criteria (ζ = 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 characteristic equation. Control response model feedforward parameters were defined for each of the response types previously described. For example, Figure 9 shows the lateral response to step force input for a rate, attitude, and velocity response type. For the angular rate command model, identical response characteristics were provided for both the attitude and velocity stabilized systems. Similarly, the attitude response model characteristics were the same regardless of the level of stabilization.

During this preliminary control response design process, information from available literature, as well as related experience, was used to develop design criteria and quantitative guidelines. Design guidance for SCAS intended for low speed and hovering flight is contained in Reference 10 which develops tentative VTOL aircraft flying qualities criteria from the existing experimental data base. Requirements for generic SCAS such as angular rate command, attitude command, and translational rate command are proposed together with suggested vertical augmentation system characteristics. In addition,

Figure 7   Lateral Axis Stability and Control Augmentation System

Figure 9   Lateral Response to Step Force Input

Figure 8   Helicopter/Stability Augmentation System Model-Longitudinal Axis

the use of velocity command system for the precision hover task was flight demonstrated on the HLH Program (References 11 and 12), and the desirability of this control concept was confirmed based on study results published in References 13 and 14.

The preliminary analytical study established baseline response characteristics to begin piloted evaluations. Final response characteristics developed during the initial phase of simulation are presented in the Experiment Results section.

IMC DISPLAY (IHADSS)

Since the ADOCS mission is to be flown in night/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 impact on handling qualities of the pilot's night vision aids. For this program it is assumed that the pilot is provided with the AH-64 Pilot Night Vision System (PNVS) and associated avionics[1] which include a helmet-mounted display of flight control and fire control symbology superimposed upon a limited field-of-view monochromatic image of the outside world slaved to the pilot's head motions.

The display system selected for simulation of the IMC mission is the Honeywell Integrated Helmet Mounted Display/Sight System (IHADSS) developed for the Army's YAH-64 Advanced Attack Helicopter (AAH). The IHADSS permits NOE, low level, and contour flight under IMC. Since the Helmet Mounted Display (HMD) is coupled to the pilot's head, he is able to scan a wide field-of-view without being constrained to a head-down or look-forward position. The pilot's line of sight is tracked with a Helmet Mounted Sight (HMS) that provides closed-loop command signals to point the sensors.

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 15. Baseline display laws and information format used for this investigation were defined based on the AH-64 Pilot Night Vision System (PNVS)[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 10 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[13], 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 is necessary also 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 13 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.

(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 13.

EXPERIMENT ACTIVITIES

To reduce the large number of possible SSC/SCAS combinations to a manageable set of configurations for evaluation, the experiment was designed with two major phases of simulation activity as shown in Figure 11. Phase I accomplished IHADSS familiarization and controller development. Phase 2 concentrated on evaluation of controller/SCAS configuration combinations.
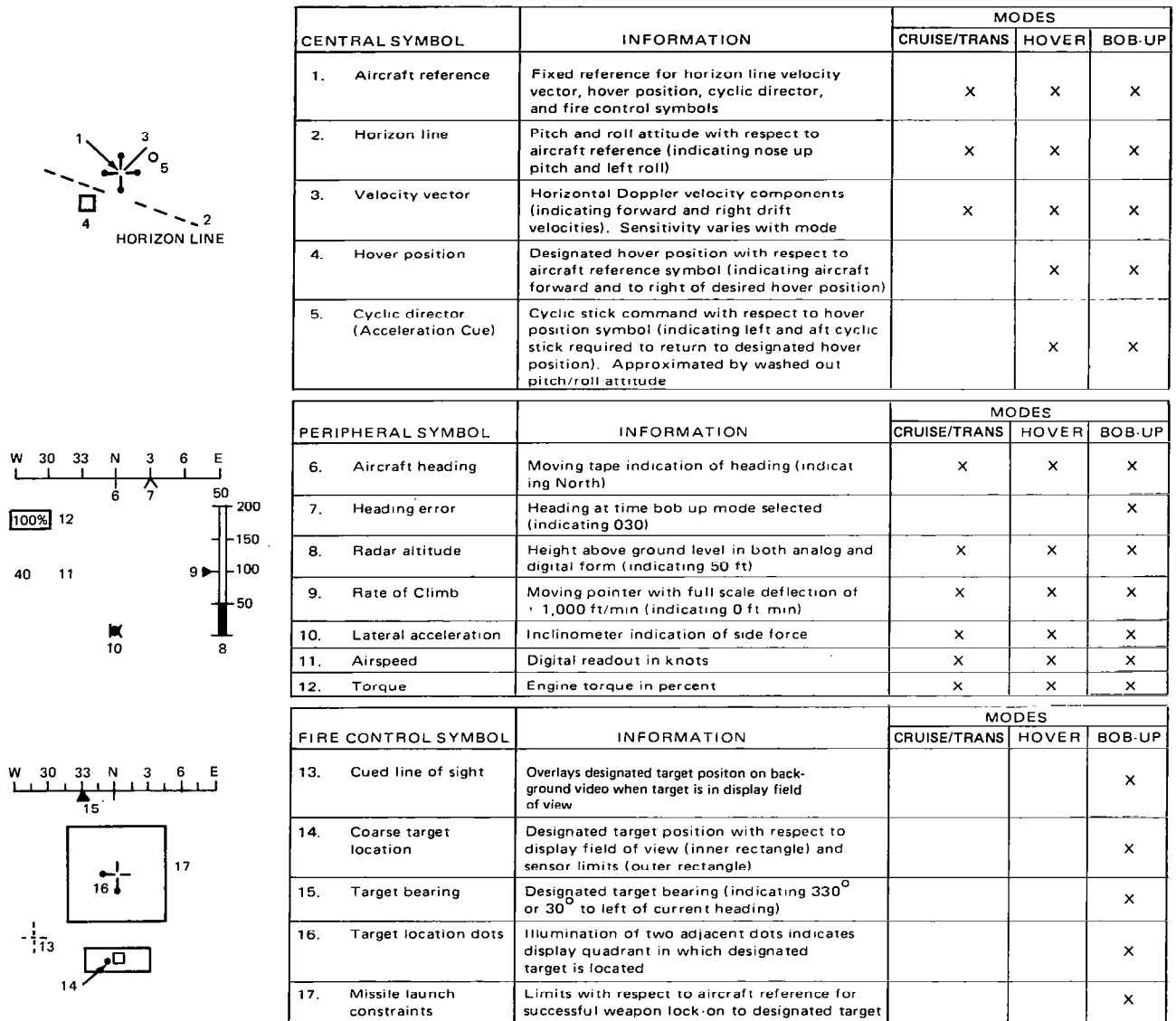
CENTRAL SYMBOL		INFORMATION	MODES		
			CRUISE/TRANS	HOVER	BOB-UP
1.	Aircraft reference	Fixed reference for horizon line velocity vector, hover position, cyclic director, and fire control symbols	X	X	X
2.	Horizon line	Pitch and roll attitude with respect to aircraft reference (indicating nose up pitch 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 10   Display Mode Symbology

Specific steps followed for controller development were:

(1) Evaluation of the 4-axis stiff-stick controller to determine best individual axis response/force characteristics and desired non-linear response shaping requirements.

(2) Evaluation of the three 4-axis deflection controllers to define effect of force/deflection gradient on pilot task performance.

(3) Comparison of the stiff-stick and deflection controllers for various pitch and roll SCAS configurations.

(4) Definition of desired response/force charac-

teristics for a conventional collective lever and pedals configured as force controllers.

A best 4-axis controller design was selected based on the above results. This design was used to evaluate the 4+0, (3+1) pedals, (3+1) collective, and 2+1+1 configurations for the primary and secondary controller/SCAS configuration matrices as follows:

(1) Primary configuration matrix - Variations to the pitch and roll SCAS with a fixed directional and vertical command/stabilization system (yaw rate command/heading hold and vertical rate command/altitude hold).

(2) Secondary configuration matrix - Variations to the vertical and directional SCAS for a limited portion of the primary configuration matrix with emphasis given to the less highly augmented pitch and roll systems, particularly the rate/attitude (RA/AT) and attitude/attitude (AT/AT) systems.
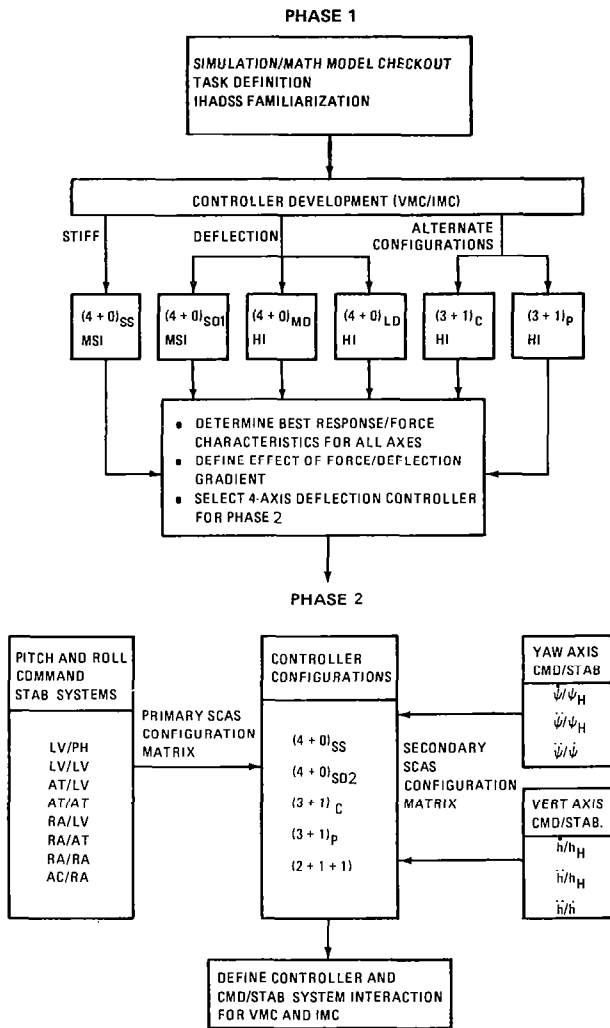
PHASE 1

PHASE 2

Figure 11   Simulation Experiment Flow Diagram

CONDUCT OF THE EXPERIMENT

EQUIPMENT

This experiment was conducted at the Boeing Vertol Flight Simulation Facility. Major elements of the facility shown in Figure 12 include:

o Single-seat cockpit cab mounted on a six-degree-of-freedom limited-motion base.

o Conventional helicopter flight and performance instruments, and a SCAS mode select panel.

o Conventional helicopter collective and directional pedals implemented as small-displacement force controllers, and three 4-axis side-stick controllers. An adjustable mounting bracket attached to the armrest allowed orientation of each 4-axis side-stick controller for comfort and to minimize inter-axis control inputs. A forward tilt of six degrees and a counter-clockwise rotation of five degrees relative to the armrest was selected.

o Xerox Sigma 9 digital computer to drive the entire simulation. The Sigma 9 was programmed with a UH-60 full-flight envelope math model and easily variable SCAS configurations for this study.

o Four-camera wide-angle television/terrain model visual display system for the simulation of terrain flight under either:

VMC - Four-window cockpit visual display covering a field-of-view 125°x75°, or

IMC - FLIR image with superimposed symbology presented by a Honeywell helmet mounted display and sight system (IHADSS) including head tracker.

The FLIR sensor signal was simulated using the center window video channel to provide a 40°x30° outside world field-of-view display. A Gaertner Symbology Generator was utilized to overlay computer generated symbols (Figure 10) on the video picture. The ability to compare directly VMC and IMC handling qualities with a specific controller/SCAS combination was a unique feature of this simulation.
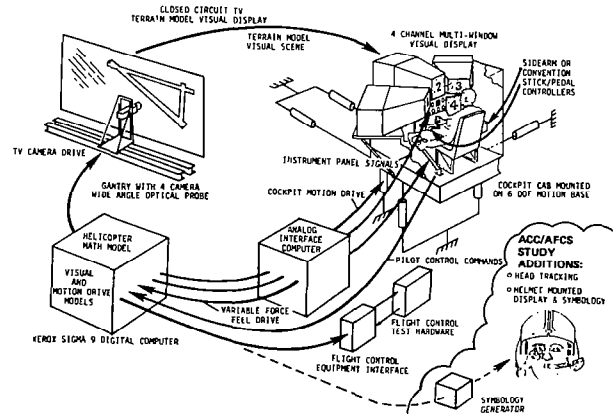
Figure 12   Boeing Vertol Flight Simulation Facility

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EVALUATION TASK DESCRIPTION

Evaluation of total system (pilot, controllers, SCAS, displays) performance was accomplished using four specific low speed tasks - the slalom, acceleration/deceleration, nap-of-the-earth, and bob-up task. No secondary duties (e.g., armament, communication, or navigation system management) were required during the performance of each task. For this experiment a 200:1 scale model board (1-1/8 mile long by 3/5 mile wide) with an existing 3000 ft airport runway was modified as shown on Figure 13 to include terrain features and obstacles necessary to perform the planned maneuvers.

Slalom - Low-speed lateral avoidance maneuver requiring the pilot to fly around 50 ft. high obstacles placed 400 feet apart on the runway centerline. From a hover at 30 feet AGL, the pilot accelerates the helicopter to an airspeed of 30 knots. The pilot appropriately controls bank angle and heading to coordinate turns around the obstacles while maintaining a constant airspeed of 30 knots and an altitude of 30 feet throughout the maneuver.

Acceleration/Deceleration - Forward translation of the helicopter while holding a lateral ground track parallel to the runway. From an initial hover position offset from the runway, the pilot acclerates the helicopter to a forward speed of 50 knots, followed by a deceleration maneuver to arrive at a desired hover position near the last runway obstacle. The pilot attempts to hold lateral ground track and altitude, as well as complete the task in minimum time.

Nap-of-the-Earth (NOE) - A multi-axis control task requiring the pilot to fly through three legs of a narrow canyon (125 feet wide and 50 feet high), having two sharp turns (70° left and 80° right) and two obstacles (50 feet high), to reach a termination hover area. During the first leg of the course, an acceleration to 50 knots is performed before crossing a road, followed by a deceleration to 25 knots while maintaining a lateral ground track and an altitude of 30 feet. After executing a coordinated left turn to enter the second leg, the pilot must control altitude to fly over an obstacle and re-mask to 30 feet in as short a time as possible while attempting to maintain an airspeed of 25 knots. Following a sharp right turn, the pilot flies over a second obstacle, controls altitude back to 30 feet, and decelerates to a hover point in the termination area.

Bob-Up - A multi-axis task consisting of a vertical unmask maneuver from 25 feet to 100 feet, a heading turn to acquire a target, and a vertical remask to the original hover height. The pilot attempts to hold a fixed horizontal ground position throughout the vertical unmask/remask and heading turn maneuvers.

TEST PILOT BACKGROUND AND PARTICIPATION

Five experimental test pilots with extensive flight experience participated in this simulation study - one each from Boeing Vertol, NASA, and the National Aeronautical Establishment (NAE) of Canada, and two pilots from the U.S. Army assigned to NASA. Table 2 presents an
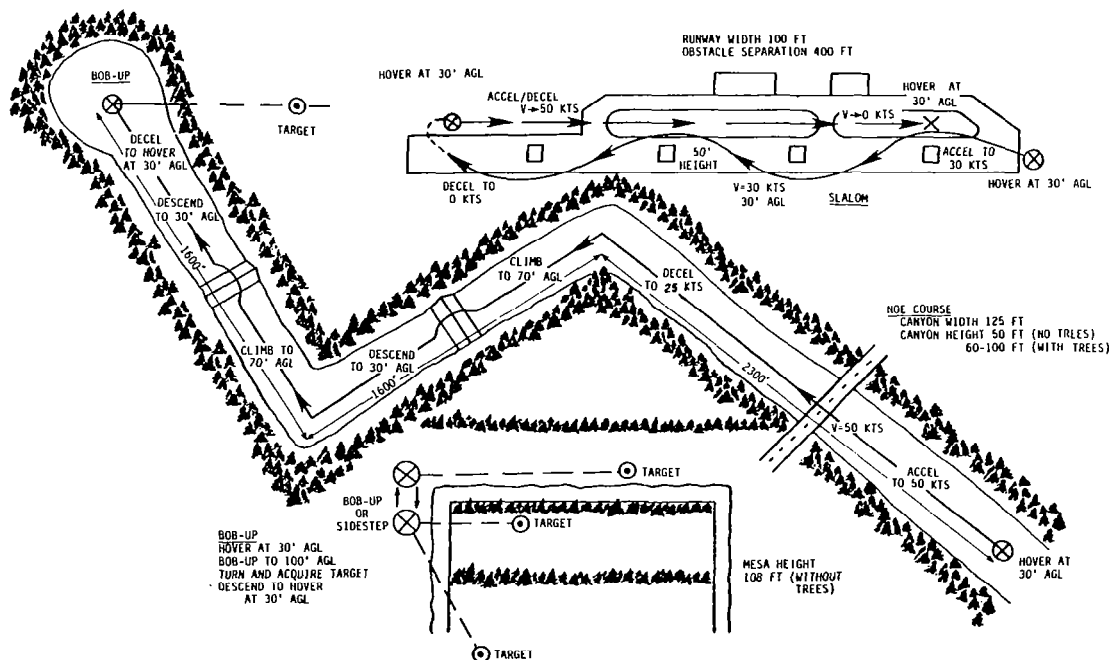
Figure 13   Terrain Model for Evaluation Tasks

experience summary for each evaluation pilot including total flight time broken down by helicopter and fixed wing time. After the initial phase of simulation development, two pilots (A and B) were given 3 hours of IHADSS flight training on the PNVS Surrogate Trainer at the U.S. Army Yuma Proving Ground.

PILOT	AFFILIATION	FLIGHT TIME (HOURS)		SIDE-STICK CONTROLLER DEVELOPMENT		VISUAL DISPLAYS FOR IMC	
		HELICOPTER FIXED-WING	TOTAL	FLIGHT TEST	SIMULATION	FLIGHT TEST	SIMULATION
A	BOEING VERTOL	3,600 (H) 2,800 (F)	6,400	X	X	X*	
B	NASA	2,300 (H) 700 (F)	3,000		X	X*	X
C	NAE CANADA	450 (H) 5,600 (F)	6,050	X	X		
D	U.S. ARMY	1,000 (H) 2,200 (F)	3,200			X	
E	U.S. ARMY	2,500 (H) 700 (F)	3,200		X		X

*IHADSS TRAINING ON PNVS SURROGATE TRAINER INCLUDED FOR PILOT A AND B

Table 2   Summary of Pilot Experience

A total of 204 simulation flight hours was accumulated during this simulation experiment. Sixty-three percent of the total time was utilized for VMC evaluation, and thirty-seven percent for IMC evaluation. A breakdown of the total hours by controller configuration and pilot is given in Table 3. Pilots A, B, and C were the primary evaluators with Pilot A having the largest flight time (54%) since he participated during all eight weeks of the experiment. Pilot B participated for three weeks of the study, and pilot C participated for four weeks. Pilot D, who had significant IHADSS experience on the AH-64, participated for one week and assessed the realism of the simulated IMC system compared to real life hardware. Pilot E, who

CONTROLLER CONFIGURATION	VMC	IMC	TOTAL
● 4 AXIS STIFF STICK	33	11	44
● 4 AXIS SMALL DEFLN (1)	19	4	23
● 4 AXIS SMALL DEFLN (2)	11	16	27
● 4 AXIS MEDIUM DEFLN	5	4	9
● 4 AXIS LARGE DEFLN	12	1	13
● 3 AXIS + PEDALS	15	11	26
● 3 AXIS + COLLECTIVE	13	15	28
● (2+1+1) PEDALS + COLLECTIVE	14	9	23
● CONVENTIONAL	7	4	11
TOTAL HOURS	129	75	204

PILOT FLIGHT HOURS	VMC	IMC	TOTAL
A	68	42	110
B	21	13	34
C	28	12	40
D	8	5	13
E	4	3	7
TOTAL HOURS	129	75	204

Table 3   Summary of Simulation Flight Hours

participated the first week, helped to define the specific tasks used for the remainder of the experiment.

DATA COLLECTION AND ANALYSIS

Experimental data collected for this investigation consist of both qualitative pilot evaluation data and quantitative system performance data. Pilot Cooper-Harper ratings and commentary were recorded for each controller/SCAS/display/task combination evaluated. At the end of each evaluation run, the pilot assigned a numerical Cooper-Harper rating to the task according to a structured decision making process defined by Reference 16. The pilot's comments were used to aid data analysis by identifying areas or parameters that most strongly influenced each rating.

Qualitative pilot rating data is emphasized in this paper. Quantitative measures of system performance and/or pilot workload are being calculated using statistical analysis programs. For instance, the mean and standard deviation of helicopter flight parameters relative to a reference position or desired flight path are being computed as a measure of system performance. As an indication of pilot workload, the mean and standard deviations of control command movements are being analyzed. Certain time indices are also being evaluated as an indication of helicopter/pilot performance. Where applicable, time to perform the entire task or portion of a task, i.e., unmask time, is used as a performance index.

OTHER EXPERIMENTAL CONSIDERATIONS

Certain factors which might affect the outcome of the evaluations were identified. An effort was made, where possible, to account for these factors. Specific examples are given below:

(1) The exact stabilization level selected for each evaluation run was not revealed to the pilot.

(2) The command response type (e.g., angular pitch/roll rate versus attitude) was revealed to eliminate surprises and to reduce effects on pilot rating and performance caused by re-learning a certain response characteristic.

(3) Established habit response patterns occasionally had a noticeable effect when changing to a different controller configuration. For instance, after many years of flying conventional pedals, an adjustment period to adapt to control of yaw from the side-stick was common for all pilots. Likewise, after flying side-stick twist to control yaw for several flight hours, converting back to the pedals was not always done with ease. A similar effect was noticed when switching vertical controller configurations, that is, changing from side-stick to conventional lever or

vice-versa. If any configuration change resulted in poor performance, the pilot repeated the run and the best one was used for valid data.

(4) Learning the IHADSS concept and symbology took a significant period of time. The rate of improvement of pilot ratings with IMC simulation flight time was much slower than for VMC flight time. IMC data presented in this paper were obtained during the second simulation phase when the pilots demonstrated a more consistent level of proficiency with IHADSS.

EXPERIMENT RESULTS

Experimental results are based on an analysis of pilot ratings and comments, and discussion of these results is organized according to the major activity phases - controller development and primary-secondary matrix evaluation. Results are summarized using average pilot ratings to indicate general trends; the statistical validity of this simplified approach is not implied and it is understood that care must be used in the interpretation of results, particularly when a large range of ratings is averaged.

CONTROL RESPONSE CHARACTERISTICS

Before different controller configurations were evaluated, a set of control response characteristics for the four control axes and the generic system types (Figure 6) were defined through a series of mini-experiments. Response time constants and sensitivities were varied within the command model and effects on controllability evaluated. A set of best response values was selected, initially for the stiff controller, and the same set of values was then evaluated using the three alternate 4-axis deflection controllers. Additional variations were made about the nominal response values to define the effects on pilot ratings and task performance.

This control response selection process is depicted by Figure 14. Roll attitude sensitivities were evaluated for the slalom maneuver with the various 4-axis controllers. Pilot comments indicated a range where the roll control sensitivity was too high producing a tendency to overcontrol. In contrast, low roll attitude sensitivities less than 4.0 degrees/lb. resulted in heavy control forces and sluggish response characteristics. The best pilot ratings were obtained when all controllers had a roll attitude sensitivity of approximately 6.0 degrees/lb. Figure 14 also shows that pilot ratings of the large-deflection controller were generally degraded compared with the other configurations, and demonstrated a rapid degradation as control response sensitivities were reduced and/or control forces became heavy. The same tendency to degrade quickly was evident with the stiff-stick. The small-deflection controller was much more tolerant to changes in sensitivity as indicated by the relatively shallow slope in the high sen-
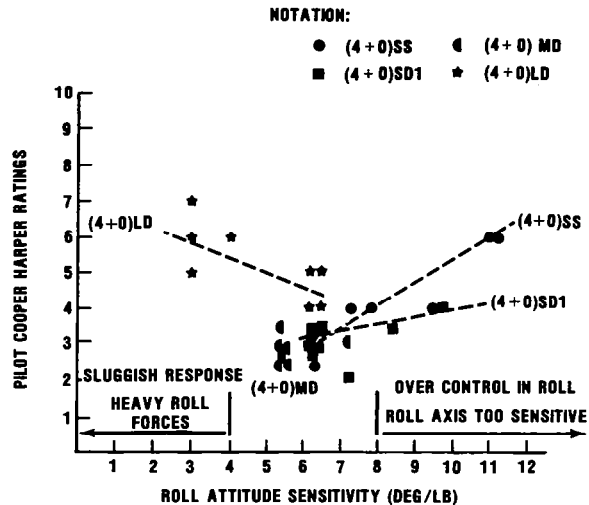
Figure 14   Control Response Selection Process

sitivity range. Best ratings were achieved with the small-deflection and medium-deflection controllers in the range from 5.5 to 7.5 degrees/lb.

The same procedure was followed to select pitch/roll rate and longitudinal/lateral velocity response characteristics. Table 4 summarizes the final selected control response characteristics. Except for the acceleration command response, characteristics are approximated by an equivalent 1st order system response. The pitch and roll acceleration response system was designed to provide a short-term rate response, with a long-term acceleration response to automatically eliminate steady control forces required for helicopter trim. This trim function was accomplished with a low-gain integral feed-forward path. Higher integral feed-forward gains were used in the yaw and vertical axes to obtain purer acceleration command responses as indicated in Table 4 by the ratio of steady-state to initial response.

To provide acceptable response characteristics for small precision control tasks and large maneuvers, as well as to minimize the effect of inadvertent inter-axis control inputs, non-linear control response shaping (Figure 15) was used. Each force command signal was passed through a shaping function that allowed variation of deadzone, initial sensitivity gradient, breakpoint, and high sensitivity gradient. Pitch, roll, and yaw control response shaping was symmetrical, whereas the vertical control shaping was asymmetric with a smaller breakout and higher response sensitivity in the down direction.

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SENSITIVITY/POUND (SENS) AND TIME CONSTANT (TC)

AXIS	CONTROLLER	ANGULAR RESPONSE						LINEAR RESPONSE			
		ACCEL (AC)		RATE (RA)		ATTITUDE (AT)		ACCEL (AC)		VELOCITY (LV)	
		INITIAL SENS (DEG/SEC²)	STEADY STATE SENS (DEG/SEC²)	SENS (DEG/SEC)	TC (SEC)	SENS (DEG)	TC (SEC)	INITIAL SENS (FT/SEC²)	STEADY STATE SENS (FT/SEC²)	SENS (FT/SEC)	TC (SEC)
LONGITUDINAL	SIDE-STICK	4.0	0.2	2.0	0.4	4.5	1.2	–	–	12.0	3.0
LATERAL	SIDE-STICK	10.0	1.0	3.5	0.25	6.0	1.2	–	–	16.0	4.0
DIRECTIONAL	SIDE-STICK	2.2	1.8	4.7	0.4	–	–	NA			
	PEDALS	0.6	0.44	1.4	0.60	–	–				
VERTICAL + UP – DOWN	SIDE-STICK	NA						+5.0 −7.7	4.0 −6.2	+6.5 −9.0	0.60
	COLLECTIVE LEVER							±1.6	±1.3	±2.0	0.50

Table 4   Selected Control Response Characteristics
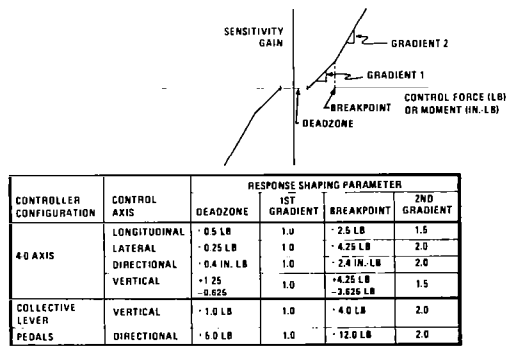
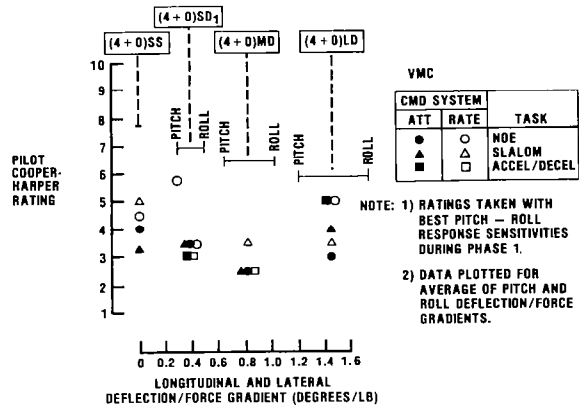*Figure 15   Force Control Response Shaping*

Figure 16   Effect of Side-Stick Controller Deflection/Force Gradient on Pilot Ratings

CONTROLLER DEFLECTION/FORCE GRADIENT

Various side-stick deflection/force gradients were evaluated using the 4-axis stiff controller and three 4-axis deflection controllers described earlier in Table 1. Task performance with each controller was rated for both rate and attitude command systems in pitch and roll. Figure 16 shows the best pilot ratings obtained as a function of controller average deflection/force gradient. The small-deflection and medium-deflection controllers achieved the best pilot ratings.

Commentary from three pilots who compared the stiff-stick and small-deflection controllers was very consistent. All agreed that task performance improved substantially with the introduction of deflection. Typical comments were as follows:

Stiff Controller:

o "Defining best control sensitivities was more difficult and more critical with a stiff controller than deflection controller."

o "Inter-axis force harmony/sensitivities appeared to be more critical, especially during larger amplitude maneuvering."

o "Tendency to over-control, particularly during high frequency manipulative control tasks."

o "Tendency to release forces abruptly and create inadvertent sharp acceleration response."

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Small-deflection Controller:

o "This controller has a softer feel of actuation than the stiff controller, and control inputs seem to be smoother in application."

o "Very noticeable improvement over stiff-stick using the same sensitivities. Ability to shape control commands during large amplitude maneuvers and control reversals was a major improvement."

o "This controller gave an immediate and very obvious improvement in handling qualities. Subjectively, I felt much more 'in the loop'. While tendencies to cross couple remained (compared to stiff controller), they were far depressed below the primary control task and were insignficant. Control inputs seemed much more natural and, although the response seemed to be more sensitive, this effect was quite tolerable."

Acceptance of the medium-deflection controller was mixed. One pilot gave the controller degraded ratings because height control was difficult due to a high force breakout in the vertical axis. A second pilot gave the same controller improved ratings compared to the small-deflection controller because he felt more in control during large maneuvers.

Two pilots evaluated the large-deflection controller and gave degraded ratings compared to the small-deflection controller. Comments indicated a more sluggish pitch control response and less precise control of attitude for high-frequency inputs.

Based on these results, a second 4-axis small-deflection controller design, (4+0)SD2, having a 50% higher deflection/force gradient, was selected for evaluation of the primary and secondary controller/SCAS configuration matrices.

PRIMARY/SECONDARY CONFIGURATION MATRIX

A basic primary matrix - consisting of five controller and five pitch/roll SCAS configurations - was evaluated for all four tasks under both IMC and VMC. The matrix for the bob-up task also included two velocity command systems - one with velocity stabilization and the other with position hold. For both IMC and VMC, a total of 220 possible task/controller/SCAS combinations was evaluated.

Figure 17 presents a matrix of data gathered for the NOE task and performed under IMC with the IHADSS. Each matrix element contains an average rating for each pilot who evaluated the particular configuration combination, as well as
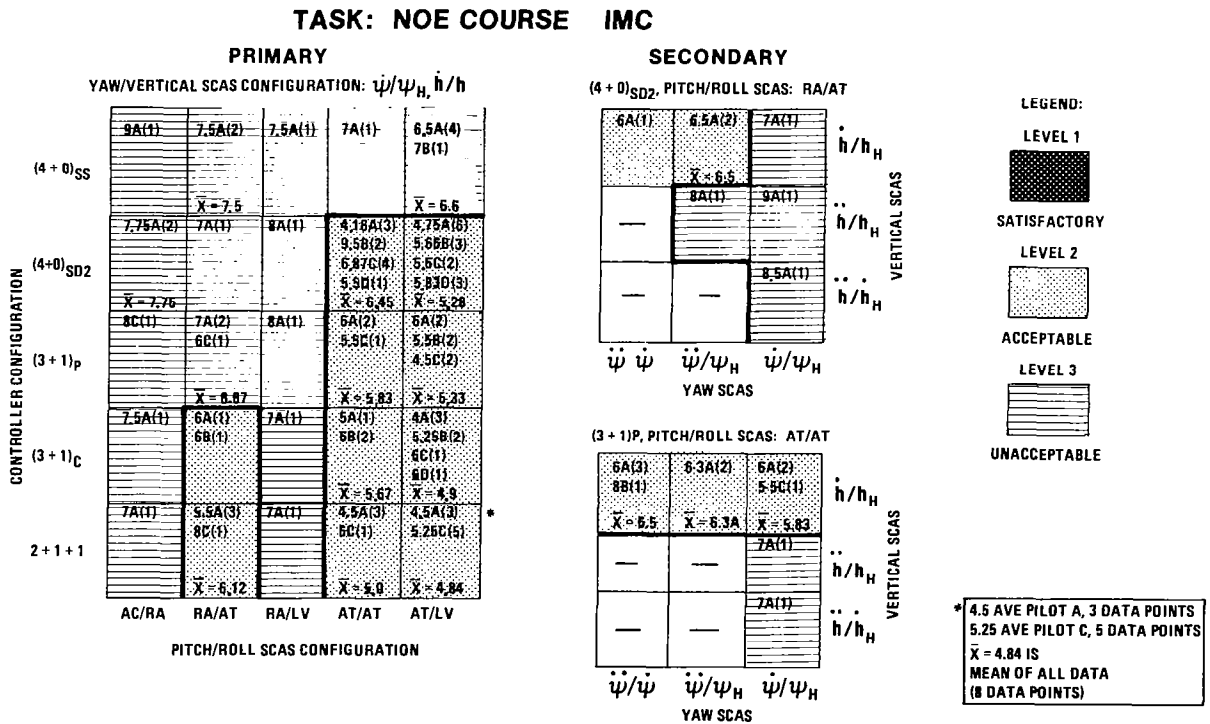

Figure 17   Controller/SCAS Configuration Matrices

the number of test data points included in the average rating. A mean of the individual average ratings in each block is also calculated. Various levels of the handling qualities rating scale are shaded on the matrix to emphasize where the major change from acceptable to unacceptable occurs. It can be seen that Level 1 flying qualities was not achieved for the NOE task under IMC for any controller configuration. The interaction of SCAS/controller configurations can be determined from the matrix. An attitude command system achieved Level 2 ratings regardless of the stabilization type for all controller configurations with the exception of the 4-axis stiff-stick. A RA/AT system exhibited marginal Level 2 flying qualities for the 2+1+1 and (3+1) collective configurations.

Secondary SCAS matrices are also shown on Figure 17. An improvement from Level 3 to Level 2 ratings occurred when a yaw acceleration command was implemented for directional control in place of yaw rate command for the (4+0)SD and RA/AT combination. In contrast, the (3+1) pedal and AT/AT combination degraded to a Level 3 rating when vertical acceleration command was used in place of vertical rate command.

Average pilot rating data contained in the primary SCAS/controller matrices are presented for the four tasks in Figures 18 and 19. Interactive effects of task, controller, and SCAS configurations are more easily seen by this method of presentation, and are described in the following discussion.

CONTROLLER/DISPLAY EFFECTS

The NOE task (Figure 18) was the most difficult of the low-speed maneuvering tasks. Primary factors causing higher workload and degraded flight path performance for the NOE task under IMC were: (1) inability to precisely control height, (2) tendency to couple side-stick vertical control imputs into pitch and/or roll, (3) difficult coordination of lateral-directional control in turns, and (4) tendency to over control roll in high workload situations.

The most serious deficiency reported was poor height and vertical speed resolution due to the small field-of-view, lack of peripheral cues, and/or lack of surface texture/picture detail. Weak motion cues as well as a lack of rotor/drive system noise may have contributed to a tendency for overcontrol of the vertical axis. The pilot had to rely almost totally on display information for vertical speed with no acceleration lead cues.

The 4+0 axis controller received poorer ratings for the NOE course where collective control inputs were required to clear the obstacles. Inadvertent inputs to pitch and roll increased the workload required to maintain airspeed and flight path control. Overcontrol in roll was occasionally experienced when corrective action

was required to compensate for an inadvertent control input.

The IMC bob-up task (Figure 18) was essentially an instrument reference task with necessary information such as velocity vector, X-Y position, acceleration cue, and altitude provided by the display symbology. Marginal Level 2 ratings were obtained with an AT/LV system. Level 1 ratings were achievable with a velocity command system having either velocity or position stabilization.

In contrast to the ratings assigned for the other tasks under VMC, ratings for the bob-up task were more degraded. This degradation in VMC ratings was caused by lack of good visual space references at altitudes above 75 feet in the bob-up location. In fact, VMC performance measured by X-Y position hold during the bob-up was significantly degraded over the IMC task.

Because of inadvertent cross-coupled inputs, the 4-axis side-stick controller received poorer pilot ratings for the bob-up task. Separation of the controllers, particularly vertical, improved pilot ratings significantly. The best ratings were achieved using a (3+1) collective configuration combined with a velocity stabilized system.

The IMC acceleration/deceleration task (Figure 19), primarily a single-axis longitudinal maneuver with altitude hold and heading hold selected, was the easiest of the four IMC tasks. Level 2 ratings of approximately 4.0 were obtained with all controllers except for the (3+1) pedal configuration. Workload and task performance were influenced primarily by the following factors: (1) tendency to couple pitch control into side-stick vertical control, (2) vertical control coupling into lateral-directional requiring pilot compensation, (3) pilot disorientation during a nose-up maneuver, and (4) poor resolution of longitudinal/lateral positioning during deceleration to hover. Precise control of aircraft position during the deceleration to hover was difficult due to poor resolution of longitudinal speeds and rate of closure, thought to be caused by the small field-of-view and limited peripheral cues. Small lateral speeds were difficult to discern from small yaw rates especially at slow forward speeds.

Performance of the slalom task (Figure 19) under IMC with altitude and heading hold selected was primarily a two-axis lateral-directional control task. Pilot ratings were degraded by approximately one point compared to the acceleration/deceleration task. Task performance was judged principally on the ability to execute coordinated turns and achieve a desired curvilinear path around obstacles at constant speed. Primary factors which increased workload and degraded pilot ratings were: (1) tendency to couple side-stick yaw control inputs into roll and/or pitch, (2) difficult turn coordination due to lack of peripheral cues with the IMC visual display, and (3) tendency to become disoriented
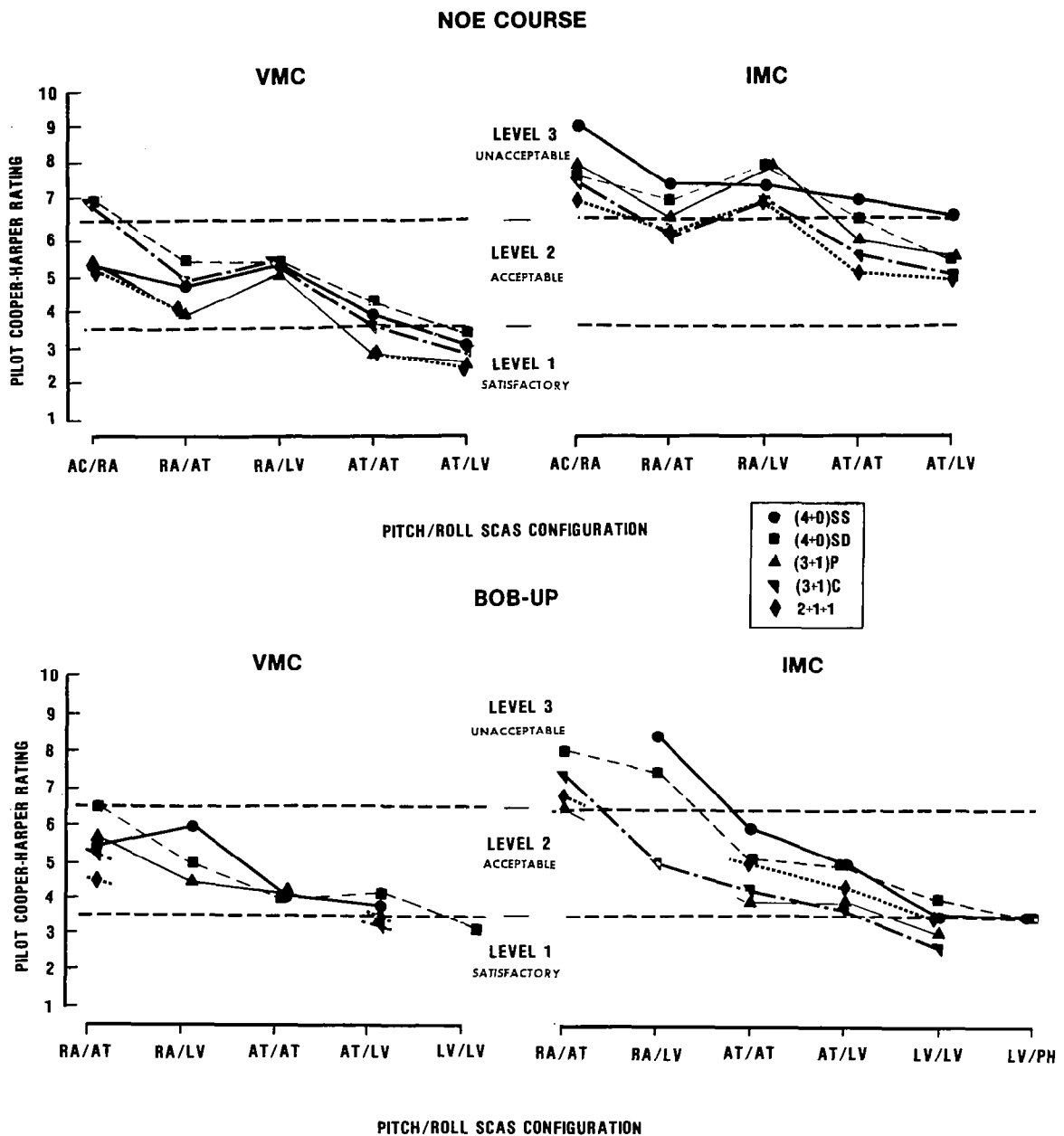
NOE COURSE

VMC

IMC

PITCH/ROLL SCAS CONFIGURATION

- ● (4+0)SS
- ■ (4+0)SD
- ▲ (3+1)P
- ◥ (3+1)C
- ◆ 2+1+1

BOB-UP

VMC

IMC

PITCH/ROLL SCAS CONFIGURATION

Figure 18   *Effect of Primary SCAS/Controller Variations*
on Pilot Ratings - NOE and Bob-Up Tasks

with IHADSS when head movements were made to locate desired flight path projection. It was difficult to distinguish head response from aircraft response.

For the acceleration/deceleration and slalom tasks, the (3+1) pedal configuration received more degraded pilot ratings than all other configurations. If large errors were allowed to build up, precise corrective control inputs with the pedals were difficult to achieve, and over-control of yaw often resulted. Precision yaw

control on the side-stick provided improved lateral-directional control for IMC.

PRIMARY SCAS EFFECTS - LONGITUDINAL/ LATERAL

For the most difficult IMC tasks (NOE and Slalom), the acceleration command/rate stabilization system (AC/RA) exhibited Level 3 handling qualities. With the addition of attitude stabilization, the RA/AT system received mar-

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ACCEL-DECEL

PITCH/ROLL SCAS CONFIGURATION

SLALOM

PITCH/ROLL SCAS CONFIGURATION
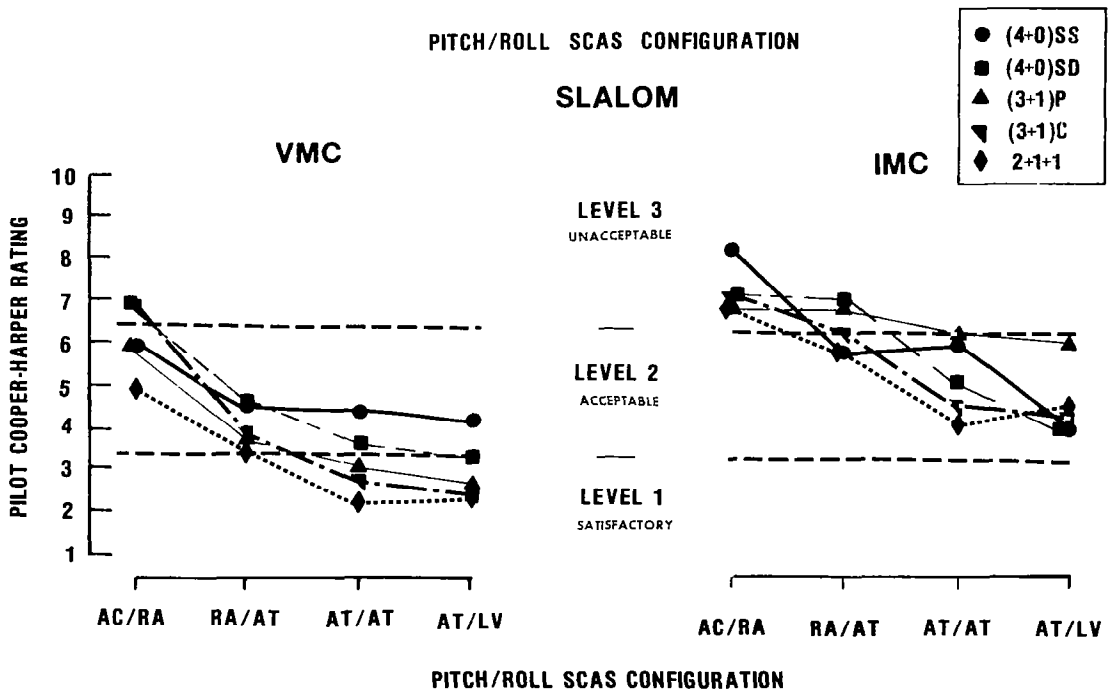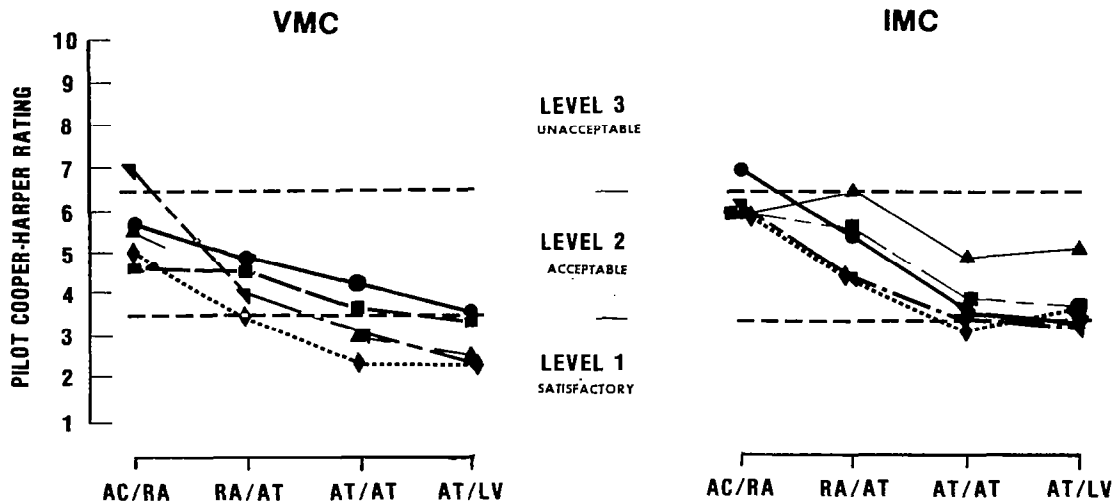
Figure 19   Effect of Primary SCAS/Controller Variations
on Pilot Ratings - Acceleration/Deceleration
and Slalom Tasks

ginal Level 2 ratings for IMC with high workload required to achieve adequate performance. It was extremely difficult to maintain precise flight control parameters (airspeed, lateral ground track, sideslip, etc.). Continuous pulse-type control inputs were required for best performance. When velocity stabilization was combined with a rate command system (RA/LV), for all low-speed maneuvering tasks there was a

significant degradation in pilot ratings (Figure 18), particularly noticed in turn maneuvers. Pilot workload and compensation to achieve lateral-directional coordination were noticeably higher, possibly indicating an inherent conceptual design problem with this combination (i.e., having the stabilization type more than one integration away from the command type).

A large improvement in IMC ratings for all tasks was obtained with an attitude command system. With the same level of attitude stabilization, an attitude command system (AT/AT) improved pilot ratings an average of one rating point when compared to the rate command system (RA/AT). A similar improvement occurred in the VMC ratings. Pilot comments indicated that the attitude command system exhibited a noticeably stronger feel of "apparent" stability. The pilots felt more continuous in the control loop with a strong force/attitude (force/linear acceleration) relation. By having more precise control of attitude, maintenance of airspeed and ground track and execution of coordinated turns were performed with lower workload. There was also less tendency to overcontrol with an attitude command system particularly for large maneuvers and/or control reversals.

When combined with an attitude command system, velocity stabilization improved pilot ratings for maneuvering tasks by about half a rating point for both IMC and VMC. It was most noticed by the ease of maintaining airspeed and effecting turn coordination during slalom and NOE tasks, and by the ease of varying airspeed and maintaining lateral ground track during the acceleration/deceleration and NOE tasks.

The influence of SCAS configuration on pilot ratings for the bob-up task is shown in Figure 18. The attitude command system yielded pilot ratings in the low Level 2 region (CHPR $\sim$ 4.5). Use of a velocity command/velocity stabilization system reduced pilot workload, improved task performance, and achieved Level 1 pilot ratings for the bob-up task with all controllers except the 4-axis small-deflection configuration.

Velocity command response characteristics were reported to be more jerky than the attitude response system, however, small position changes could be made easily. The addition of position stabilization, evaluated only with 4-axis controllers, made the bob-up task a series of single-axis control maneuvers. Level 1 ratings were achieved and excellent position hold was generally achieved.

Figure 20 presents an example of bob-up task performance achieved as a function of SCAS configuration. Deviations in longitudinal and lateral position from the initial/desired hover location are used to calculate a mean radius, i.e. a circle containing one-half the total number of data points. Data are presented for Pilot A and five controller configurations as a function of pitch/roll SCAS configuration. Compared to the rate command system, a large improvement in performance and pilot rating can be seen for an attitude command system. Best performance was achieved with a velocity command system (mean radius $\leq$ 12 feet) for all controller configurations. Data for the 4-axis controllers show degraded performance and pilot ratings, particularly for the attitude command system.
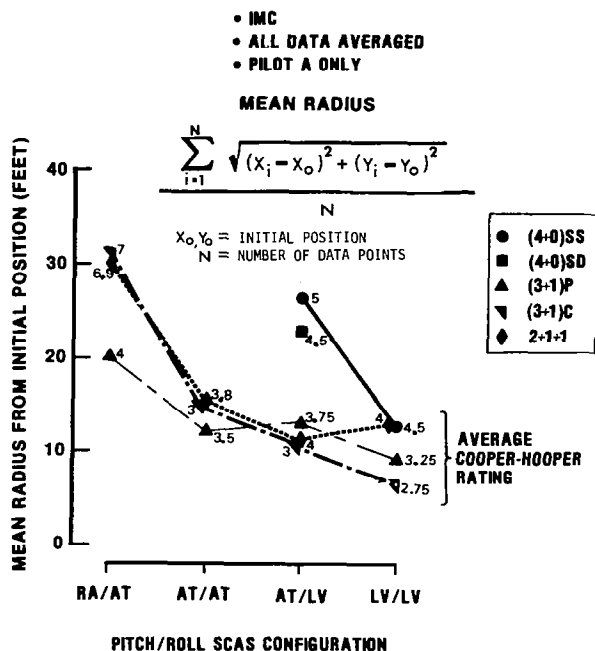

Figure 20   Bob-Up Task Performance

SECONDARY SCAS/CONTROLLER EFFECTS - DIRECTIONAL/VERTICAL

Directional and vertical SCAS configurations were varied for the RA/AT, AT/AT, and AT/LV systems of the primary SCAS matrix. All controller configurations were evaluated. In general, the yaw rate command/heading hold system provided the best pilot ratings with the pitch/roll attitude command systems for all controller configurations and tasks. Turn coordination and lateral ground track could be controlled easily, particularly for VMC. A yaw acceleration command system made it more difficult to execute precise heading changes or to establish a zero yaw rate at a desired heading. Low speed turn coordination and lateral ground track were also degraded due to this inability to modulate or vary yaw rate precisely, particularly with the pedals.

An important interactive directional SCAS/controller effect is shown in Figure 21 where yaw control on the 4-axis side-stick is compared to yaw control with the (3+1) pedal configuration for the slalom task. Yaw acceleration command from the (3+1) pedal or 2+1+1 configuration degraded pilot ratings with all pitch/roll SCAS configurations when compared to the yaw rate command system. When yaw acceleration command was implemented on the side-stick, either a (3+1) collective or 4+0 configuration, pilot ratings were degraded with the pitch/roll attitude command system, but improved with the rate command system. For the low speed coordinated turn maneuver, yaw acceleration com-

mand improved control capability by eliminating the requirement for steady forces to control yaw rate. It is difficult for the pilot to modulate forces in one or two axes (pitch/roll rate control) while holding a steady force in another axis (yaw rate command for turn coordination). The yaw acceleration command system provided improved control harmony for lateral-directional maneuvering when implemented with the pitch and roll rate command systems.
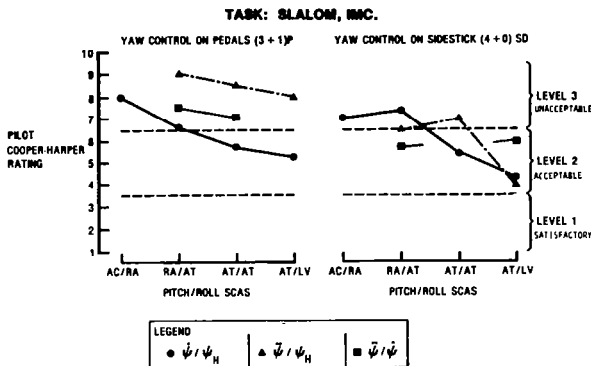

TASK: SLALOM, IMC.

Figure 21   Effect of Yaw SCAS Variations on Pilot Ratings

Also shown on Figure 21, the yaw acceleration command/yaw rate stabilization system generally received better pilot ratings than the yaw acceleration command/heading hold system. As previously noted for the primary SCAS RA/LV system, a degradation of task performance was observed if the stabilization level was more than one integration away from the command type.

The vertical rate command/altitude hold system achieved the best pilot ratings for all pitch/roll SCAS systems and controller configurations. Vertical rate command provided good control of vertical speed and precise control of altitude, particularly for VMC. Acceleration command in

TASK: NOE COURSE IMC
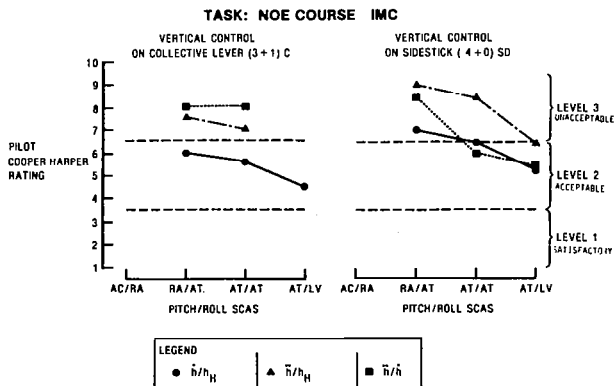
Figure 22   Effect of Vertical SCAS Variations on Pilot Ratings

the vertical control axis degraded control accuracy and necessitated pulse control inputs to achieve the best flight path performance.

Figure 22 compares vertical control on the side-stick and conventional collective lever. Vertical acceleration command on the collective lever degraded the IMC handling qualities to Level 3. As with yaw control on the side-stick, vertical acceleration command on the side-stick offers the benefit of eliminating the need to hold steady vertical control forces to achieve a steady vertical rate. However, based upon the results, the benefit of altitude hold and vertical rate command apparently offset the requirement to hold vertical control forces. These particular results may be biased by the lack of strong vertical motion and rotor/drive system noise cues in the simulator.

SUMMARY OF PILOT RATINGS

In order to summarize task and SCAS configuration effects on pilot workload and performance, all data were reorganized into a task/ SCAS matrix. Pilot rating data for all controller configurations were averaged for each task/SCAS combination. Figure 23 presents the results of this analysis. In addition to the effect of SCAS configuration, there was a significant effect of task on pilot ratings for IMC. The IMC display effects showed an additive degradation of pilot workload/performance as task difficulty increased. In comparison, VMC pilot ratings were predominantly affected by SCAS configuration and, except for the bob-up task where visual cues become weak, task had little effect. When comparing IMC results to VMC, the mean increase in pilot rating points for each task was: NOE course 2.3, slalom 2.0, acceleration/deceleration 1.2, and bob-up 1.3.
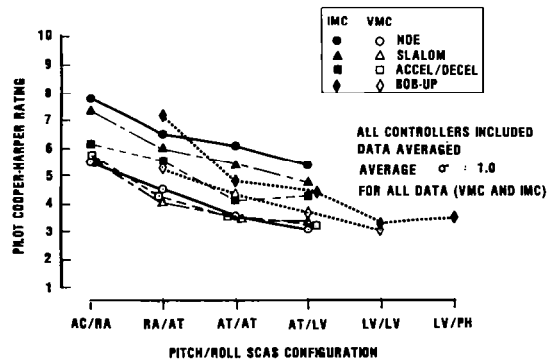

Figure 23   Summary of Task Effect on Pilot Ratings

The effect of primary SCAS configuration on pilot ratings for the slalom, acceleration/ deceleration, and NOE tasks is summarized in Figure 24. Pilot ratings from the three tasks were combined into a single primary SCAS/ controller matrix, thereby tending to average out the ef-

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fect of task. A comparison of VMC with IMC is also shown. The average degradation of IMC ratings compared to VMC ratings for all SCAS configurations is 1.8 on the Cooper-Harper rating scale. For each SCAS configuration, the range of pilot ratings from the best to worse controller configuration was an average of one and one-half rating points for both IMC and VMC.
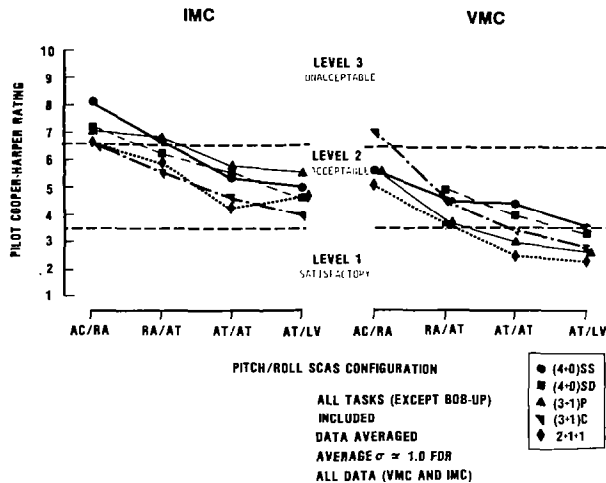

Figure 24   Summary of Primary
             SCAS/Controller Effects

Figure 24 shows that an acceleration command/ rate stabilization system (AC/RA) exhibited Level 3 ratings for the IMC tasks, and the addition of attitude stabilization with a rate command response system (RA/AT) received marginal Level 2 ratings. With the same level of attitude stabilization, an attitude command system (AT/AT) improved both IMC and VMC pilot ratings by over one rating point. When velocity stabilization was combined with an attitude command system, pilot ratings for the maneuvering tasks improved an average of half a rating point for IMC and VMC.

Based on average pilot ratings, from Figures 18 and 19, a ranking of controller configurations was determined for each task as shown in Table 5. Each task was weighted equally to obtain an overall IMC and VMC ranking for each controller configuration.

The (3+1) collective controller configuration provided the best overall pilot ratings for all IMC tasks. A tendency to cross-couple directional control into roll was observed during coordinated lateral-directional turn maneuvers, particularly during initial evaluations. However, this cross-coupling tendency diminished quickly and pilot adjustment to yaw control on the side-stick was easily made.

Pilot ratings for the (3+1) pedal configuration were more degraded than other controller configurations for lateral-directional maneuvering

tasks under IMC (Figure 24). However, for the VMC tasks, the (3+1) pedal ratings ranked in the middle and received improved ratings when compared to the 4-axis configuration.

The 2+1+1 controller configuration in general achieved good pilot ratings for all three IMC low-speed maneuvering tasks. For the IMC bob-up task (Figure 18), the 2+1+1 configuration ranked better than the 4+0 but worse than the 3 + 1 configurations. The 2+1+1 configuration achieved the best ratings for all the VMC maneuvering tasks.

DISPLAY	CONTROLLER CONFIGURATION	RANKING BY TASK				OVERALL RANKING (ALL TASKS)
		ACCEL/DECEL	SLALOM	NOE	BOB-UP	
IMC	(4 + 0) SS	3	4	5	4	5
	(4 + 0) SD	4	3	4	4	3
	(3 + 1) PEDAL	5	5	3	2	3
	(3 + 1) COLLECTIVE	1	1	1	1	1
	2 + 1 + 1	2	1	1	3	2
VMC	(4 + 0) SS	5	5	4	DATA NOT AVAILABLE FOR ALL CONTROLLER CONFIGURATIONS	5
	(4 + 0) SD	4	4	5		4
	(3 + 1) PEDAL	2	3	1		2
	(3 + 1) COLLECTIVE	2	2	3		3
	2 + 1 + 1	1	1	1		1

Table 5   Controller Configuration Ranking

CONCLUSIONS

Piloted simulation investigations of the effects on handling qualities of variations in side-stick controller configuration and stability and control augmentation system characteristics for both day VMC and night IMC terrain flight were conducted using the Boeing Vertol Flight Simulation Facility.

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

SIDE-STICK CONTROLLER DESIGN

A small-deflection side-stick controller is preferred for low speed NOE maneuvering and precision hover tasks when compared to a stiff-stick controller for the following reasons:

(1) It is easier to modulate force control inputs, particularly during large maneuvers and control reversals. In high workload situations, there is less tendency to over-contol and/or cross-couple control inputs.

(2) 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 character-

istics for a wider range of pilot preferences if a small-deflection device were implemented.

CONTROLLER CONFIGURATION

The (3+1) collective configuration achieved the best overall pilot ratings for all IMC tasks, followed in rank order by the 2+1+1 and 4+0 or (3+1) pedal configurations. This particular controller configuration provides the following significant advantages for IMC terrain flight:

(1) A separate collective controller eliminates unintentional collective to pitch/roll coupling common to the 4-axis and (3+1) pedal configurations.

(2) Directional control on the side-stick 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 significantly degrades pilot ratings because of yaw controllability for the IMC tasks. The limited field-of-view helmet-mounted display had a strong effect on lateral-directional control.

In contrast, the 2+1+1 and (3+1) pedal configurations achieved the best pilot ratings for VMC. With good peripheral visual cues, directional control becomes a less demanding task.

SCAS DESIGN

A trend of handling qualities improvements attainable by various generic SCAS configurations was defined. Conclusions based upon these results are as follows:

(1) Level 1 handling qualities were not achieved for any of the controller/SCAS combinations investigated for the maneuvering tasks conducted in IMC.

(2) A longitudinal and lateral velocity command system provided Level 1 handling qualities for the bob-up task.

(3) A pitch and roll attitude command system with longitudinal and lateral velocity stabilization generally provided the best pilot ratings for the low-speed maneuvering tasks conducted in IMC.

(4) Altitude and heading stabilization were beneficial for all tasks and controller configurations.

(5) Yaw rate and vertical rate command systems are generally preferred for all tasks and controllers. 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.

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

IMC DISPLAY EFFECTS

Pilot ratings for the most difficult IMC maneuvering task were degraded by approximately two points when compared to the same task under VMC; degradation in both longitudinal and lateral handling qualities was caused by the limited field-of-view available from the helmet-mounted display.

RECOMMENDATIONS

Continued simulation studies and design effort should be directed toward:

(1) Improvement of vertical axis control using a (3+1) collective or 4-axis configuration. Emphasis should be given to human factor aspects such as grip design, side-arm support, and controller orientation.

(2) Development of a (3+1) collective configuration using a left-hand side-stick vertical controller instead of a conventional collective lever. Consideration should be given to having both controllers available for vertical control. The 4-axis controller would be used for low workload situations, i.e., level flight and contour flying to free the left hand for cockpit adjustments and secondary functions. The separate left-hand controller would be available for high workload flight maneuvers, e.g., IMC/VMC nap-of-the-earth maneuvers, autorotational landings, emergency situations.

(3) Refinement of control laws to achieve Level 1 pilot ratings for IMC. Possible SCAS modifications include: Automatic low-speed turn coordination, inter-axis control paths to decouple responses, and alternate control response shaping characteristics.

(4) Assessment of the effect of large motion cues on vertical SCAS/controller design and overall pilot ratings using the Vertical Motion Simulator at NASA Ames.

(5) Investigation of the effects of turbulence on system performance and pilot workload.

(6) Comparison of alternate configurations for SCAS off or degraded mode conditions.

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