NASA CONTRACTOR REPORT 177339 USAAVSCOM TR 84-A-7

(NASA-CR-177339-Vol-2) DEVELOPMENT OF ADOCS CONTROLLERS AND CONTROL LAWS. VOLUME 2: LITERATURE REVIEW AND PRELIMINARY ANALYSIS Final Report, Jan. 1981 - Jun. 1984 (Boeing Vertol Co., Philadelphia, Pa.) 163 p N87-17708

Unclas

G3/08 43365

IN-08
58113
P163

DEVELOPMENT OF ADOCS CONTROLLERS AND CONTROL LAWS

VOLUME 2 - LITERATURE REVIEW AND PRELIMINARY ANALYSIS

Kenneth H. Landis
Steven I. Glusman

release March 1987

CONTRACT NAS2- 10880
March 1985

NASA

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

NASA CONTRACTOR REPORT 177339 USAAVSCOM TR-84-A-7

DEVELOPMENT OF ADOCS CONTROLLERS AND CONTROL LAWS

VOLUME 2 - LITERATURE REVIEW AND PRELIMINARY ANALYSIS

Kenneth H. Landis
Steven I. Glusman
Boeing Vertol Company
Philadelphia, PA 19142

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

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

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

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

List of Illustrations (Continued)

List of Illustrations (Continued)

List of Illustrations (Continued)

LIST OF TABLES

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
CHR	Cooper-Harper Rating
CMD/STAB	Command/Stabilization
EASY5	Engineering Analysis System Rev. 5
FBW	Fly-by-Wire
HLH	Heavy Lift Helicopter
HMD	Helmet Mounted Display
HMS	Helmet Mounted Sight
IHADSS	Integrated Helmet and Display Sighting System
IMC	Instrument Meterological Conditions
LCC	Load-Controlling Crewman
LV/LV	Velocity Command/Velocity Stabilization
LV/PH	Velocity Command/Position Hold
NAE	National Aeronautical Establishment
NOE	Nap-of-the-Earth
PFCS	Primary Flight Control System
PIO	Pilot Induced Oscillations

Acronyms (Continued)

PNVS	Pilot Night Vision System
PSD	Power Spectral Density
RAE	Royal Aircraft Establishment
RA/AT	Rate Command/Attitude Stabilization
SCAS	Stability and Control Augmentation System
SD	Small Deflection
SS	Stiff Stick
SSC	Side-Stick Controller
TAGS	Tactical Aircraft Guidance System
VMC	Visual Meterological Conditions
VMS	Vertical Motion Simulator

NOMENCLATURE

C(s)	Command Model Transfer Function
D(s)	Desired Response Transfer Function
DELB	Pilot Longitudinal Cyclic Input (in)
DELC	Pilot Collective Input (in)
DELR	Pilot Pedal Input (in)
DELS	Pilot Lateral Cyclic Input (in)
g	Acceleration of Gravity (ft/sec^2)
H(s)	Stabilization Loops Transfer Function
h	Radar Altitude (ft)
$\dot{h}$	Vertical Velocity (ft/sec)
$\ddot{h}$	Vertical Acceleration (ft/sec^2)
IHT	Incidence of Horizontal Tail (deg)
K_θ	Pitch Attitude Feedback Gain (in/rad)
K_ϕ	Roll Attitude Feedback Gain (in/rad)
K_ψ	Heading Feedback Gain (in/rad)
K_q	Pitch Rate Feedback Gain (in/rad/sec)
K_p	Roll Rate Feedback Gain (in/rad/sec)
K_r	Yaw Rate Feedback Gain (in/rad/sec)
K_{SS}	Steady State Response Sensitivity (rad/sec/in)
L/IXX	Normalized Rolling Moment (ft lb/slug ft^2)
M/IYY	Normalized Pitching Moment (ft lb/slug ft^2)
M_r	Stability Derivative, Pitching Moment Due to Yaw Rate (ft.lb/(rad/sec))
M_{δ_B}	Control Sensitivity - Pitching Moment due to Longitudinal Cyclic Input (ft.lb/in)
N/IZZ	Normalized Yawing Moment (ft.lb/slug.ft^2)

N_{δ_R}	Control Sensitivity - Yawing Moment Due to Pedal Input (ft.lb/in)
N_r	Stability Derivative - Yawing Moment Due to Yaw Rate (ft.lb/(rad/sec))
p	Aircraft body-axis roll rate (rad/sec)
P(s)	Plant Transfer Function
q	Aircraft Body-axis Roll Rate (rad/sec)
r	Aircraft Body-axis Yaw Rate (rad/sec)
r_c	Commanded Yaw Rate (rad/sec)
RL	Rate Limiter
u	Aircraft Body-axis Longitudinal Velocity (ft/sec)
v	Aircraft Body-axis Lateral Velocity (ft/sec)
w	Aircraft Body-axis Vertical Velocity (ft/sec)
X/M	Normalized Longitudinal Force (lb/slug)
Y/M	Normalized Lateral Force (lb/slug)
Z/M	Normalized Vertical Force (lb/slug)
ϕ	Aircraft Roll Attitude (rad)
ϕ_c	Commanded Roll Attitude (rad)
ψ	Heading (rad)
$\dot{\psi}$	Yaw Rate - Earth Axis (rad/sec)
$\ddot{\psi}$	Yaw Acceleration - Earth Axis (rad/sec^2)

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:

- 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.

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 simulation. Nonpiloted simulations and analysis were also conducted during both Phase 1 and Phase 2 in parallel with the piloted simulations to evaluate effects of control law implementation using fixed point computation algorithms. The ADOCS demonstrator aircraft will process control laws using a fixed-point digital flight control computer.

Findings from the literature review and the analysis and synthesis of the desired control laws are reported in Volume 2 provided herein. Results of the five piloted simulations conducted at the Boeing Vertol and NASA-Ames simulation facilities are presented in Volume 3. Conclusions drawn from an 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.

Summary of Literature Review and Preliminary Control/Display Law Analysis

Side-stick controllers (SSC) have been evaluated during various research programs and proven to be superior to a conventional center stick for certain tasks. The successful implementation of a SSC depends greatly on the controller force/deflection characteristics, controller orientation, control response sensitivities, and grip design. Studies conducted by the Air Force Flight Dynamics Laboratory (AFFDL) provided guidelines for SSC design including recommended values for force/deflection characteristics and criteria for controller orientation. Based on findings of the literature review, candidate 4-axis controllers with different force deflection characteristics were selected for evaluation. A wide range of force/deflection gradients were chosen to bracket AFFDL recommended values.

Various integrated controller configurations (e.g., four control axes on a single SSC, or two axes on the SSC with separated conventional pedals and collective) have been investigated by other studies. Test results indicate that a helicopter can be flown through a wide range of Visual and Instrument Meterological Condition (VMC and IMS respectively) tasks using a 4-axis or 3-axis SSC without requiring exceptional pilot skill or concentration. Pilots can easily adapt to most multifunction isometric controller configurations. Adjustment to yaw control on the right-hand SSC in a 4-axis configuration can be easily accomplished by the pilot.

Four variations in controller configuration representing different levels of control integration were chosen for investigation during the ACC/AFCS study.

(1) <u>(4+0)</u>: All control axes (pitch, roll, yaw, and vertical) on the right-hand side-stick controller.

(2) <u>(3+1) Collective</u>: 3-axis side-stick for pitch, roll, and directional control, and a separate left-hand collective controller .

(3) <u>(3+1) Pedal</u>: 3-axis side-stick for pitch, roll, and vertical control, and pedals for directional control.

(4) <u>(2+1+1)</u>: 2-axis right-hand side-stick for pitch and roll control, with separated collective controller for vertical control and pedals for directional control.

Control law analysis and synthesis resulted in a generic SCAS design concept for the ADOCS incorporating main features such as: (1) full-time feedback stabilization loops to improve gust rejection characteristics, (2) feed-forward command shaping using a model following technique to provide desired response characteristics, and (3) automatic force trimming functions and logic implemented as part of the software to eliminate mechanical force trimming hardware.

Stabilization loop gains are defined for each axis using a decoupled aircraft model incorporating actuator dynamics and a fourth-order rotor model. Classical techniques are employed to determine stabilization gains which would result in dominant roots exhibiting a damping ratio between .65 and .75. Time history responses of the aircraft model to a gust input are presented and a comparison of gust rejection characteristics in terms of power spectral density is made for the unaugmented UH-60A, the production UH-60A SCAS design, and the modified SCAS developed for the ADOCS. Improved gust rejection characteristics with the new SCAS design is demonstrated.

Feed-forward command model gains are mechanized in a manner such that engagement/disengagement of stabilization loops is not required. A model-following design concept results in a set of feed-forward gains which produces desired response characteristics regardless of the level of stabilization. Numerous levels of command and stabilization are defined for investigation by piloted simulation, each having a unique set of feed-forward gains. Preliminary system response sensitivities and nonlinear control response shaping are specified for initial SCAS implementation and evaluation. Methods for automatically switching control laws between forward flight and low speed are developed, as well as requirements for selectable modes to provide precision hover hold capability. Required levels of command/stabilization to achieve different levels of handling qualities are determined during simulation studies (Volume 3).

Since the attack helicopter mission dictates operation in limited visibility conditions as well as in clear daytime conditions, the effect of a visual display system for IMC was an important issue to be examined during the ACC/AFCS study. The Integrated Helmet and Display Sight System (IHADSS) system was chosen as the baseline system to simulate IMC flight. Some modifications to the standard AH-64 symbology format and sensitivities were made based on results of other simulation studies (Reference 1) and a review of display law characteristics implemented on the PNVS surrogate trainer at the U.S. Army Test Proving Ground, Yuma, Arizona. Pilot participants in the simulation study, who also flew the surrogate trainer, judged the IHADSS presentation in the simulation to be very representative of the real world.

2.0 INTRODUCTION

The Advanced Cockpit Controls/Advanced Flight Control System (ACC/AFCS) design study was performed 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. 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 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.

An objective of the ACC/AFCS study was to provide design data to support the development of the flight control system to be implemented and evaluated on the ADOCS demonstrator aircraft. Conceptual design and piloted simulation studies were performed to define the cockpit controller configuration(s), flight control laws, and display requirements to achieve satisfactory handling qualities for an attack helicopter mission. Achievement of Level 1 handling qualities for both day and night/ adverse weather conditions was a system design goal. Five major piloted simulation phases were completed between June 1981 and May 1983. Three simulation periods were conducted at the Boeing Vertol Simulation Facility followed by two simulation periods performed at the NASA-Ames Vertical Motion Simulator (VMS) Facility. Pilot ratings were obtained and interactive effects of controller configuration and AFCS characteristics, and the impact of the pilot's night vision aids on the helicopter handling qualities were assessed. Results and data from the simulation study (Volume 3) were available for use during the initial flight control system design phase of the ADOCS demonstrator program.

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

ACC/AFCS PROGRAM SCHEDULE

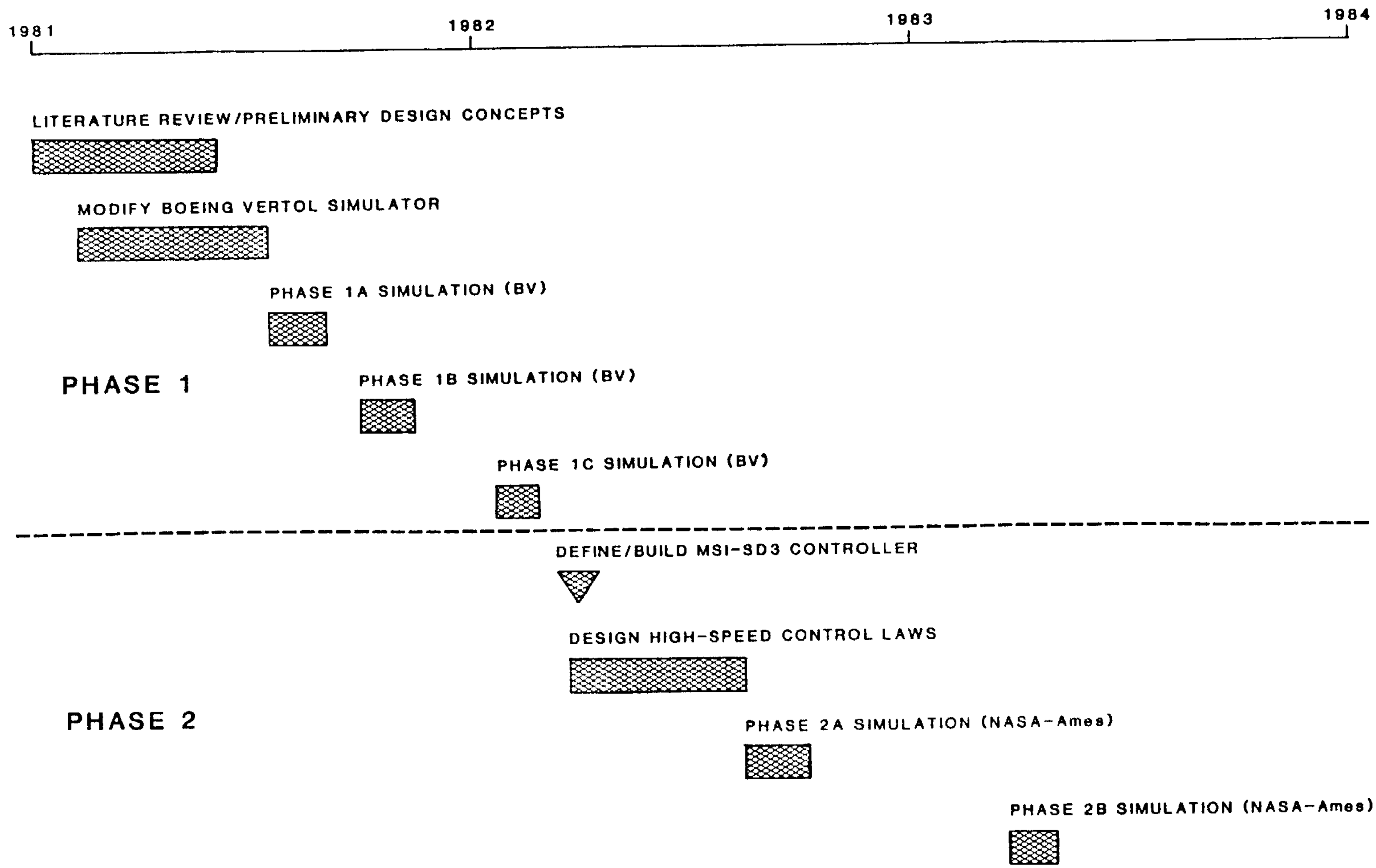


Figure 2-1

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.

The literature review examined the state-of-the-art of advanced flight control concepts and was conducted using the services of the NASA Industrial Application Center at the University of Pittsburgh. Findings from the literature review, along with results of the analysis and design activity performed to establish specific SSC configurations and control law characteristics for evaluation are documented herein. Organization of Volume 2 is according to three major areas of study:

(1) Side-Stick Controller Design Characteristics - Numerous SSC flight research studies are reviewed, providing design data and a multitude of recommendations. This information is analyzed and four candidate 4-axis controller configurations are selected for evaluation during the initial Phase 1 simulation.

(2) Control Law Design - Stabilization requirements are defined for the ADOCS demonstrator helicopter (UH-60A Black Hawk) using classical control theory analysis. Desired control response characteristics systems are selected based on a review of documented analytical studies. Preliminary response sensitivities are selected based on results obtained from various experimental flight test and simulation programs.

(3) Visual Display Systems - Variations to the basic IHADSS symbology are defined. The literature review suggested potential improvements to the display symbology format, and guided the selection of the control laws and dynamics for specific symbology parameters.

3.0 SIDE-STICK CONTROLLER DEVELOPMENT

This section reviews the history of side-stick controller (SSC) development in the aircraft industry with emphasis on research programs directed toward the use of a SSC for rotary-wing aircraft. Data from published literature were utilized to form a data-base to: (1) aid in the selection of side-stick controller characteristics for evaluation by piloted simulation, and (2) guide the development of design requirements for the ADOCS side-stick controller. Major design considerations identified during the literature review are discussed and findings are organized according to the following topics:

- Controller Configuration - number of control axes integrated on a SSC.
- Controller Orientation - geometric location of the SSC with respect to pilot armrest and seat.
- Grip Design/Switch Requirements
- Force/Deflection Characteristics
- Aircraft Response/Controller Force Sensitivities

3.1 FEASIBILITY STUDIES

The use of side-stick controllers in place of the conventional center-stick as the primary control input device in high performance aircraft is not a recent innovation. As part of a NACA sponsored program in 1957 (Reference 2), Sjoberg equipped a Navy F9F Grumman Panther with a SSC to investigate the control implications of using a SSC as the primary controller. None of the 14 pilots that participated in Sjoberg's experiment reported any difficulty in flying or controlling the aircraft with a SSC. The pilots were able to execute precision flying tasks without any degradation in performance. Pilot effort was actually felt to be reduced when flying with a SSC because of the lighter control forces required and the increased pilot comfort provided by the SSC armrest.

In 1970, a F-104 was flown with a SSC during a study conducted by the Air Force Aerospace Research Pilot School (now the USAF Test Pilot School). The 60 pilots who participated in this experiment (Reference 3), preferred the SSC to a conventional center-stick controller. In the 870 hours of flight time accumulated, no failures of the SSC occurred. The SSC was felt to provide superior trajectory control with a drastic reduction in pilot workload.

A direct comparison of pilot performance using a conventional center stick and a SSC was performed in a study for the Aeronautical Systems Division at Wright-Patterson Air Force Base (Reference 4). This study concluded that a SSC, especially a dual SSC configuration, was feasible for use in high speed, high altitude maneuvering tasks. Performance for landings and precision maneuvers was found to be improved with the SSC, but in gross maneuvering at a low altitude a degradation in performance was felt to occur with the SSC.

Research involving the use of side-stick controllers in Army helicopters began in 1968 with the Tactical Aircraft Guidance System (TAGS) Program (References 5 and 6). The system was implemented in a CH-47B aircraft and initially included an integrated 4-axis displacement controller; but because of command coupling problems between the longitudinal and vertical axes, a 3-axis controller (Figure 3-1) was eventually implemented with vertical control effected through a standard collective lever. Even after the vertical axis control was removed from the TAGS side-stick controller, pilot comments were critical of the longitudinal control implementation. Longitudinal control in the TAGS aircraft was effected by sliding the controller longitudinally a distance proportional to the desired velocity change. Total travel for full forward speed was 4.5 inches. Pilots found it very difficult to modulate longitudinal control inputs when required to make high frequency reversals and other sudden inputs in the other control axes. The force-feel system implemented resulted in a force proportional to the rate of change of controller position. Because of the damping characteristics implemented in the TAGS controller, it felt massive and heavy. Pilot comments rate the lateral and directional control implementation above average. Roll control was mechanized with the more common and classical base-pivot and yaw control was obtained through grip twist.

The use of multi-axis controllers was considered, but rejected for the Heavy Lift Helicopter (HLH) primary flight control system. The selection of conventional controls for the HLH pilot's station is explained in Reference 7. Conventional controls were felt at that time, to be more suitable for dual primary pilot controls requiring a complex force-feel system and ballistic tolerance. However, McManus of Boeing Vertol explains that during the HLH preliminary design, a SSC was felt to be appropriate for a multi-axis, single pilot task in an aircraft having a simplified force-feel system and high-order control laws, where reversion to unaugmented control is not required. A 4-axis medium-displacement controller was implemented at the load-controlling crewman's (LCC) station in the HLH. This controller (Figure 3-2) was used solely for precision cargo handling tasks with a highly augmented aircraft. In this application, Level 1 Cooper-Harper pilot ratings were achieved using the SSC (Reference 7).

More recently at Boeing Vertol, a ground based simulation of an Advanced Scout Helicopter (ASH) incorporated a SSC (Reference 8). A Lear Siegler A-7/F16 2-axis SSC was used in simulation studies along with separated collective and directional pedal force controllers. For harmony between control axes, all

TAGS MODIFIED SIDE-ARM CONTROLLER

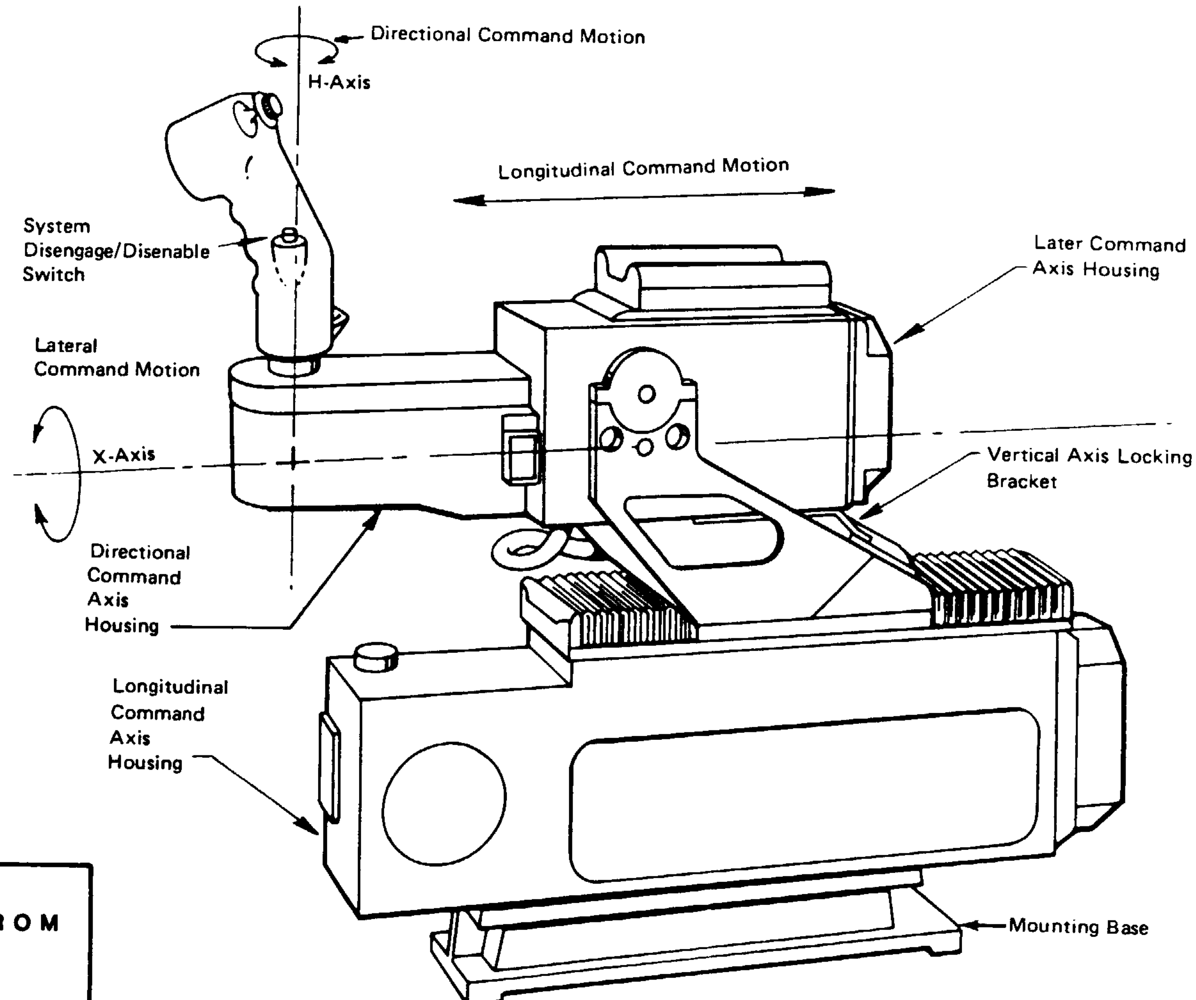


FIGURE FROM REF. 6

Figure 3-1

ORIGINAL PAGE IS
OF POOR QUALITY

HLH 4-AXIS FINGER/BALL CONTROLLER

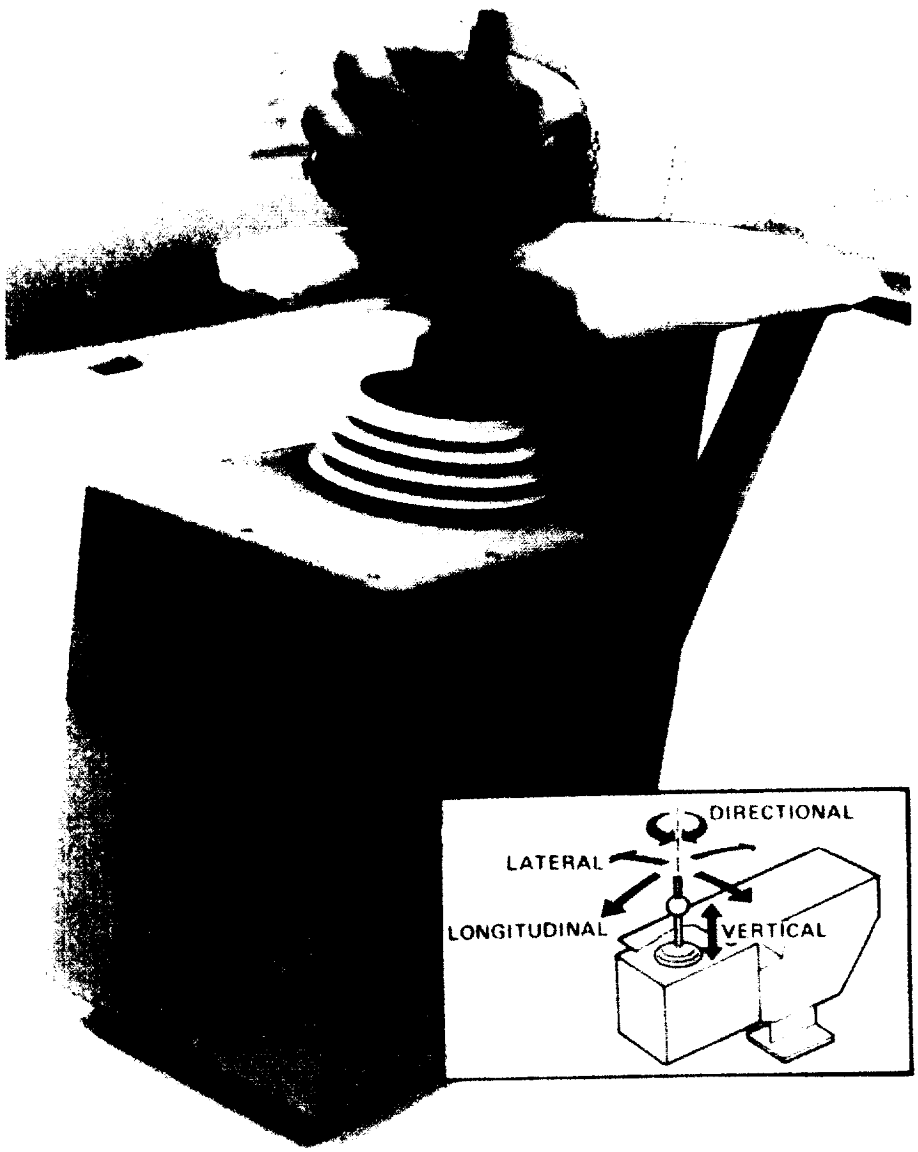


Figure 3-2

controllers were stiff with essentially no deflection. Acceptable control laws for an ASH mission were developed and the feasibility of a side-stick force controller was demonstrated during this study.

In a three-degree-of-freedom moving-base simulation at the Royal Aircraft Establishment (RAE) Bedford, U.K. (Reference 9) of an unaugmented Lynx helicopter, a 2-axis displacement side-stick was compared to the conventional cyclic controller for eleven different flight tasks; when a suitable control sensitivity was selected, the side-stick compared favorably with the conventional controller and, in fact, was preferred for certain tasks.

A feasibility study of a 4-axis isometric side-stick controller was conducted by the National Aeronautical Establishment of Canada (Reference 10). A wide range of flight tasks were evaluated in a Bell 205A-1 using various side-stick controller configurations. With appropriate gains, shaping, and prefiltering applied to the pilots' force input in each controlled axis, pilot ratings comparable to those obtained with conventional controllers were achieved by a 4-axis side-stick configuration.

In applications to production helicopters, only the Bell AH-1 series Cobra has been equipped with a SSC. In the Cobra, a 2-axis SSC is installed, but only at the copilot/gunner's station. The ADOCS program, through side-stick controller and control law design and evaluation, will develop the technology which will enable a multi-axis SSC to be included as the primary pilot controller in a production helicopter design.

3.2 CONTROLLER CONFIGURATION

Application of fly-by-wire and fly-by-light technology to the design of advanced helicopter control systems could result in a potentially significant change to standard cockpit design practice. One of the most significant changes is that alternate configurations which provide increased comfort, convenience, efficiency, and viewing area to the pilot can be considered.

Fixed-wing aircraft equipped with a SSC normally control only pitch and roll through the SSC and use conventional pedals for directional control and a separate throttle lever for engine thrust/power management. Helicopter research programs have explored the option of adding directional and/or vertical control to a right-hand side-stick controller. The various controller configurations evaluated range from a fully integrated 4-axis configuration to more conventional (2+1+1) configurations using a 2-axis SSC for pitch and roll control, pedals for directional control, and a separated left-hand collective controller. Pedals have been either conventional large-displacement type or force pedals with little or no displacement. Left-hand vertical control in the (2+1+1) configuration has been effected through a standard large-displacement collective lever or a modified collective lever (or side-arm controller) with small displacement for better harmony with the other controller axes. In all cases studied, integration of yaw control on a right-hand multi-axis SSC has been successfully achieved through a twist (torque) about the grip vertical axis. Vertical control has been most commonly implemented on the right-hand SSC as a pure up/down displacement or force application along the grip's vertical axis.

A brief review of helicopter research programs which evaluated various multi-axis SSC configurations follows. As previously mentioned, the TAGS aircraft (Reference 5) initially included a fully integrated 4-axis SSC but because of coupling problems between the longitudinal and vertical axes, switched to a (3+1) Collective controller configuration, (i.e. pitch, roll, and yaw on the right-hand controller and a standard left-hand collective lever for vertical control). The longitudinal/vertical coupling problem associated with the TAGS controller was, at least in part, due to the rotational inertia of the controller. Under moderate longitudinal or lateral accelerations, the force required for a vertical input was exceedingly high with the 4-axis controller configuration.

The Model 347/HLH aircraft demonstrator successfully employed a 4-axis displacement controller at the load-controlling crewman's station (Reference 7). A unique finger/ball controller design (Figure 3-2) had medium control travel in each axis: (±2.75 inches in pitch, ±1.5 inches in roll, ±1.05 inches in vertical, and ±27 degrees directional twist for yaw). The fully integrated SSC was used only in and around the hover flight regime with a highly stabilized aircraft. Level 1 Cooper-Harper pilot ratings were achieved for precision maneuvering and position hold tasks.

Since 1969, the National Aeronautical Establishment (NAE) of Canada has conducted flight research pertaining to helicopter control with a side-arm controller (Reference 10). This work has been conducted in the NAE Airborne Simulator, a specially modified Bell 205A-1 helicopter equipped with a full-authority fly-by-wire system and dual isometric side-stick controllers. Various controller orientations were investigated, as shown in Figure 3-3, ranging from a more conventional arrangement (right-hand side-stick, left-hand collective, and pedals) to a fully integrated 4-axis SSC. The dual SSC implementation used by NAE enabled direct comparisons of a left-hand versus a right-hand 4-axis controller orientation. Non-linear control shaping was employed as well as a force-trimming system utilizing a four-way beep trim switch.

Some conclusions from the NAE flight research study (Reference 10) are summarized as follows:

- A helicopter can be flown through a wide range of VMC and IMC flight tasks using a 4-axis SSC or a 3-axis SSC

CONFIGURATIONS EVALUATED BY NAE IN AIRBORNE SIMULATOR

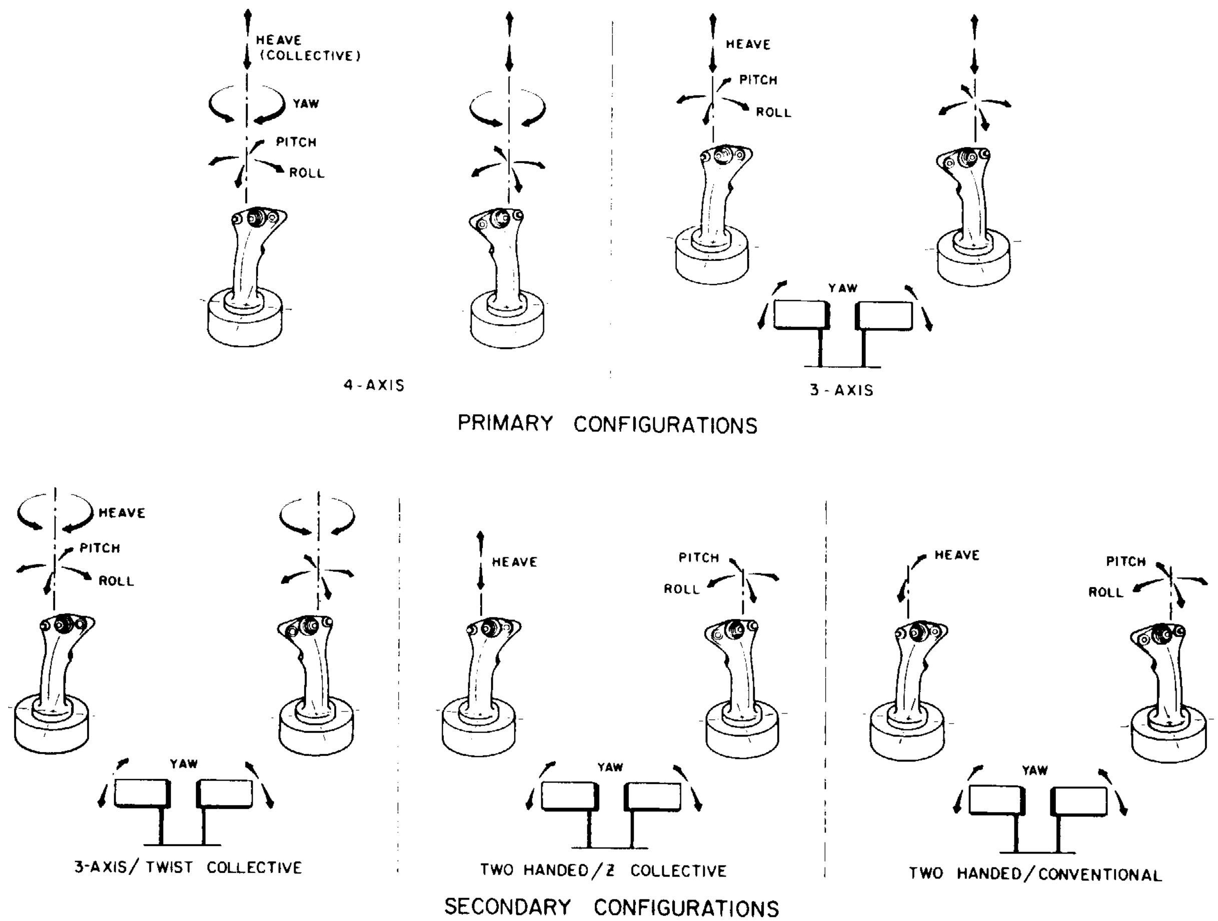


FIGURE FROM REF. 10

Figure 3-3

(pitch, roll, and collective with separate pedals) without requiring exceptional pilot skill or concentration.

- Pilots can easily adapt to most multifunction isometric controller configurations. Adjustment to yaw control on the right-hand side-stick in a 4-axis configuration was easily made and certain pilots felt that there was added comfort with feet-on-the-floor. Some pilots favored the (3+1) Pedal configuration due to concern that the fully integrated controller might be more vulnerable to cross-coupled inputs in emergency situations and during high-workload operations. However, the 3-axis SSC with separated collective control achieved through a grip twisting motion (Figure 3-3) was not readily accepted and was found to be confusing.

- The 4-axis right-hand SSC was preferred over the left-hand 4-axis location but many of the pilots could adapt to either.

- The (2+1+1) configuration, with essentially conventional assignments of the left and right hand control functions, was evaluated briefly by several pilots and could be flown with ease and presented no problems.

Based on results obtained from the previously discussed programs, four configurations were selected as primary candidate configurations to be evaluated during the ACC/AFCS simulation studies. Figure 3-4 illustrates the configurations selected for evaluation during Phase 1. The most conventional (2+1+1) configuration, represents the most subtle way of transitioning from conventional controls to a multi-axis SSC configuration. Both the (3+1) Pedals and (3+1) Collective configurations integrate only one additional control axis on the right hand SSC. The 4-axis configuration integrates all four control axes on a single right-hand SSC. Evaluation of the (3+1) Collective, (3+1) Pedal, and (2+1+1) controller configurations was performed during Phase 1 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.

Phase 1 simulation results showed an advantage to having a separate controller for vertical control (Reference 11). The (3+1) Collective and (2+1+1) configurations achieved the best overall pilot ratings for all IMC/VMC tasks. A separate collective controller eliminated unintentional collective to pitch/roll coupling common to the 4-axis and (3+1) Pedal configurations. Based on Phase 1 simulation results, Phase 2 simulation studies and controller design development was directed toward improve-

PHASE 1 CONTROLLER CONFIGURATIONS

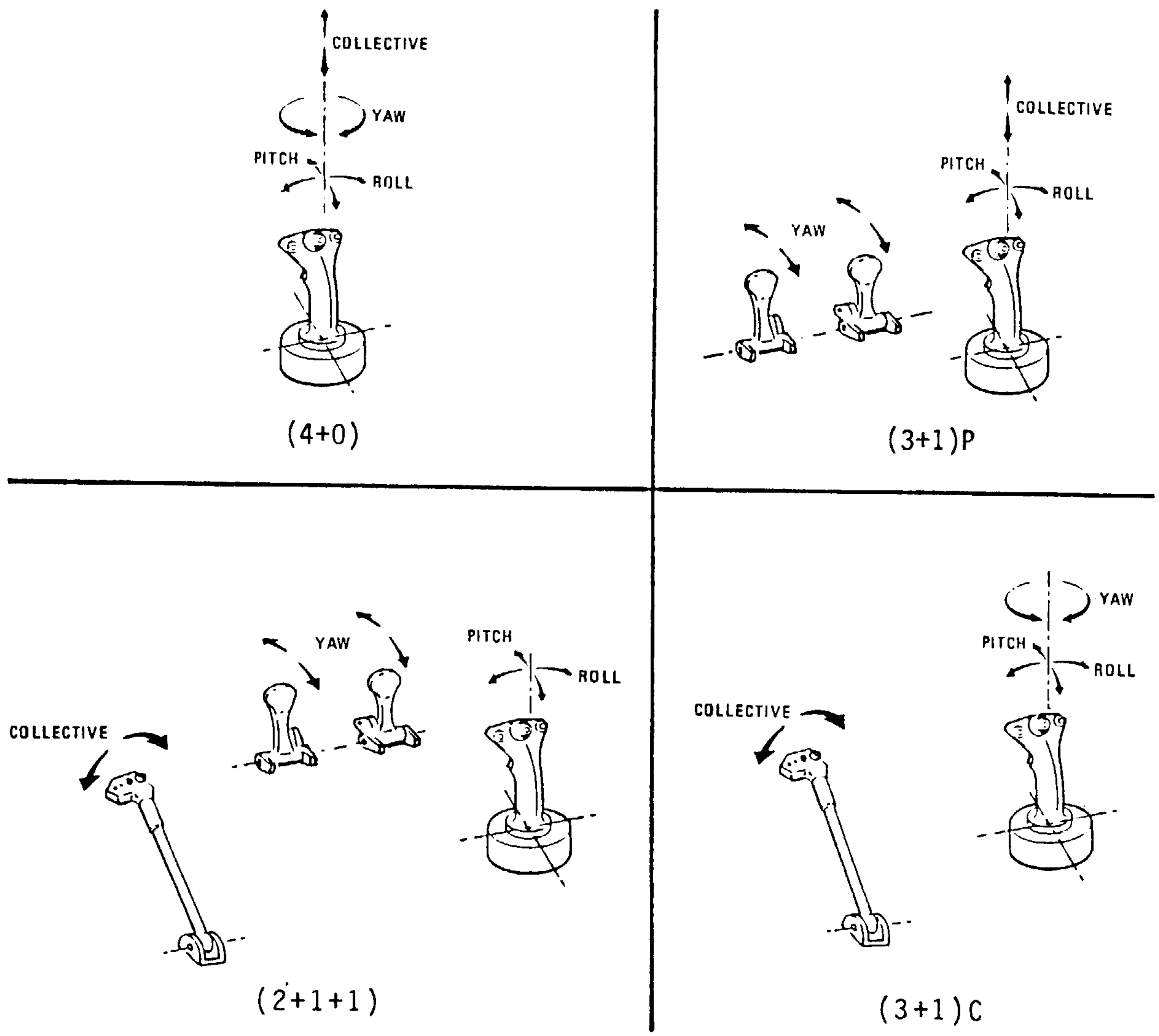


Figure 3-4

ment of vertical axis control. The (3+1) Collective and (2+1+1) configurations were implemented using a left-hand side-stick controller instead of a conventional collective lever (Figure 3-5). Orientation of the armrest and mounting of the left-hand controller was accomplished such that vertical control inputs were made through the longitudinal control axis (pitch rotation) of the SSC. A picture of the installation of the right-hand and left-hand side-stick controllers in the NASA-Ames simulator is shown in Figure 3-6. Improvement of the 4-axis controller design was also emphasized during Phase 2 by modification of the grip design, controller orientation, and force/deflection characteristics.

3.3 ORIENTATION

Throughout all SSC evaluation studies conducted to date, the increased comfort provided by the SSC armrest has been noted as a major benefit. Orientation of the controller must not only be comfortable, but optimized to prevent or reduce inherent anthropometric cross-axis coupling. Proper controller orientation can also reduce pilot workload and improve precision control.

Pilots who flew a Navy F9F in Sjoberg's experiment (Reference 2) felt that pilot effort was actually reduced when flying with a SSC. One of the two main reasons for this was considered to be the increased comfort provided by the SSC armrest. Sjoberg's conclusions state that proper SSC orientation should allow pilots to use finger and wrist motions as they were preferred over arm motions for control inputs.

Conclusions from an F-104 SSC study (Reference 3) included data on SSC orientation requirements as well. The orientation of the controller was found to be an important human factors consideration. The controller was rolled inboard 12 degrees and pitched nose-down 17 degrees in order to maximize pilot comfort and useful wrist deflection. The armrest was located 4 to 6 inches from the pilots side and parallel to the longitudinal axis of the aircraft. This position was comfortable for all pilots leaving seat height as the only required adjustment.

Simulations in support of the ASH study (Reference 8) utilized a 2-axis stiff SSC for pitch and roll control. Results from this study showed the importance of position and orientation of the SSC to reduce unintended cross-axis coupling of control inputs.

Pilot's comments reported during the TAGS study (Reference 6) included unfavorable feelings toward the geometry of the armrest in the TAGS aircraft.

A summary of recommended design criteria for 2-axis side-stick controllers is presented in an Air Force Flight Dynamics Laboratory (AFFDL) technical report (Reference 12). The recommen-

PHASE 2 CONTROLLER CONFIGURATIONS

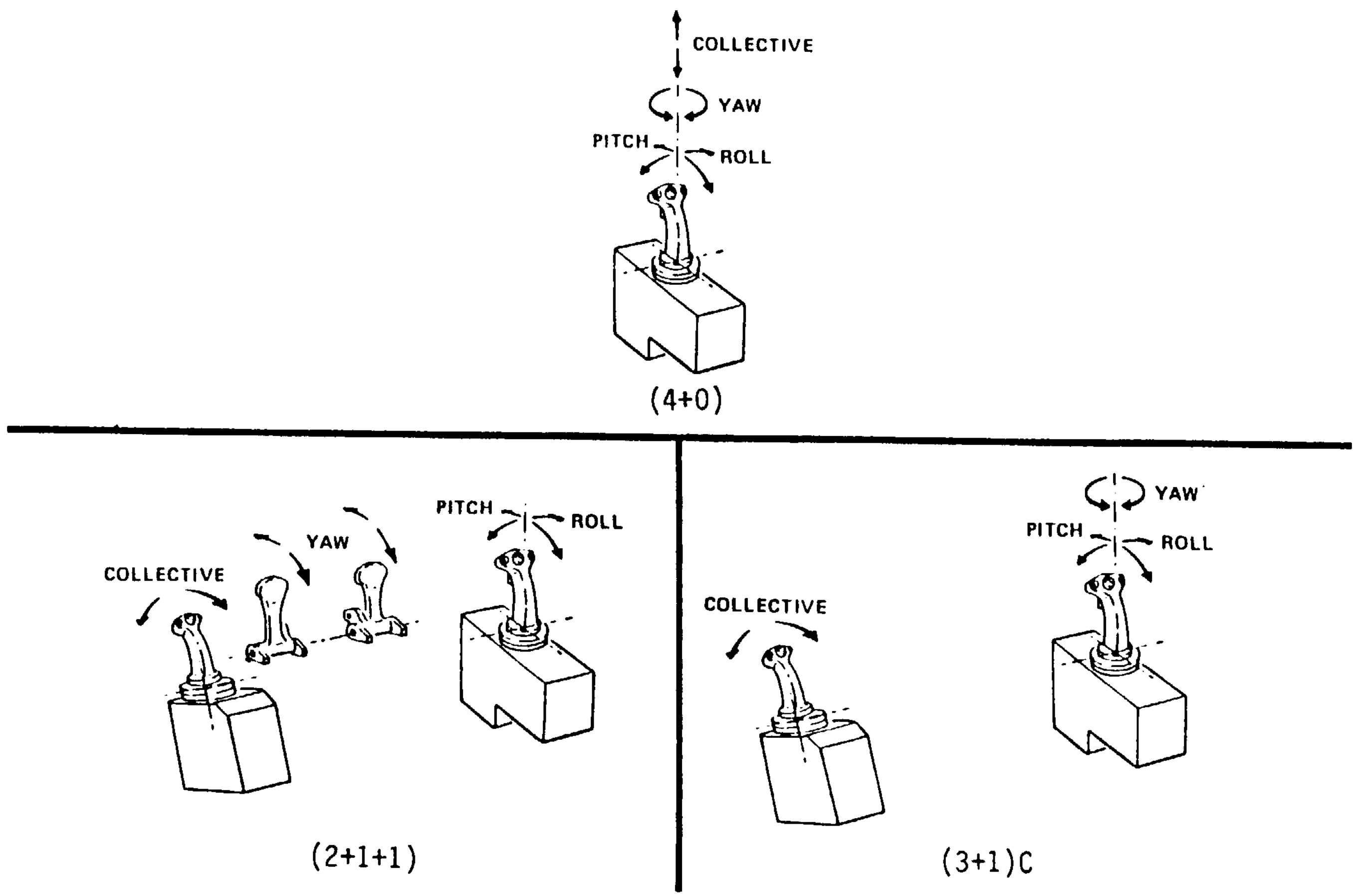


Figure 3-5

ORIGINAL PAGE IS
OF POOR QUALITY

(3+1) COLLECTIVE CONFIGURATION NASA-AMES

Figure 3-6

dations made by Black and Moorehouse in this document are directly applicable to the ADOCS program. Recommended requirements for controller orientation and installation are summarized as follows:

- The SSC neutral position should be oriented 10-17 degrees forward of vertical and 8-12 degrees inboard of vertical to minimize pilots wrist displacements.
- A pilot adjustable armrest is ABSOLUTELY necessary and its design can easily influence other parameters.

An adjustable armrest and mounting bracket to allow easy variation of side-stick controller orientation were installed for the ACC/AFCS simulation studies. Controller orientations were optimized for the right-hand SSC (Phase 1 and Phase 2) and the left-hand controller (Phase 2 only) based on subject pilots' comments. Figure 3-7 illustrates the orientation utilized in the final simulation phase (Phase 2B) and the orientation recommended for the ADOCS demonstrator vehicle. This orientation was found acceptable by the five subject test pilots who participated in the Phase 2B simulation, as well as numerous other pilots who participated in a post-simulation demonstration.

3.4 CONTROLLER/GRIP DESIGN

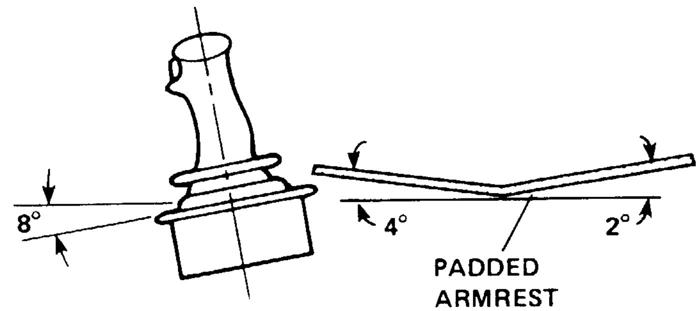
During the Phase 1 literature review, Boeing Vertol contracted Honeywell, Inc. to review potential controller designs and present recommendations concerning side-stick controllers and associated grips. Honeywell's background in SSC design is extensive, including related work on the SSC employed for the Apollo and Space Shuttle vehicles. The findings of the Honeywell study are summarized as follows in Sections 3.4.1 and 3.4.2. Information from other sources pertaining to SSC buttons and switches are presented in section 3.4.3.

3.4.1 Hand-Controller Pivot Sets

A number of 2- and 3-axis hand controllers have been investigated for fighters, spacecraft and helicopters. These controllers have used a number of pivot sets as shown in Figure 3-8. The roll control axis has been parallel to the forearm and beneath the hand in almost every stick tested. The most intuitively correct pitch control axis (with this roll axis) is horizontal, perpendicular to and intersecting the roll axis. This is the axis set for the classic cockpit center-stick, for a number of "pencil sticks", and for the F-16 side-stick. It is an excellent pivot set in a displacement stick but has one disadvantage; the pitch control motion requires that the forearm move on its rest, which is awkward if control must be maintained in a high g-field or in heavy vibration (as in a helicopter). For this reason, other pitch control pivots which allow operation without arm movement have been investigated. It should be noted, however, that leaving the classic pitch/

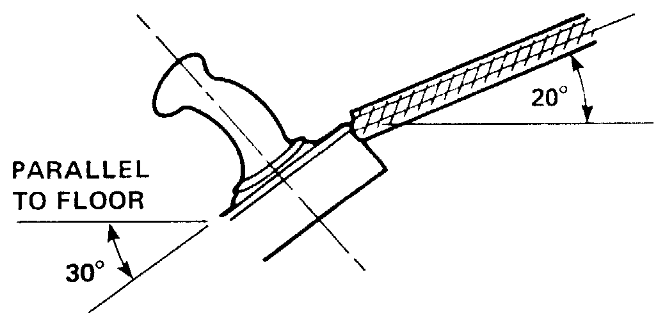
FINAL CONTROLLER ORIENTATIONS

RIGHT HAND CONTROLLER MOUNTING



0.5° INBOARD LATERAL TILT
AND 3° INBOARD TWIST ABOUT ℄

LEFT HAND CONTROLLER MOUNTING



8° INBOARD LATERAL TILT
AND 4° INBOARD TWIST ABOUT ℄

Figure 3-7

VARIOUS CONTROLLER IMPLEMENTATIONS

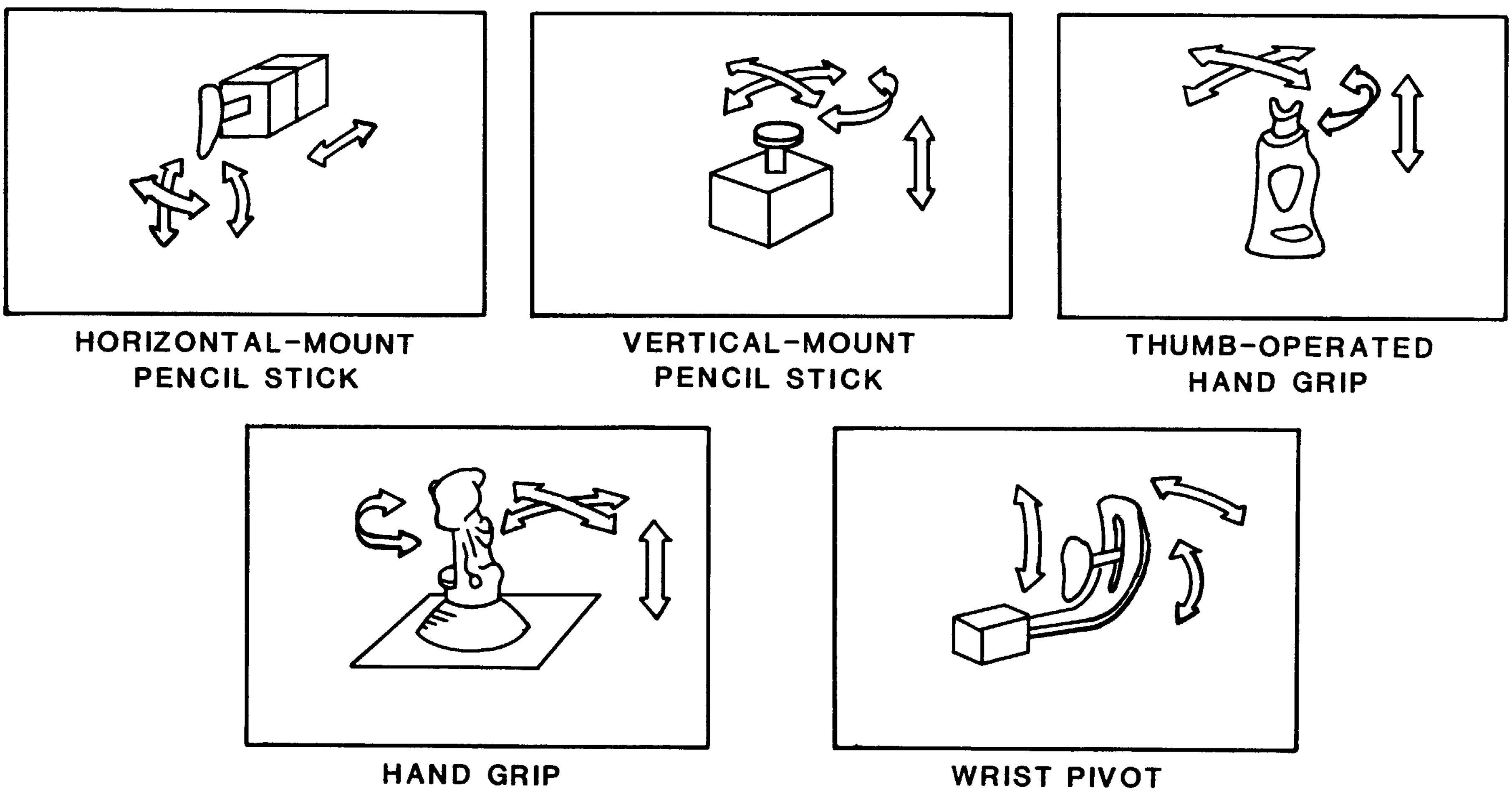


Figure 3-8

roll pivot set for more innovative controllers may involve risk. For example, most pilots of interest have had thousands of flight hours with a large-displacement center stick which can be "pushed" around in pitch and roll. Most innovative pitch pivots do not move for a push (except for the TAGS controller) and a stressed pilot may revert to a "push" mode - a hazardous possibility in some conditions.

Two innovative pitch pivots which have been intensively flight tested are the wrist pivot (X-15 and JF101A test bed) and the palm pivot (Apollo rotational stick and Shuttle "space" and "atmospheric" sticks). A palm pivot was found to give better control harmony between pitch and roll than the wrist pivot, allowing better simultaneous 2-axis control than the wrist pivot.

The yaw axis of control in a hand controller has been implemented in several ways; the most prevalent has been the grip twist about the vertical axis of the hand grip itself, and an alternative method has been a thumb lever. Although the thumb lever avoids the cross-coupling problem obvious in the grip twist, problems of hand fit and fatigue make it a poor controller.

For the ACC/AFCS simulation studies, all candidate controllers chosen for evaluation have a "classical" base-pivot design, i.e., the pitch and roll pivot point located beneath the hand with the axes of rotation oriented approximately parallel to the aircraft body axes. Controllers with this type of pivot set are readily available either as a prototype controller from another experimental development program or by purchase of an off-the-shelf design. A palm pivot, as used on the Apollo and Shuttle spacecraft, is an attractive alternative but could not be procured in a timely manner for simulation testing during the ACC/AFCS study. Yaw control on the side-stick controllers evaluated was obtained by twisting about the grip centerline; vertical control, using the right-hand controller, is effected through the application of pure up and down forces.

Evaluation of vertical control when implemented on a left-hand side-stick controller, instead of a conventional collective lever, was also performed. The left-hand side-stick was oriented so that vertical control inputs were accomplished through the rotational pitch axis of the SSC.

3.4.2 Grip Design

Grip designs for use on Side-Stick Controllers range from conventional hand grips as used on production helicopter center-stick controllers to innovative designs as used on the HLH (Figure 3-2). Honeywell summarized a wide range of possible grip designs and noted the requirements for an acceptable grip design. The Honeywell study concluded that the grip of a multi-axis controller having "classical" pivot points described must:

- o Be so shaped that the hand, upon grasping it, is clearly positioned with respect to motions that allow the operator to:
  - twist the grip about the vertical (Z-Z) axis (yaw)
  - rotate the grip about the lateral (Y-Y) axis (pitch)
  - displace the grip about an axis (X-X) below it (roll)
- o Be so shaped that the position of the hand with respect to the grip is constant, permitting the operator to immediately determine if the grip has been moved with respect to any of the control axes.

To achieve these goals the grip must:

- o Have finger depressions along its front surface to position the hand with respect to the grip's top and bottom.
- o Position the thumb and index finger approximately parallel to each other, permitting immediate tactile and visual awareness of the grip's position within the hand with respect to rotation about its longitudinal axes. Having properly positioned the thumb and index finger, grasping the grip with the remaining fingers should not result in a rotation of the grip, either about its palm pivot or about its longitudinal axis.

During the course of the ACC/AFCS simulation study, various grip designs (Figure 3-9) were evaluated including (1) a HLH prototype hand grip, (2) a standard off-the-shelf grip design manufactured by Measurement System, Inc., Norwalk, Conn. (MSI), (3) the Canadian NAE type grip, and (4) an experimental grip design fabricated by Boeing Vertol. Simulation results detailed in Volume 3 indicate pilot preference for the Canadian type of grip design. This grip provided pilots with better vertical control surfaces than the standard MSI design or HLH prototype hand grip. The Boeing experimental grip was not found to be acceptable.

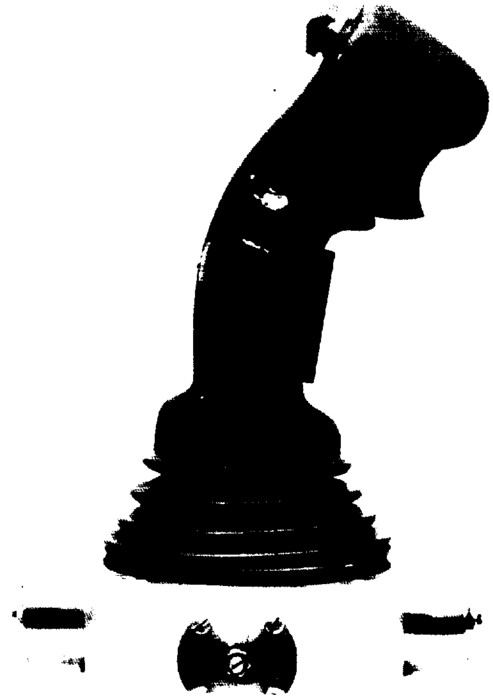
3.4.3 Buttons/Switches

Numerous buttons/switches are presently located on the standard pilot and copilot controller grips. These switches/buttons activate a variety of equipment functions, such as:

- o Radio Operation
- o Weapons Discharge
- o Cargo-hook release
- o Search-light operation
- o Engine RPM trim

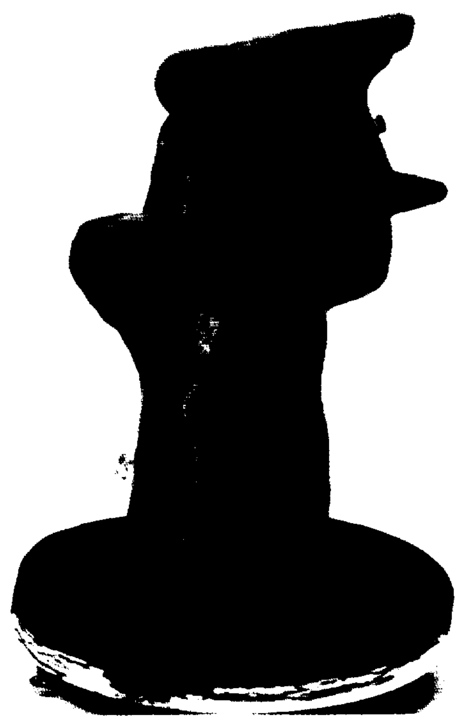
SSC GRIP COMPARISON

HLH SIDE-STICK GRIP



STANDARD MSI GRIP

NAE-TYPE GRIP



BOEING EXPERIMENTAL GRIP DESIGN

Figure 3-9

- o Force-trim release
- o Vernier beep trim commands
- o IHADSS mode selection

Previous research studies provide design criteria for locating switches and buttons on a SSC. Experiments conducted by the Air Force Aerospace Research Pilot School (Reference 3) found that the switches on the SSC must have deflection to provide feedback to the pilot and inform him of activation. The Air Force experiments concluded that the switch deflection/activation force must be less than 50 percent of the control breakout force. Switches should be positioned no more than 1 inch above the pilot's forefinger because of human factor considerations.

Morgan's conclusions from his study of side-stick controller force-trimming systems (Reference 10), reiterate the findings of Reference 3. Stiff four-way beep trim switches resulted in inadvertent inputs through the SSC. Flight test results on the NAE airborne simulator show that an effective force trimming system for a helicopter equipped with a SSC is essential. Of the systems evaluated, the best results were obtained with an automatic or self-trimming system. An inherent self-trimming system implemented through control law design eliminates the requirement for force-trim/release switches on the SSC.

For ACC/AFCS simulation studies, it was decided to activate a limited number of functions from the SSC. Buttons/switches to control only three of the functions listed previously--IHADSS mode selection, vernier beep trim, and force trim--were included on the side-stick controllers purchased from MSI (Figure 3-10). All switches were low force spring-loaded on-off switches with breakout forces ≦ 1.0 lb. The IHADSS mode select switch for IMC evaluation was always located on the left-hand controller for all controller configurations, even when a 4-axis SSC was operated by the right-hand. Capability for vernier beep trim commands with AFCS ON was provided from four-way trim switches located on the top of the left-hand controller for collective and yaw, and on the right-hand controller for pitch and roll. Vernier beep trim was provided as a secondary control law function, and was used to make fine adjustments to heading, altitude, and longitudinal/lateral velocity. Beep trim was not required by the pilots for performance of evaluation tasks defined for the ACC/AFCS simulation study.

The force trim/release button was utilized to relieve steady trim forces for AFCS OFF operation during initial investigation of unaugmented characteristics. Upon activation of the force-trim button, the required trim to reduce steady-state trim forces to zero was injected into the control system at a slow controllable rate. An alternate design concept was later developed to automatically trim forces with AFCS OFF, thereby eliminating the requirement for a trim release button on the ADOCS demonstrator aircraft. Automatic trimming of steady-

ACC/AFCS SWITCH IMPLEMENTATION

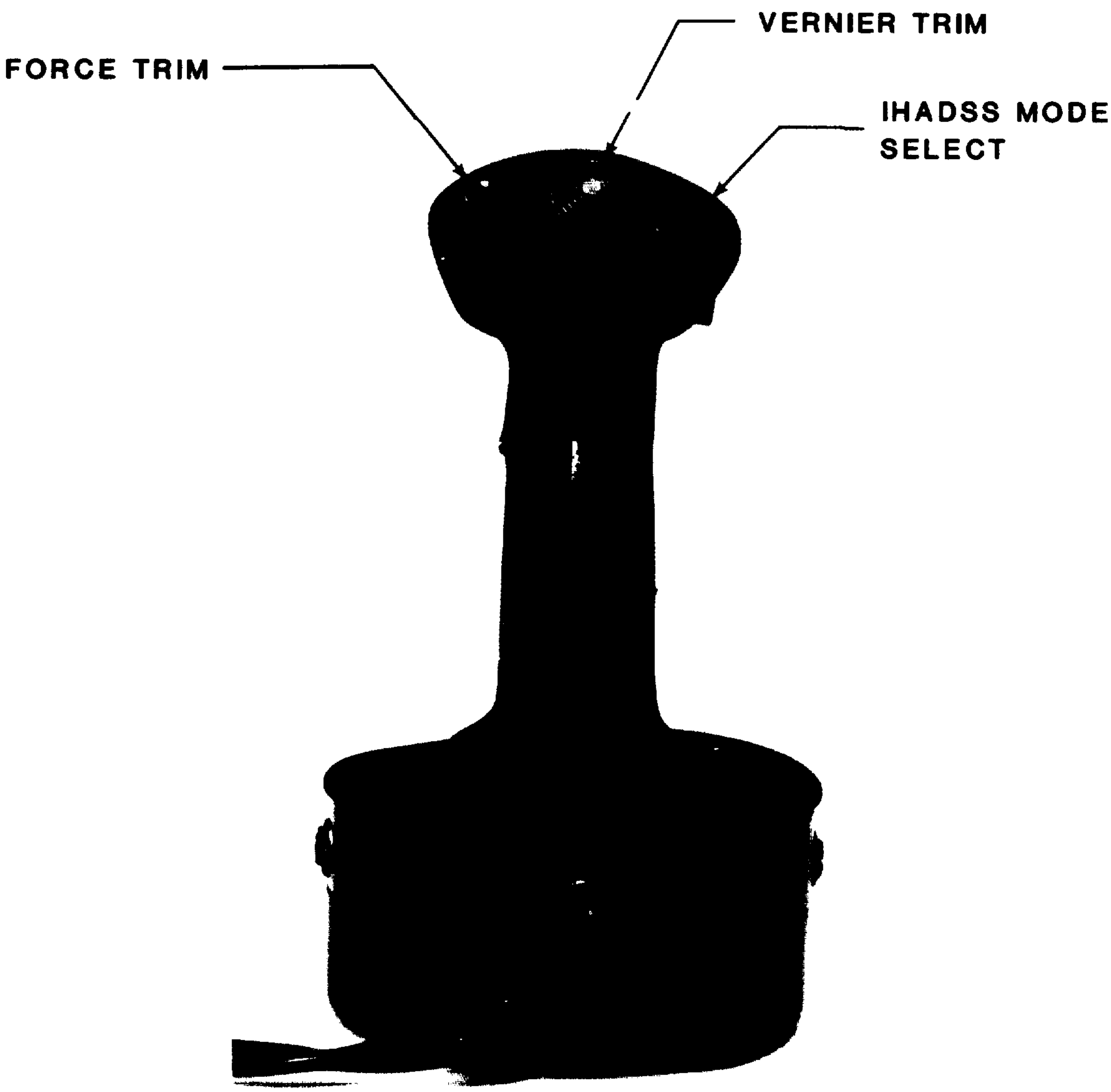


Figure 3-10

state forces with AFCS ON is inherent in the control law design concept chosen for the AFCS.

3.5 FORCE/DEFLECTION CHARACTERISTICS

Much flight research and simulation testing has been conducted to investigate the effect of SSC force/deflection characteristics on handling qualities. Side-stick controller force/deflection characteristics implemented on various aircraft range from the very stiff stick design of the F-16 to a medium-deflection relatively "soft" controller as used on the HLH demonstrator vehicle. This section summarizes findings of the literature review and results of a few side-stick development programs. Force/deflection characteristics chosen for the base-line controller(s) used in the ACC/AFCS simulation are presented and compared to recommended characteristics determined from the literature review.

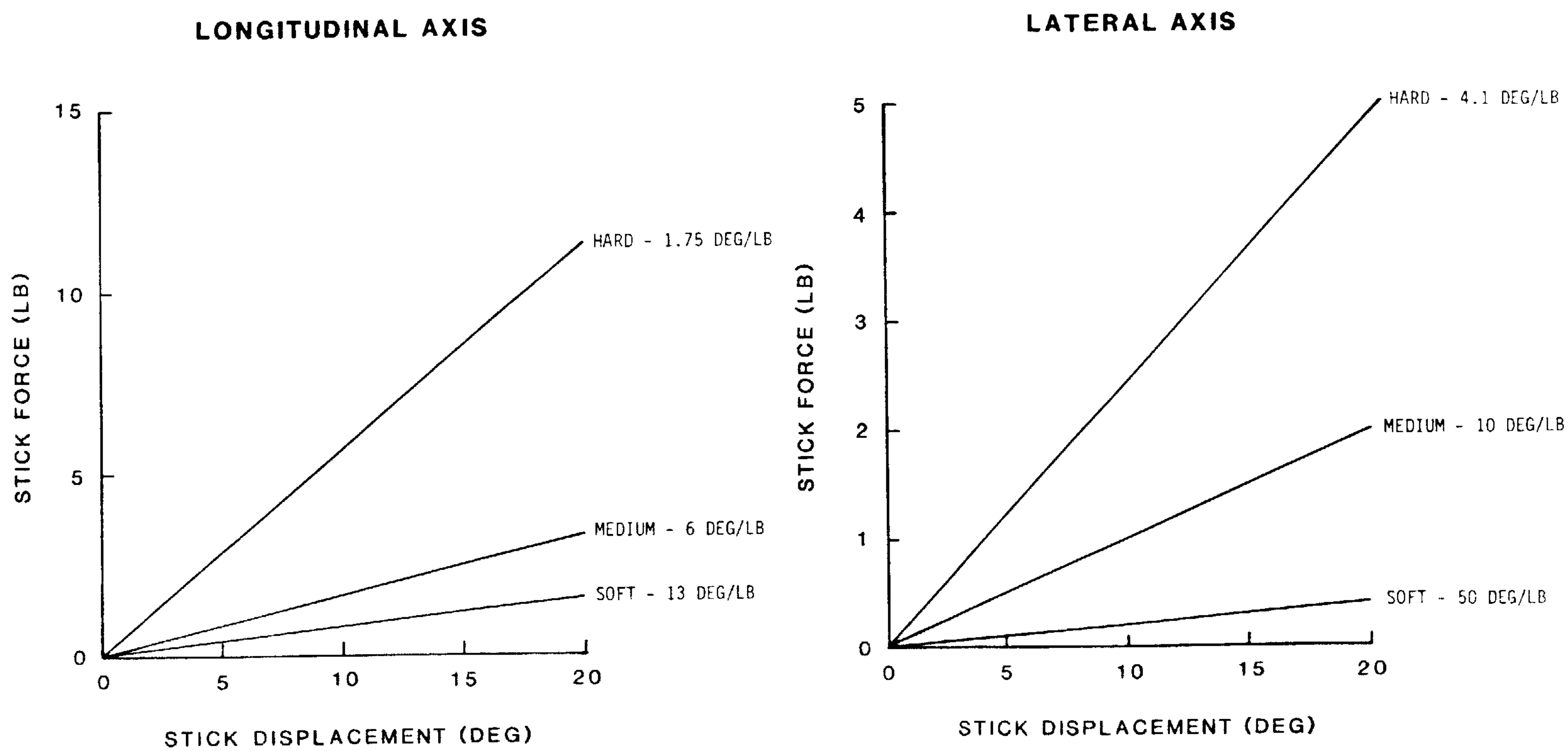
In the study conducted by the Air Force Aerospace Research Pilot School (Reference 3), three force/deflection characteristics were tested in both the pitch and roll axes (Figure 3-11) resulting in nine possible combinations. Maximum controller deflection was kept constant at 20 degrees for all force/deflection configurations tested. The favored gradients in this study were found to be the "hard" gradient in pitch (1.75 deg/lb) and the "medium" gradient in roll (10 deg/lb).

Further studies to investigate SSC force/deflection characteristics were performed using a NT-33A aircraft equipped with a variable force/deflection side-stick controller (References 13 to 15). A wide range of force/deflection characteristics was evaluated and their effect on pilot handling qualities ratings identified. Pilot ratings were used to define iso-opinion contour boundaries outlining adequate, marginal, and poor regions of force/deflection and response/force gradients. A preferred region of force versus deflection gradient was identified (Figure 3-12) and certain general conclusions were drawn from the test results:

(1) In the region of very small motion (fixed stick), tracking performance was very sensitive to changes in force/response gradient. The range of stick force/response gradients that result in adequate performance is very restricted. There appears to be a narrow area in the medium to heavy force/response gradient range where performance in air-to-air maneuvers was adequate. Lighter or heavier forces with small motion will result in objectionable or unacceptable handling qualities.

(2) As motion increased, the region expands to a point where the results were fairly insensitive to changes in force/response gradients. Moderate stick motion

FORCE/DEFLECTION CHARACTERISTICS EVALUATED IN F-104 STUDY



DATA OBTAINED FROM REFERENCE NO. 2

Figure 3-11

PILOT RATINGS FOR COMBINATIONS OF LONGITUDINAL FORCE-DEFLECTION GRADIENT FOR AIR-TO-AIR TRACKING TASK (REFERENCE 14)

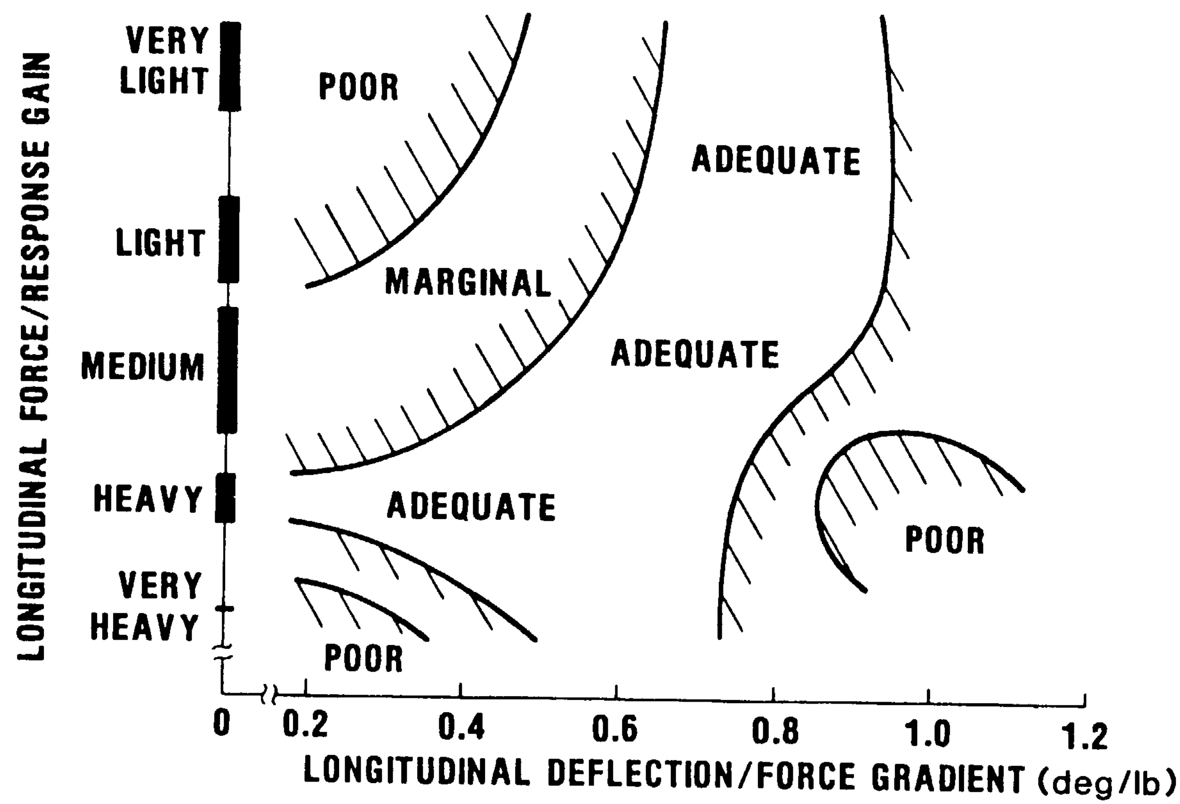


Figure 3-12

coupled with light to moderate stick force gradients results in the best tracking performance.

(3) As stick motion was increased further, comments about excessive stick motion, encountering the stops, and overshoots arose. With more than 20° deflection, excessive wrist bending caused pilot control to deteriorate.

(4) A comparison of results for both gross maneuvering and precision tracking tasks indicated no noticeable disparity in the results obtained from the two types of maneuvers. The boundaries of Figure 3-12 apply to all air-to-air maneuvers investigated.

In the summary of SSC design criteria presented in an AFFDL technical report (Reference 12), the following recommendations were included:

- o Minimum full longitudinal deflection should be greater than 2 deg from neutral to full aft.
- o Longitudinal and lateral deflection values should be consistent for a harmonious feel.
- o Lateral deflection/force gradient should be 1 to 1.6 times the longitudinal deflection/force gradient.
- o Longitudinal control should have a deflection/force gradient between 0.5 and 0.8 deg/lb.
- o Hard stops that are easily discernible to the pilot should be used.

As noted by the above recommendation from Reference 12, the relationship between the longitudinal and lateral force/ deflection characteristics was found by Air Force testing to be an important design criteria. Figure 3-13 defines the AFFDL preferred region of longitudinal/lateral force-deflection gradient which provided good control harmony. Various controller configurations that were acceptable based on flight test evaluation are identified. The candidate controller designs, as described below, were selected for ACC/AFCS simulation evaluation and are also presented in Figure 3-13 for comparison.

Side-stick configurations used for a number of aircraft/helicopter flight research and development programs are summarized in Table 3-1. Controller configurations included 2-axis (pitch and roll), 3-axis (pitch, roll, and yaw), and 4-axis designs. The majority of the controllers had a base pivot design for pitch and roll with exception of the Shuttle and Apollo aircraft which mechanized a unique palm pivot for pitch control application. The TAGS controller also deviated from the conventional base-pivot for pitch control to a design requiring

PREFERRED LONGITUDINAL/LATERAL CONTROL HARMONY
NORMALIZED DEFLECTION FORCE/GRADIENTS

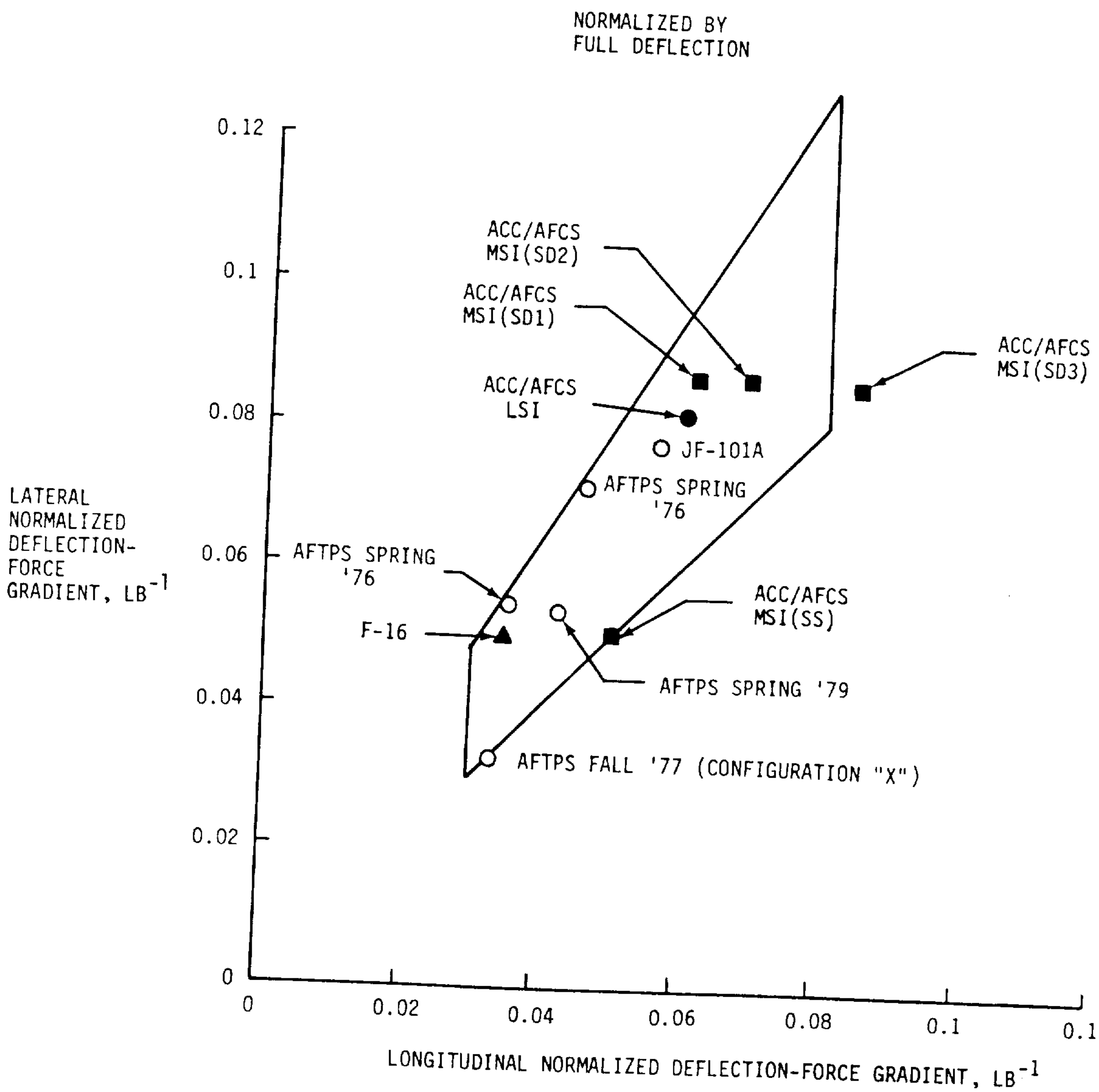


Figure 3-13

ORIGINAL PAGE IS OF POOR QUALITY

SIDE-

PROGRAM/TEST VEHICLE (CONTROLLER MANUFACTURER)	REFERENCE NO.	NO. AXES ON SIDE-STICK CONTROLLER	PIVOT	CTION	
				VERTICAL	DIRECTIONAL
AIR FORCE AEROSPACE PILOT SCHOOL F-104D	3	2	PITCH BASE	—	—
AFFDL TESTING NT-33A (CALSPAN)	14	2	PITCH BASE	—	—
F-16 (LEAR-SIEGLER)	36	2	PITCH BASE	—	—
SHUTTLE + APOLLO (HONEYWELL)	—	3	PITCH-P ROLL BA YAW-GRI	—	0.7 IN-LB/DEG
NAE AIRBORNE SIMULATOR BELL 205-1 (MEASUREMENT SYSTEM, INC)	10	4	PITCH PIVOT YAW-GRI VERTICAL	400 LB/IN	—
MODEL 347/HLH DEMONSTRATOR (HONEYWELL)	22	4	PITCH PIVOT YAW-GRI VERTICAL	1.05 LB/IN	0.12 IN-LB/DEG
TAGS CH-47B	6	4	PITCH-LON TRANSL ROLL-BAS YAW-GRIP VERTICAL-	—	0.093 IN-LB/DEG

e 3-1

FOLDOUT FRAME

FOLDOUT FRAME 2

PREFERRED LONGITUDINAL/LATERAL CONTROL HARMONY NORMALIZED DEFLECTION FORCE/GRADIENTS

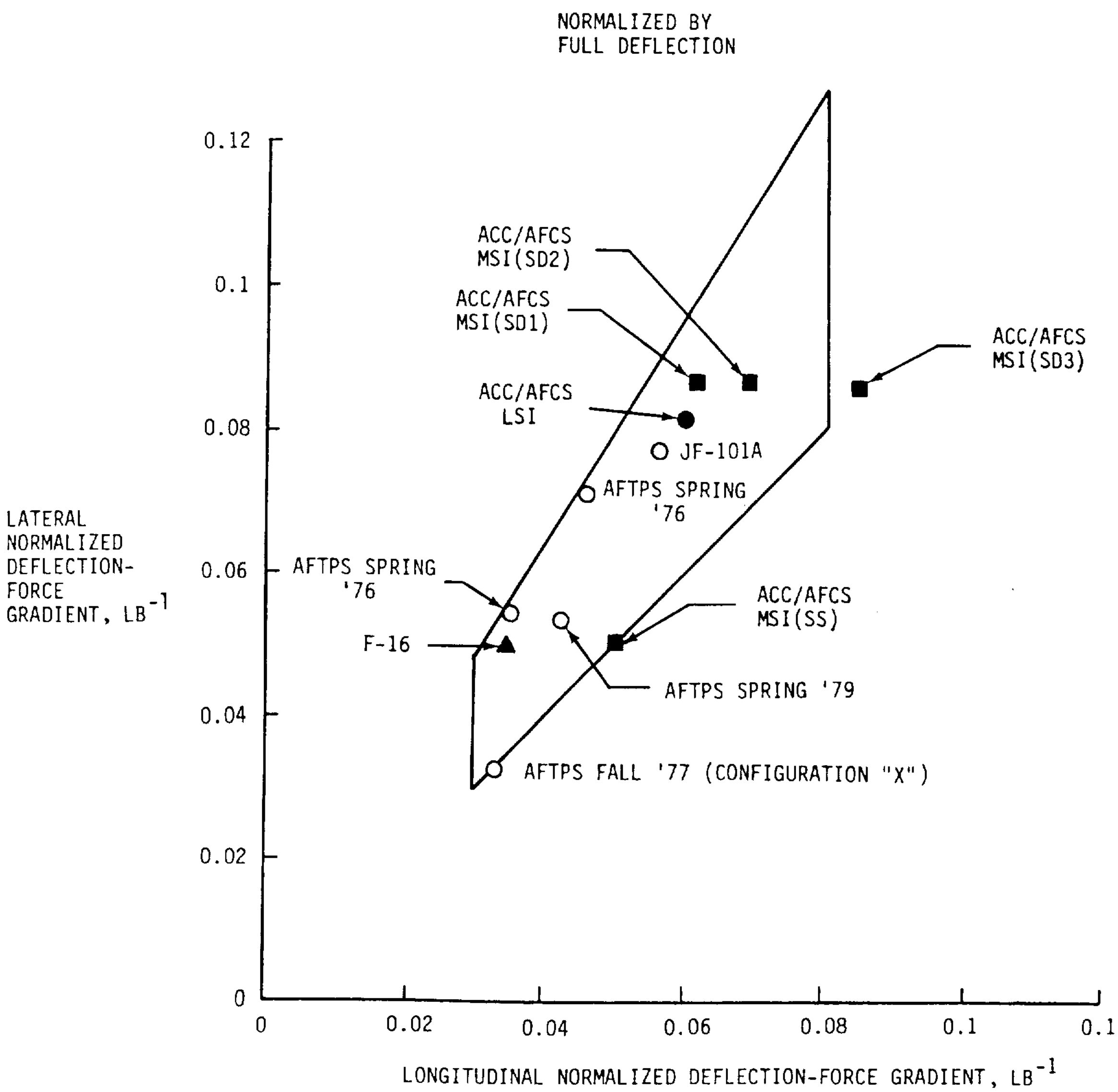


Figure 3-13

SIDE-STICK CONTRO

PROGRAM/TEST VEHICLE (CONTROLLER MANUFACTURER)	REFERENCE NO.	NO. AXES ON SIDE-STICK CONTROLLER	PIVOT TYPE	MAXIMU	
				LONGITUDINAL	LATI
AIR FORCE AEROSPACE PILOT SCHOOL F-104D	3	2	PITCH + ROLL BASE PIVOT	VARIABLE	VARI
AFFDL TESTING NT-33A (CALSPAN)	14	2	PITCH + ROLL BASE PIVOT	VARIABLE	VARI
F-16 (LEAR-SIEGLER)	36	2	PITCH + ROLL BASE PIVOT	AFT - 26 LB FWD - 32 LB	± 20
SHUTTLE + APOLLO (HONEYWELL)	—	3	PITCH-PALM PIVOT ROLL BASE PIVOT YAW-GRIP TWIST	34 IN-LB	43 I (9.5
NAE AIRBORNE SIMULATOR BELL 205-1 (MEASUREMENT SYSTEM, INC)	10	4	PITCH + ROLL PIVOT BASE YAW-GRIP TWIST VERTICAL - UP/DOWN	± 20 LB	± 20
MODEL 347/HLH DEMONSTRATOR (HONEYWELL)	22	4	PITCH + ROLL PIVOT BASE YAW-GRIP TWIST VERTICAL - UP/DOWN	—	-
TAGS CH-47B	6	4	PITCH-LONGITUDINAL TRANSLATION ROLL-BASE PIVOT YAW-GRIP TWIST VERTICAL-ROTATIONAL	—	-

SIDE-STICK CONTROLLER FORCE/DEFLECTI

PROGRAM/TEST VEHICLE (CONTROLLER MANUFACTURER)	REFERENCE NO.	NO. AXES ON SIDE-STICK CONTROLLER	PIVOT TYPE	MAXIMUM OPERATING FORCES				
				LONGITUDINAL	LATERAL	VERTICAL	DIRECTIONAL	LONGITUDIN
AIR FORCE AEROSPACE PILOT SCHOOL F-104D	3	2	PITCH + ROLL BASE PIVOT	VARIABLE	VARIABLE	—	—	± 20 DEG
AFFDL TESTING NT-33A (CALSPAN)	14	2	PITCH + ROLL BASE PIVOT	VARIABLE	VARIABLE	—	—	± 20 DEG
F-16 (LEAR-SIEGLER)	36	2	PITCH + ROLL BASE PIVOT	AFT - 26 LB FWD - 32 LB	± 20 LB	—	—	AFT - 1.8 I FWD - 0.5 I
SHUTTLE + APOLLO (HONEYWELL)	—	3	PITCH-PALM PIVOT ROLL BASE PIVOT YAW-GRIP TWIST	34 IN-LB	43 IN-LB OR 9.5 LB	—	10 IN-LB	19.5 DEG
NAE AIRBORNE SIMULATOR BELL 205-1 (MEASUREMENT SYSTEM, INC)	10	4	PITCH + ROLL PIVOT BASE YAW-GRIP TWIST VERTICAL - UP/DOWN	± 20 LB	± 20 LB	± 40 LB	± 60 IN-LB	0.5 DEG
MODEL 347/HLH DEMONSTRATOR (HONEYWELL)	22	4	PITCH + ROLL PIVOT BASE YAW-GRIP TWIST VERTICAL - UP/DOWN	—	—	0.53 IN	1.8 LB	± 8 - 12 DE
TAGS CH-47B	6	4	PITCH-LONGITUDINAL TRANSLATION ROLL-BASE PIVOT YAW-GRIP TWIST VERTICAL-ROTATIONAL	—	—	—	3.26 IN-LB	+ 4.44 IN - 1.06 IN

 2

ION CHARACTERISTICS

	MAXIMUM DEFLECTION			FORCE/DEFLECTION			
AL	LATERAL	VERTICAL	DIRECTIONAL	LONGITUDINAL	LATERAL	VERTICAL	DIRECTIONAL
	± 20 DEG	—	—	VARIABLE $.077$ TO $.57 \frac{LB}{DEG}$ ($.57 \frac{LB}{DEG}$ BEST)	VARIABLE $.02$ TO $.24 \frac{LB}{DEG}$ ($.1 \frac{LB}{DEG}$ BEST)	—	—
	± 12 DEG	—	—	VARIABLE $.9$ TO $5 \frac{LB}{DEG}$ ($1.4 \frac{LB}{DEG}$ BEST)	VARIABLE $.9$ TO $5 \frac{LB}{DEG}$ ($1.4 \frac{LB}{DEG}$ BEST)	—	—
EG EG	± 1.4 DEG	—	—	AFT - $14.4 \frac{LB}{DEG}$ FWD - $64.0 \frac{LB}{DEG}$	$14.4 \frac{LB}{DEG}$	—	—
	19.5 DEG	—	10 DEG	$1.65 \frac{IN\text{-}LB}{DEG}$	$2.1 \frac{IN\text{-}LB}{DEG}$ OR $0.47 \frac{IN\text{-}LB}{DEG}$	—	$0.7 \frac{IN\text{-}LB}{DEG}$
	0.5 DEG	0.1 IN	—	$40 \frac{LB}{DEG}$	$40 \frac{LB}{DEG}$	$400 \frac{LB}{IN}$	—
G	± 8 - 12	± 0.5 IN	± 15 DEG	$0.14 \frac{LB}{DEG}$	$0.11 \frac{LB}{DEG}$	$1.05 \frac{LB}{IN}$	$0.12 \frac{IN\text{-}LB}{DEG}$
	± 30 DEG	± 4.56 IN	± 35 DEG	PROPORTIONAL TO RATE	$0.054 \frac{LB}{DEG}$	—	$0.093 \frac{IN\text{-}LB}{DEG}$

Table 3-1

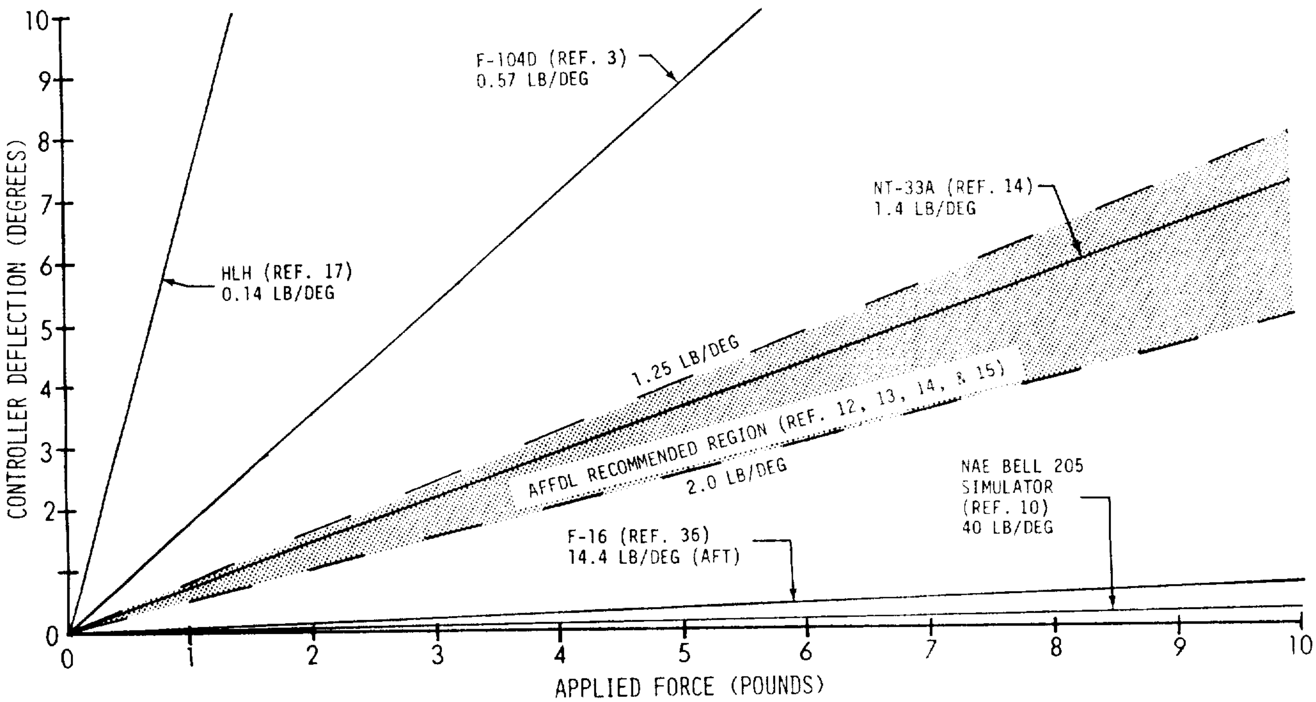
longitudinal translation (displacement) of the controller to command pitch. All controllers used grip twist about the vertical axis for yaw control. Two of the three 4-axis controller configurations evaluated on helicopter programs (HLH Demonstrator and the NAE Bell 205A-1 Airborne Simulator) mechanized vertical control by pure up/down force application along the grip vertical axis. The TAGS 4-axis controller design used a rotational displacement of the controller for vertical control inputs. This configuration was not successfully implemented because of the high inertia of the control mechanism about the vertical rotational control axis. As described previously in Section 3.1, excessive longitudinal/vertical coupling resulted during flight test evaluation of the TAGS 4-axis controller. The vertical axis was locked out and the controller configuration was modified to a (3+1) Collective configuration using a standard collective lever.

A comparison of the force/deflection characteristics listed in Table 3-1 shows a wide range of values from very stiff stick designs -- NAE Bell 205 Airborne Simulator and F-16 -- to extremely "soft" designs -- F-105D (Air Force Research Program) and Model 347 (HLH Demonstrator Program). Figure 3-14 compares the longitudinal and lateral force/deflection characteristics for the side-stick controllers included in Table 3-1. A recommended region developed for the longitudinal and lateral control axes through AFFDL testing of an NT-33A aircraft (References 12, 13, 14 and 15) is shown.

Comparison of controller force/deflection characteristics showed a large variation in the extremes of acceptable configurations. Therefore, it was necessary to consider a wide range of controller force/deflection characteristics during ACC/AFCS simulation testing. Four candidate controllers were selected to bracket the AFFDL recommended area. Figure 3-15 defines the four specific force/deflection configurations evaluated during Phase 1A simulation of Boeing Vertol. Two 4-axis controllers manufactured by MSI were purchased. The stiff-stick designated MSI-SS is an off-the-shelf unit identical to the controller used by NAE for testing on the Bell 205 Airborne Simulator. A second small-deflection controller was fabricated to design characteristics chosen specifically for the ACC/AFCS study. The small-deflection controller design designated as MSI-SD1 incorporated ± 5.3 degrees of motion in pitch and roll, and provided force/deflection gradients between the AFFDL recommended values and the stiff-stick design. A variable force/deflection controller used for HLH simulation studies was also utilized to obtain a medium- and large-deflection configuration. Yaw and vertical controller compliance for both MSI controller 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.

TYPICAL SSC FORCE/DEFLECTION CHARACTERISTICS

LONGITUDINAL AXIS



LATERAL AXIS

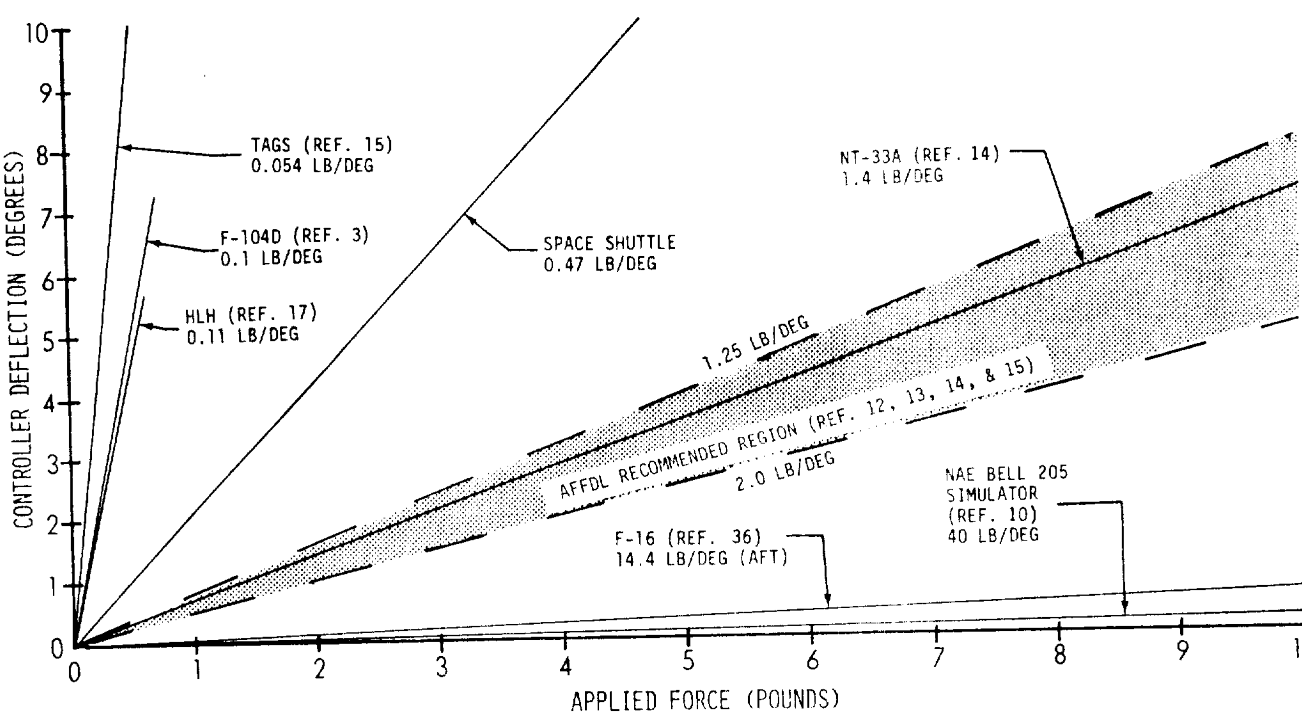
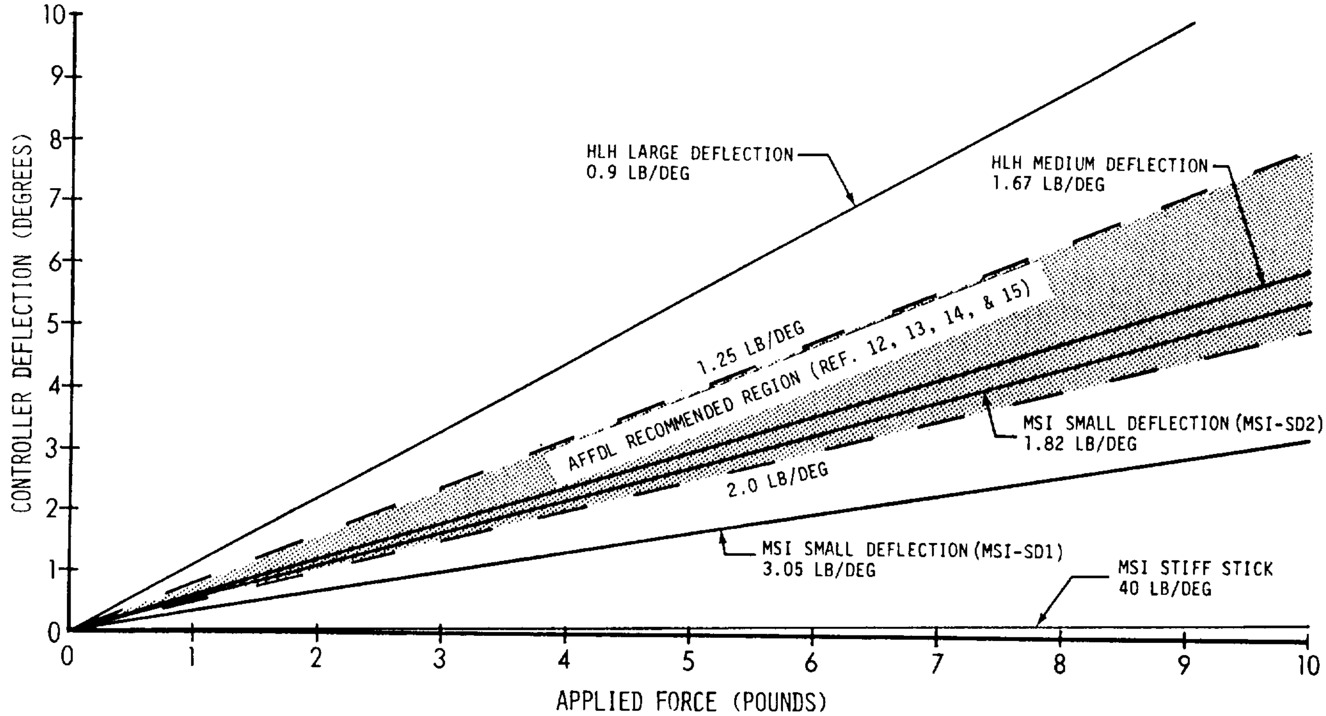


Figure 3-14

ACC/AFCS CANDIDATE SSC CONTROLLERS FORCE/DEFLECTION CHARACTERISTICS

LONGITUDINAL AXIS



LATERAL AXIS

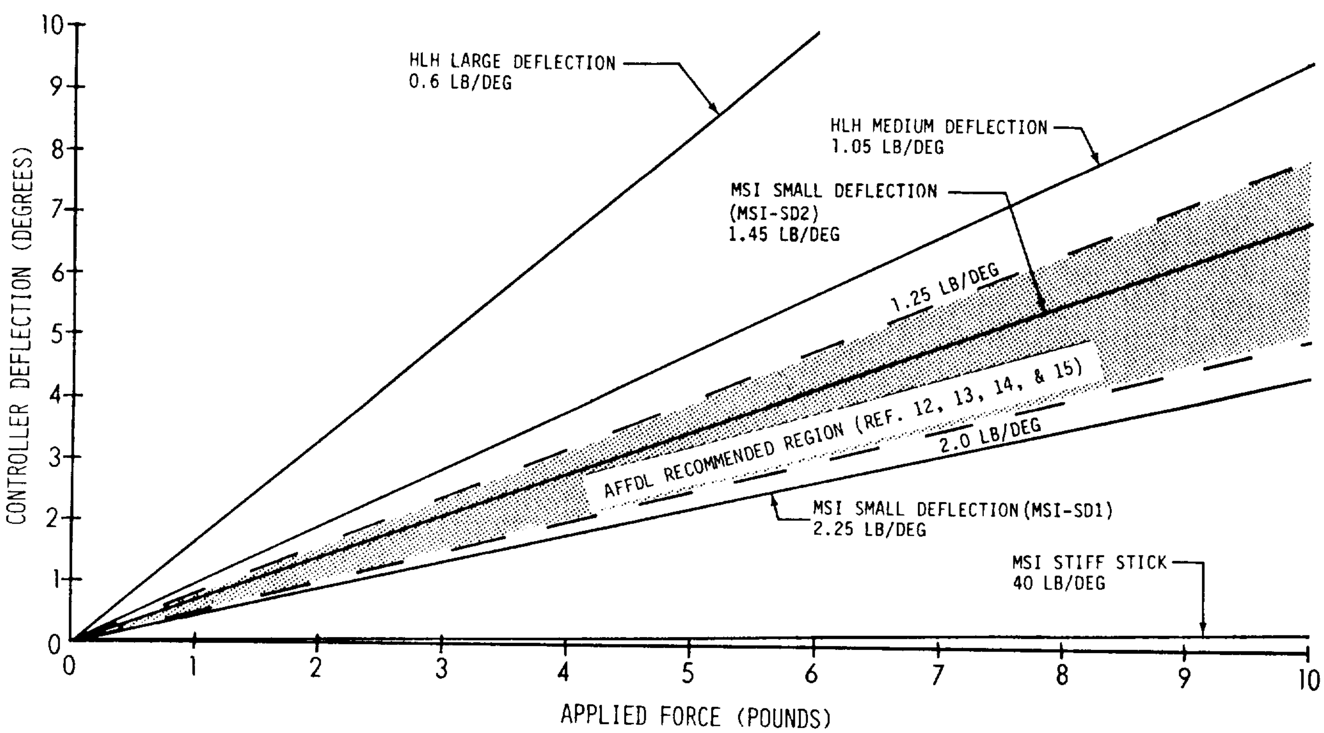


Figure 3-15

Task performance with the 4-axis stiff-stick and three 4-axis deflection controllers described in Figure 3-15 was rated for both rate and attitude command systems in pitch and roll (Figure 3-16). The small-deflection, MSI-SD1, and medium-deflection controllers achieved the best average pilot ratings. Commentary from the 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. Acceptance of the medium-deflection controller was mixed. One pilot gave this controller degraded ratings because height control was difficult due to a high force breakout in the vertical axis. A second pilot gave the medium-deflection controller improved ratings compared to the small-deflection controller because he felt more in control during large maneuvers. The large-deflection controller received degraded ratings compared to the controllers with smaller deflection. Comments indicated a more sluggish pitch control response and less precise control of attitude for high frequency inputs. Based on these initial Phase 1A simulation results, the small-deflection controller was modified by MSI to have a higher deflection/force gradient in each axis. The gradient values selected approached those of the medium-deflection controller and fell within the AFFDL recommended region. This controller design specified as MSI-SD2 was used for further evaluation of controller/SCAS configurations during Phase 1 simulations (Phases 1B and 1C).

Complete force/deflection characteristics for the five 4-axis controller configurations utilized during Phase 1 are presented in Table 3-2. Two additional small-deflection controllers used during Phase 2 at NASA-Ames are also shown and described below. Operating force range, maximum deflection, and force/deflection gradient are given for the four control axes of each controller design.

The Phase 1 simulations at Boeing Vertol showed that improved handling qualities for specific tasks resulted from adding limited deflection to the longitudinal and lateral axes of the side-stick. However, pilot comments indicated that poor control force harmony resulted from the combination of two stiff control axes and two deflection control axes on the same controller. High frequency force modulation for yaw and collective control was difficult and performance of the precision hover task, although better than the stiff controller, was marginally acceptable. Therefore, a third MSI controller -- MSI-SD3 -- was developed for Phase 2 simulation evaluation. This controller with small-deflection in all axes was unanimously preferred over a 4-axis stiff-stick design, or the MSI-SD2 design having limited deflection in the pitch and roll axes. All pilots felt that deflection in all control axes improved the pilot's ability to modulate single-axis forces, produced less tendency for overcontrol and input coupling, and enhanced control precision for high-gain tasks such as the Precision Hover (Reference 16).

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

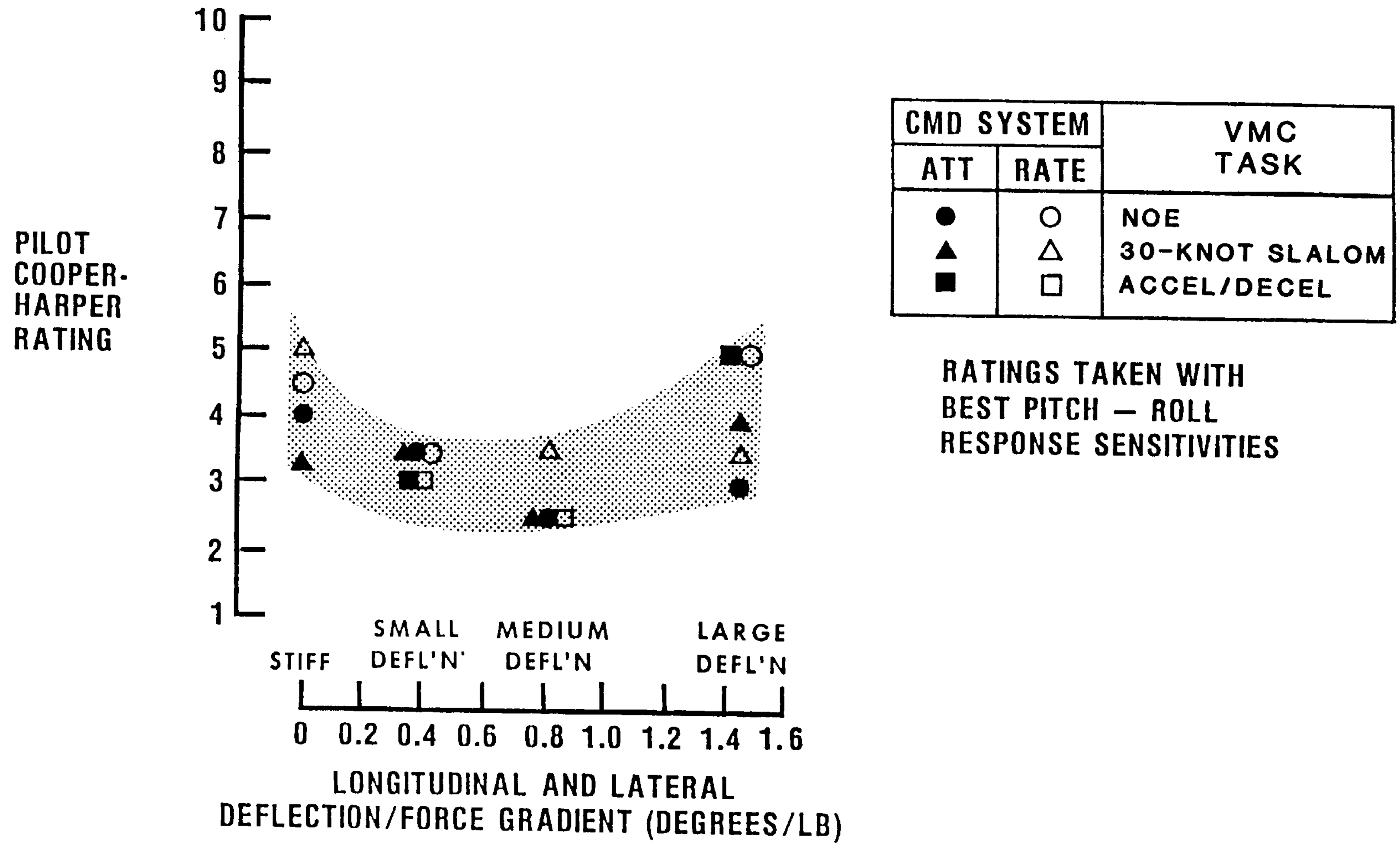


Figure 3-16

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 3-2

Based on the ACC/AFCS simulation results, design characteristics very similar to those of the MSI-SD3 controller were specified for the ADOCS demonstrator aircraft. The demonstrator controller will be manufactured by Lear Siegler, Inc. (LSI), Santa Monica, California. A brassboard controller very similar in design to the demonstrator unit was available for the final simulation period at NASA-Ames (Phase 2B). The Lear Siegler brassboard controller was also equipped with a grip similar to the one used on the MSI-SD3 controller and the controller evaluated during NAE flight testing (Reference 10). This grip was designed to improve the pilot's ability to apply single-axis vertical and directional inputs and to minimize inter-axis coupling of these inputs. Comparable ratings were obtained with the LSI Brassboard and MSI-SD3 controllers, therefore, the LSI unit was used for the majority of Phase 2B simulation testing (Reference 17).

3.6 RESPONSE/FORCE SENSITIVITY CHARACTERISTICS

Information obtained from the literature review emphasized the many variables affecting the development of an optimum set of controller response/force characteristics. Variables to be considered include:

- Aircraft type
- Controller design characteristics (force/deflection gradients, control axes integrated on controller, etc.)
- Command system type
- Pilot personal preferences
- Evaluation tasks
- Stability augmentation level

The importance of force/response sensitivity was noted in many of the studies reviewed. Pilots who participated in Sjoberg's experiment (Reference 2) cited the light forces required in maneuvering as a major factor providing reduced workload with the SSC. In other fixed-wing SSC studies, such as those conducted using an F-104 (Reference 3), varying controller sensitivity without also modifying force/deflection characteristics resulted in situations where full deflection of the control surfaces was not possible. This circumstance illustrates the importance of considering the interaction of all the SSC parameters while defining design parametric evaluations. This same study found that higher sensitivities resulted in Pilot Induced Oscillations (PIO).

The summary of SSC design criteria contained in an AFFDL technical report (Reference 12), addressed the specification of force/response sensitivities and shaping characteristics for a two-axis SSC. Based on Air Force testing with a fixed-wing aircraft, two design guidelines for control response characteristics were given as follows:

(1) Non-linear force/response gradients are preferred with the final slope being no more than twice the initial slope.

(2) Symmetric force/response shaping is recommended for longitudinal and lateral control. However, some data support a requirement for higher response sensitivity gain for right roll control than for left roll control commands.

The range of lateral force/response gradient and shaping characteristics evaluated by the Air Force (References 12 and 14) is shown in Figure 3-17. A preferred region of "medium" sensitivity is identified for the vehicle tested. Non-linear response shaping was also found to be important when implementing a side-stick for helicopter control. As documented in References 8 and 10, human arm/wrist motion limits must be considered. The lateral response shaping derived for an Advanced Scout Helicopter (ASH) from a simulation study at Boeing (Reference 8) is shown for comparison in Figure 3-17. Similar response shaping and sensitivity gains resulted for both vehicles with a benefit of asymmetric shaping identified for the ASH. A requirement for a higher response sensitivity gain for right roll control than for left roll control commands was suggested by the ASH data. However, this result may be due to the fact that the side-stick controller installed for the ASH simulation study was fixed with its rotational pitch and roll axes aligned with the aircraft body axes.

Variation of the controller orientation for anthropometric considerations was not performed during this study and a requirement for asymmetric shaping could have been influenced by the controller installation.

Conclusions from the NAE flight testing of a 4-axis side-stick controller identified a requirement for asymmetric response/force characteristics for the vertical axis when collective control was effected through the right-hand SSC. Shaping was employed which produced a 3:2 ratio of down to up aircraft response sensitivity for the same magnitude of force input.

An abundance of information exists in literature concerning the selection of satisfactory, or "optimum", control response characteristics for VTOL aircraft. Most of the information is developed for conventional displacement-type controllers, that is, a center-stick with relatively large motion compared to a side-stick controller with very small motion. Conventional displacement helicopter controllers with force-trim capability typically have 5.0 inches of total motion at the grip for pitch and roll control. Control force/deflection gradients about the trim position are relatively low for the conventional controls, and are tailored for both small precision hover tasks and larger forward flight maneuvers.

LATERAL CONTROL FORCE/RESPONSE GAINS

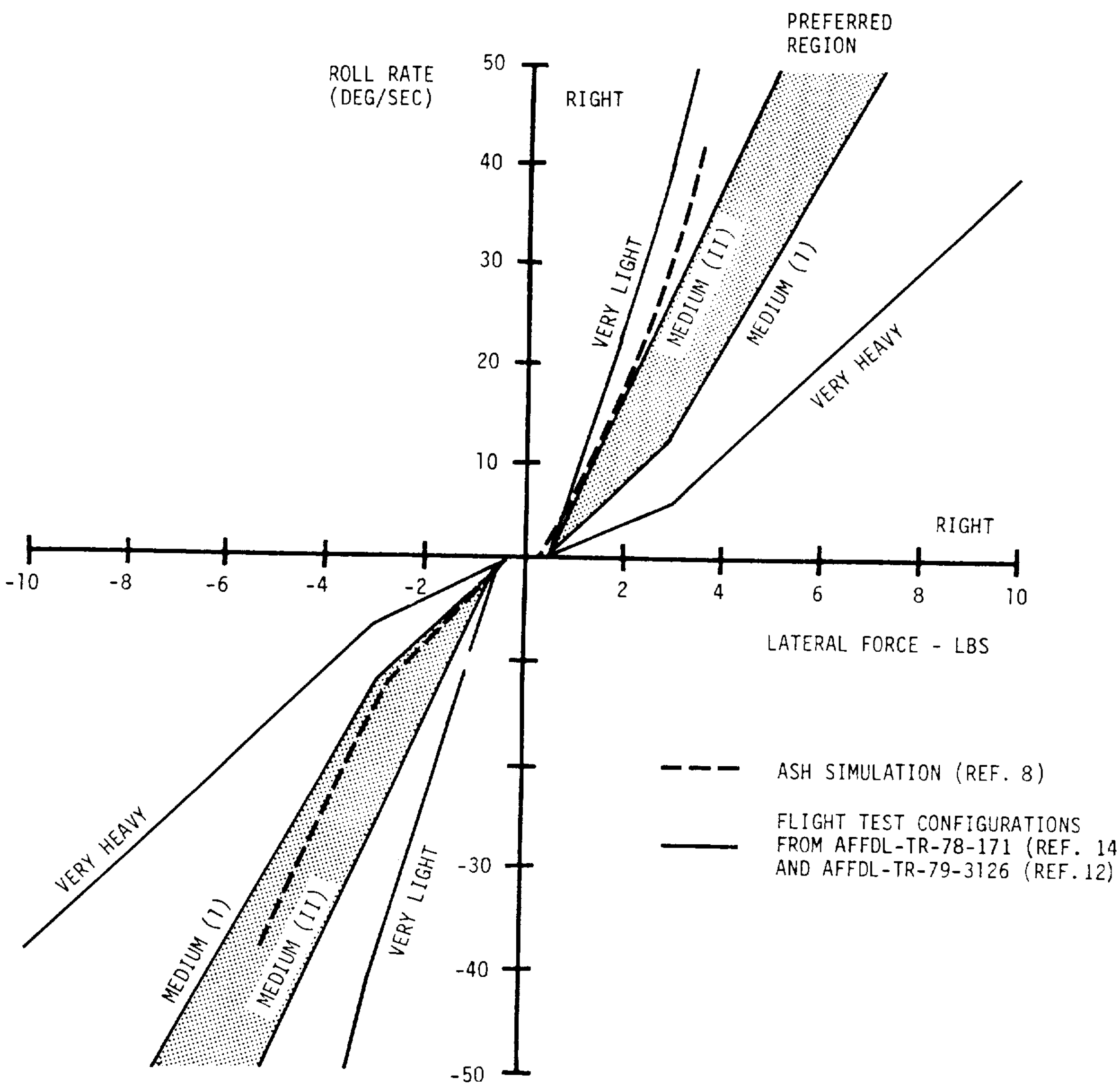


Figure 3-17

Typical examples of data specifying desired control response characteristics are presented in References 18 and 19. The effect of controller sensitivity in hovering flight was examined in Reference 18 using the NASA Ames six-degree-of-freedom simulator with 1:1 motion gains. A parametric study was performed to optimize longitudinal and lateral control sensitivity values using pilot Cooper-Harper ratings as the primary criteria. Results from Reference 18 were also presented in Reference 19 in a more concise manner. Figure 3-18 was obtained from Reference 19 and shows preferred ranges of sensitivity for three command system types including an acceleration, rate, and attitude system. Optimum values of damping and frequency (stiffness) are also specified for a generalized aircraft model representation. Optimum design values for a translational rate (velocity) command system were developed in the study of Reference 20. Results from Reference 20 which were also presented in Reference 19 are summarized in Figure 3-19.

It should be noted that the preferred ranges of sensitivity defined for each command system type in Reference 19 are given for a conventional displacement controller in terms of centimeters (cm) of controller deflection. Little published data were available for desired response/force characteristics for a helicopter employing a side-stick force controller. Therefore, a preliminary test phase during Phase 1 simulation at Boeing Vertol was directed strictly to the selection of a desired set of response/force characteristics for a side-stick controller. This initial phase of simulation was necessary to investigate the large number of combinations of controller configurations and generic command response types under consideration for the ADOCS demonstrator aircraft. Further discussion of the testing procedure used to define the desired response characteristics for a limited-motion or "stiff" side-stick force controller design is given in the Command Model Design (Section 4.2.2) of the Control System Design section, of this report.

OPTIMUM CONTROL SENSITIVITIES FOR ACCELERATION, RATE, AND ATTITUDE COMMAND SYSTEMS

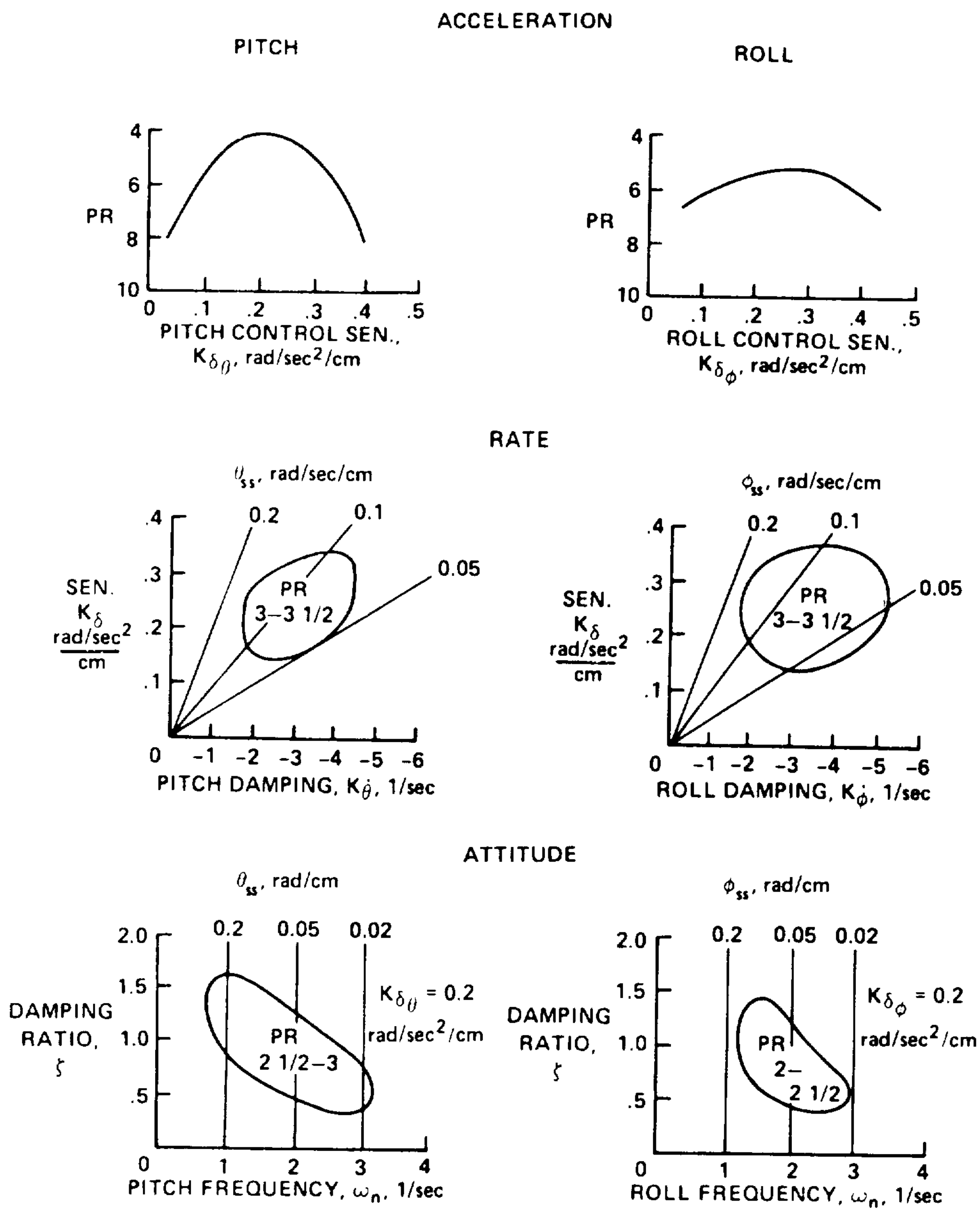


FIGURE FROM REF. 19

Figure 3-18

OPTIMUM CHARACTERISTICS FOR TRANSLATIONAL RATE COMMAND SYSTEM

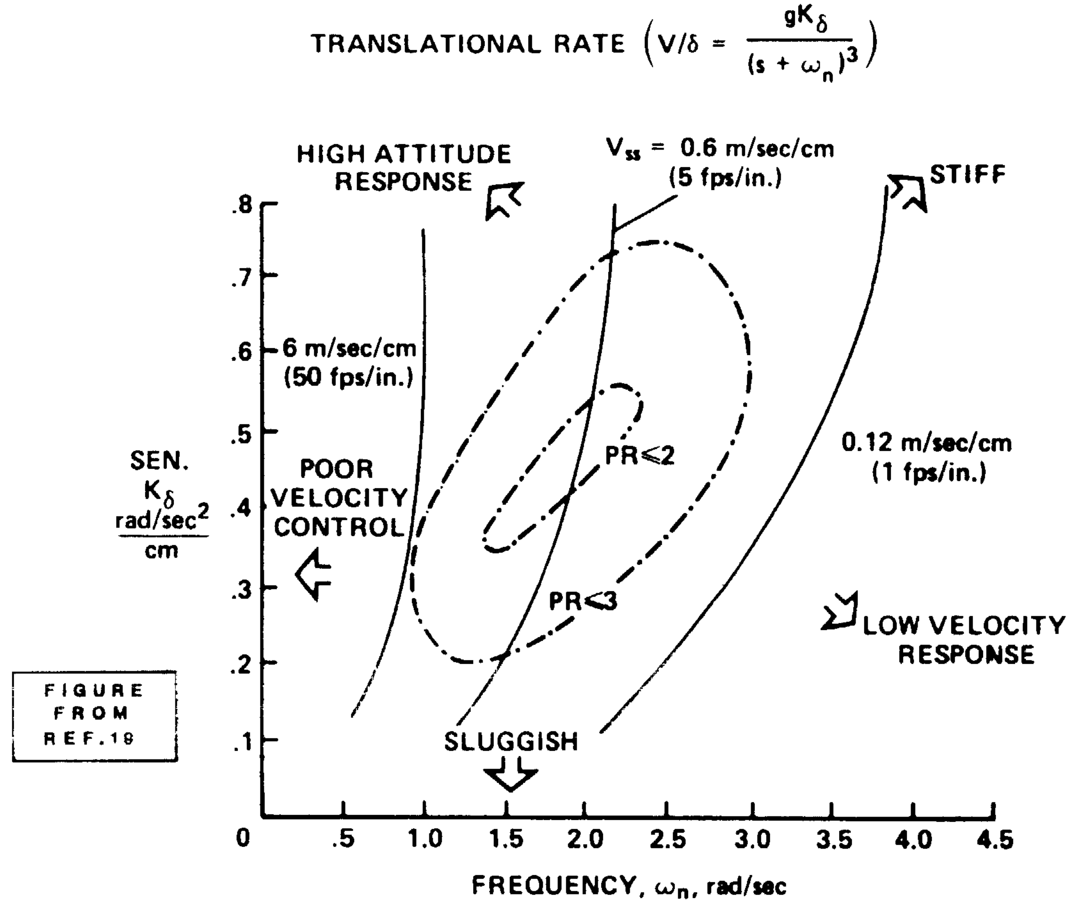


Figure 3-19

4.0 CONTROL SYSTEM DESIGN

Previous control law development conducted by Boeing Vertol during the TAGS (Reference 6) and HLH (References 21 and 22) programs provided an important technology data base and valuable experience to guide design of control laws for an attack helicopter employing an advanced flight control system. The TAGS and HLH flight control systems were advanced designs employing digital flight control processors and side-arm force controllers. Therefore, results from these programs are directly applicable for the ADOCS design. Trade studies performed during both programs are reviewed below along with associated simulation and flight test results.

The HLH Fly-By-Wire (FBW) flight control system (Figure 4-1) was divided into two parts: (1) a Primary Flight Control System (PFCS), and (2) an Automatic Flight Control System (AFCS). The PFCS consisted of flight critical control elements and control paths which formed an "electrical linkage" between the cockpit controls and the rotor actuators. The AFCS provided stability and control augmentation along with autopilot type functions. The various control modes required for each segment of the HLH mission were controlled through the AFCS.

Rationale given in Reference 22 for separating the PFCS and AFCS includes:

- Ultimate flight safety need only be insured through the PFCS allowing the AFCS to be as complex as required.
- AFCS optimization can be carried out independent of the PFCS.
- The PFCS and AFCS can utilize different redundancy management levels and techniques.
- PFCS and AFCS digital computations can be completed using different computation time frames.

Unlike the HLH design, the TAGS aircraft (Reference 6) maintained a direct mechanical link between the cockpit controllers and the rotor controls. A digital PFCS sacrifices this direct mechanical link design approach, but offers several advantages particularly significant when implementing a side-stick as the primary pilot controller. Important advantages of a digital PFCS design are summarized as follows:

- Non-linear force/response characteristics required for a SSC can be easily programmed in the digital flight control processor
- Desired feed-forward command shaping for both AFCS ON and AFCS OFF operation can be easily implemented.

HLH FLIGHT CONTROL SYSTEM CONFIGURATION

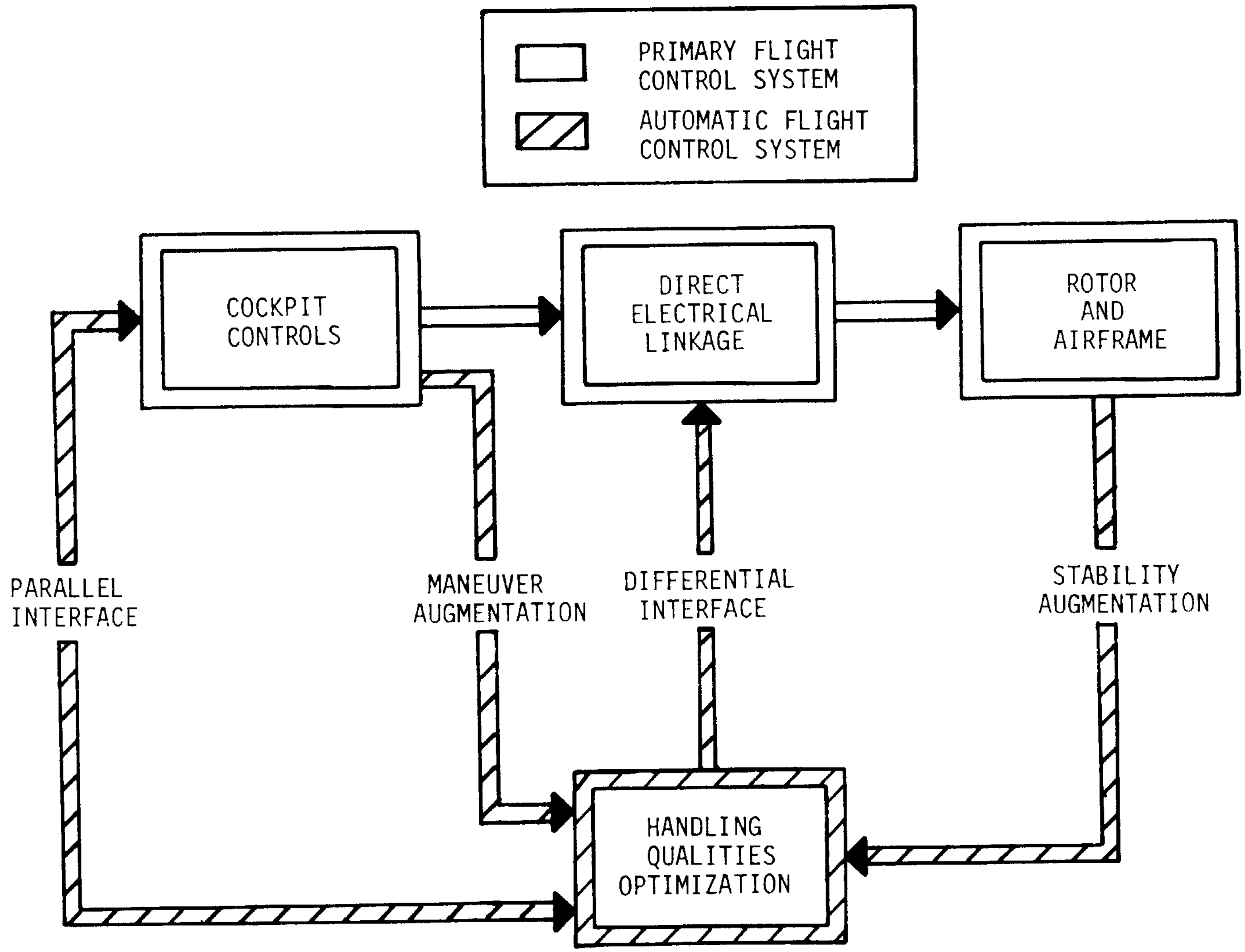


Figure 4-1

- o Automatic force trimming functions and logic can be incorporated as part of software, thereby eliminating mechanical force trimming hardware.
- o Improved reliability/survivability can be attained through redundant paths.
- o Mechanical anomalies such as backlash and slop) which inhibit precise control can be eliminated.
- o A full-authority AFCS with appropriate PFCS interface limiting can be designed for safety.

Benefits provided by separation of AFCS and PFCS functions as well as digital processing of control laws led to the conceptual ADOCS design approach shown in Figure 4-2. Implementation of the generic control systems evaluated during the ACC/AFCS study and development of the ADOCS demonstrator flight control system design were performed utilizing this design approach. The use of this system formulation allows flexibility for development of handling qualities requirements while still considering aspects of hardware design and redundancy management. Major advantages of this system design approach for control law development are:

- o Satisfactory unagumented 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.
- 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.

A functional description of the PFCS and AFCS including details of the analytical methods employed to define specific control system parameters and characteristics is provided in the following paragraphs.

ADOCS FLIGHT CONTROL SYSTEM CONCEPT

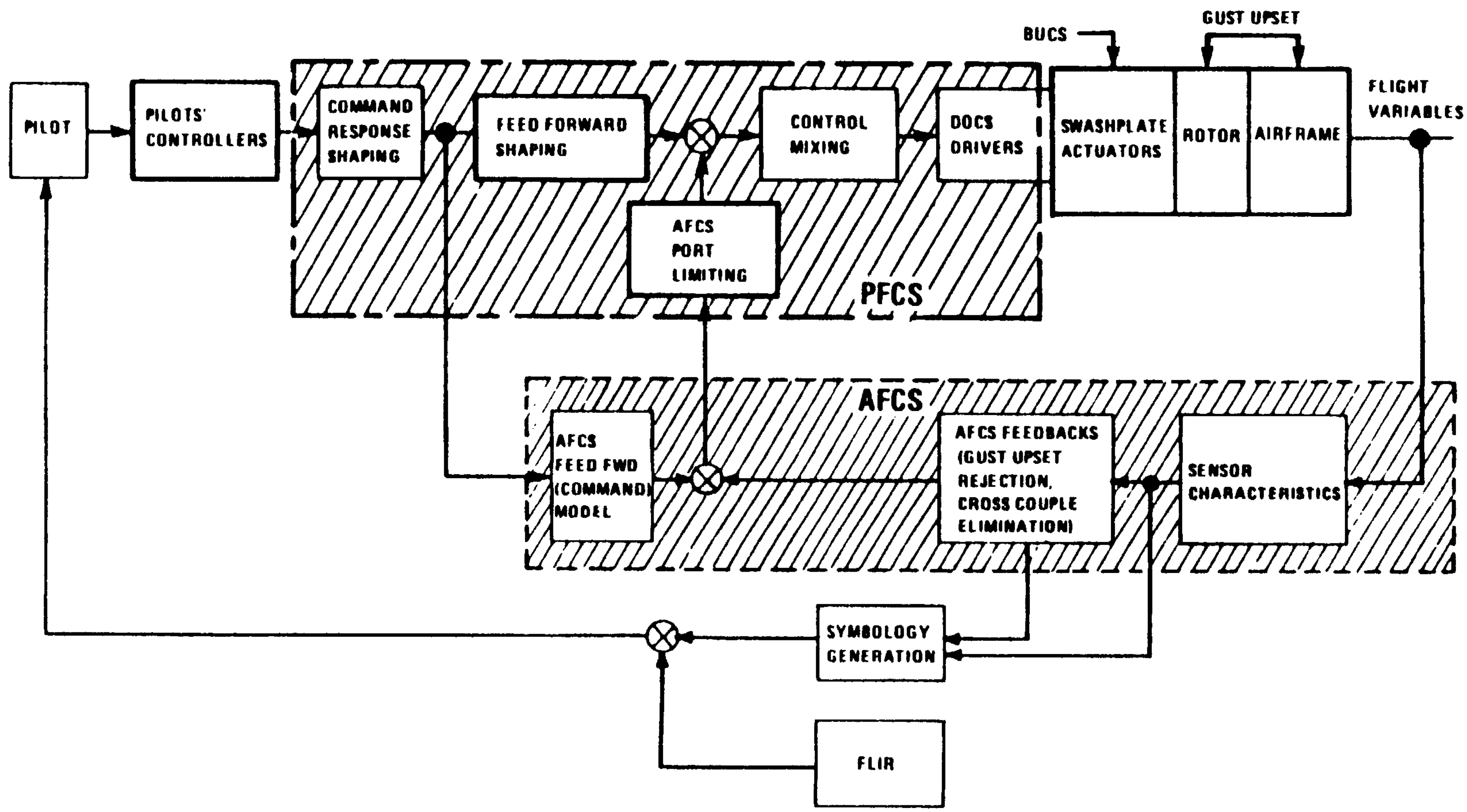


Figure 4-2

4.1 PFCS DESIGN

The PFCS design mechanization implemented for the ACC/AFCS study is illustrated in the block diagram of Figure 4-3. With the exception of AFCS port limiting, all the PFCS elements shown were included in the control system model evaluated during piloted simulation at Boeing (Phase 1) and NASA-Ames (Phase 2). AFCS limiting was not incuded during control law evaluation to eliminate any possible effects of authority or rate limits on pilot ratings and/or performance. Significant features of the PFCS design are described in the following discussion.

Force Transducer Quantization

Piloted simulation experiments were conducted at Boeing as part of the ADOCS Demonstrator Program to quantify the effects of controller force signal resolution and provide guidelines for specification of quantization requirements for the digital/optical controller force transducer. Pilot input force resolution was varied between an analog (non-quantized) signal and 1.0 lb digital increments. The pilot was requested to record any handling quality changes in terms of Cooper-Harper ratings during both IMC and VMC tasks (NOE, SLALOM and AFCS OFF). Typical results are shown for the lateral control axis in Figure 4-4 for the NOE Task with an attitude command/velocity stabilization system.

The pilot could not perceive changes in performance when aircraft peak rate response resolution was less than .54 deg/sec/lb (0.08 lb). A 1.08 deg/sec/lb (0.16 lb) peak rate response resolution was perceptible to the pilot but no significant control degradation was observed. Attitude control was degraded between 1.08 deg/sec/lb and 4.1 deg/sec/lb with the roll axis being most noticeable and providing the earliest cue of handling qualities degradation. At resolutions above 4.1 deg/sec/lb, roll control became particularly difficult and degraded faster than the other three control axes (pitch, yaw and vertical). The effect of large resolution step size was manifested as a large "freeplay" or an apparent deadzone. With larger force resolution in all axes it was easier to make single axis control inputs (i.e., cross-coupling was inhibitied).

ACC/AFCS simulation studies conducted at NASA-Ames also showed that 8-bit signal quantization did not have a noticeable effect on pilot ratings or task performance when compared to smaller values of force/response resolution. 8-bit force signal quantization was selected for the 4-axis controller in the demonstrator aircraft to provide acceptable response resolution in each axis. Controller resolution in terms of force and equivalent aircraft response for the demonstrator controller design is summarized in Table 4-1.

ADOCS PFCS DESIGN

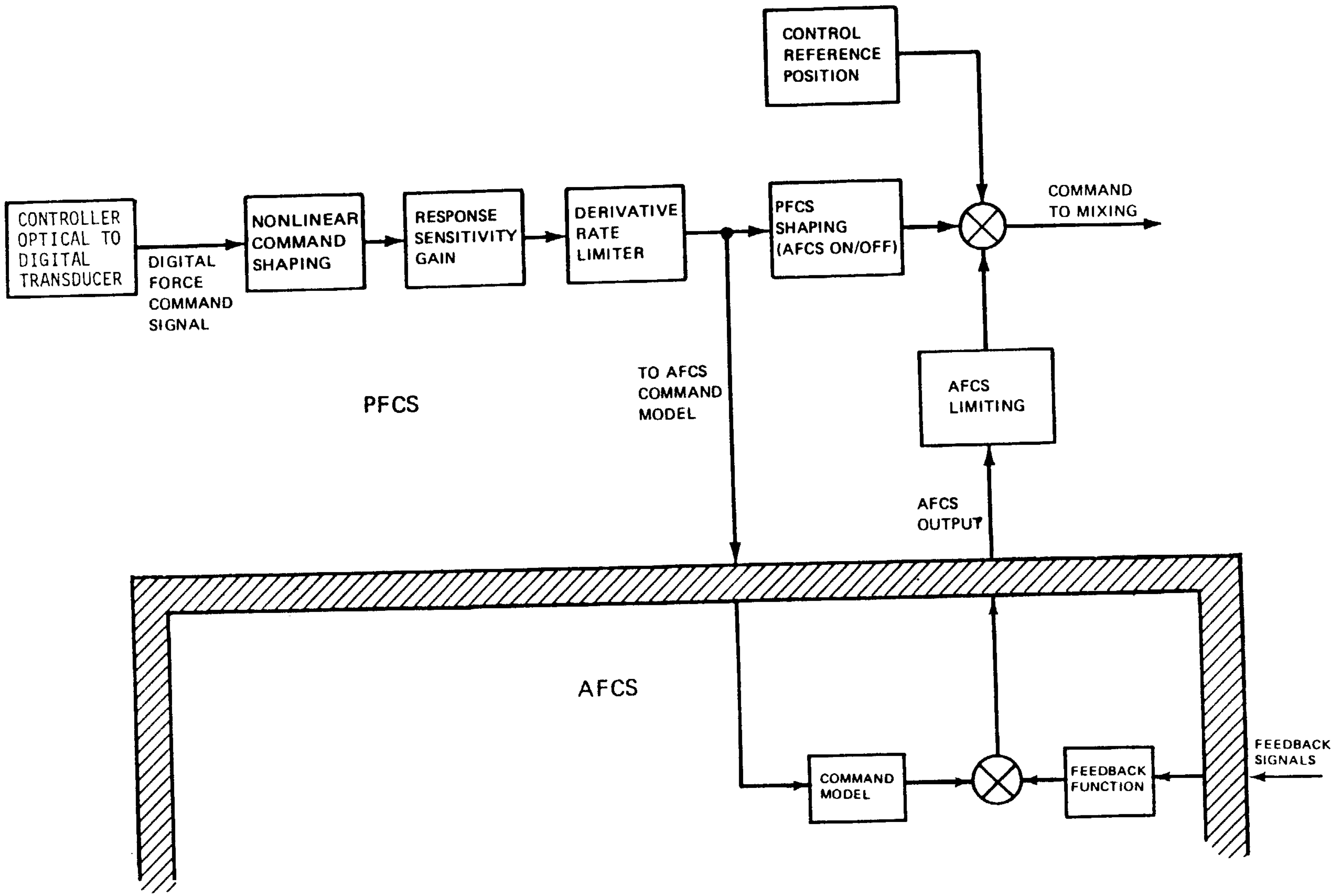


Figure 4-3

CONTROLLER FORCE INPUT QUANTIZATION EVALUATION

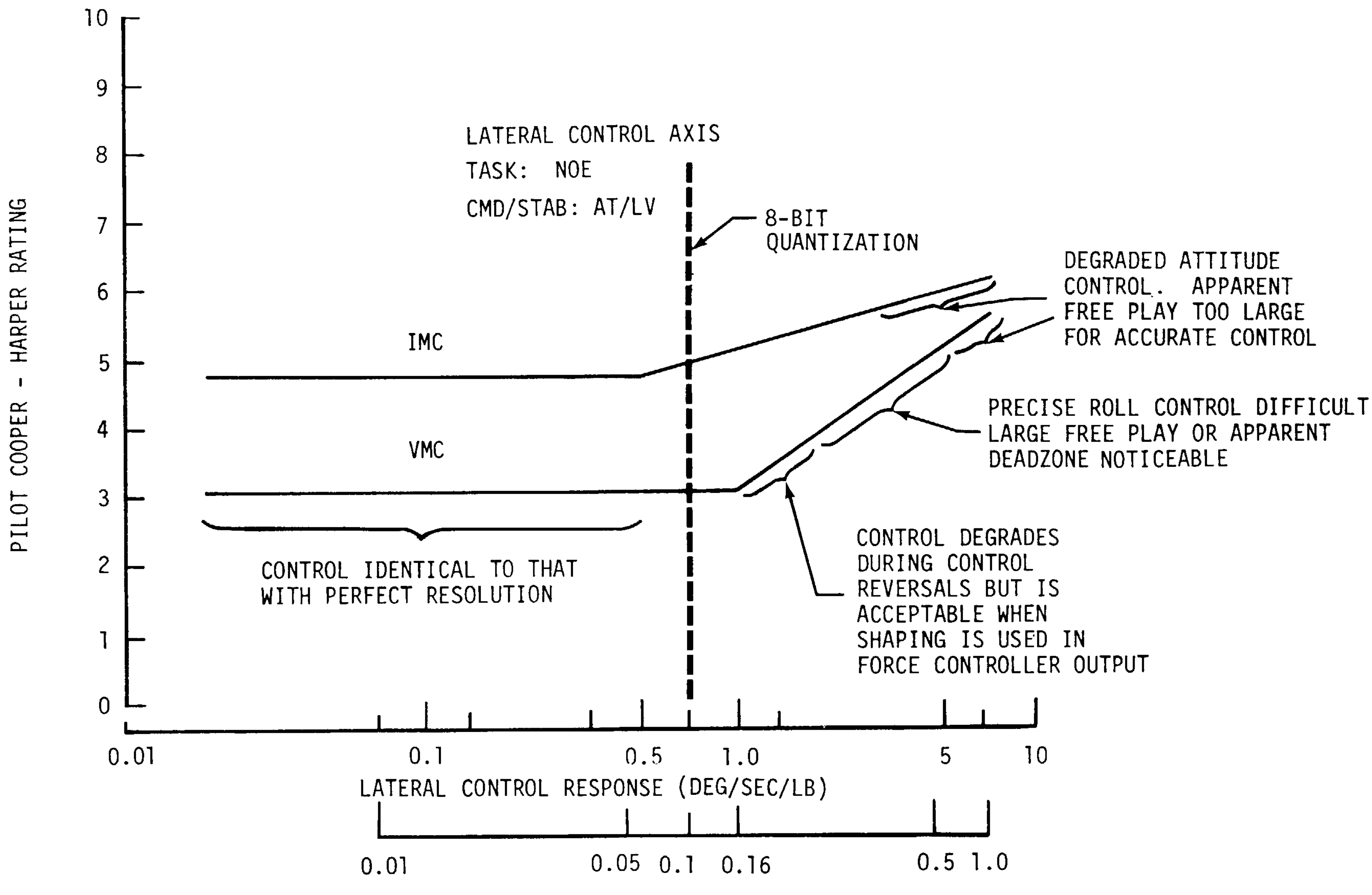


Figure 4-4

TABLE 4-1
SUMMARY OF CONTROLLER RESOLUTION

Controller Axis	Maximum Operating Range	Force Resolution "8 bit" Quantization	Aircraft Peak Rate Response Resolution
Longitudinal	±15.9 lbs	.12 lbs	.42 deg/sec
Lateral	±12.8 lbs	.10 lbs	.6 deg/sec
Directional	±35 in lbs	.27 in lbs	.6 deg/sec
Vertical	±15.8 lbs	.12 lbs	.36 ft/sec

Non-Linear Command Response Sensitivity

To provide acceptable response characteristics for both small precision control tasks and large maneuvers, non-linear command shaping as discussed in Section 3.6 is required. Shaping is provided in each axis by a dead-zone and a control sensitivity function made up of a number of segments of increasing response/force sensitivity. In all axes less sensitivity was provided for lower values of control force. In the longitudinal and lateral axes, the shaping function was symmetrical about zero force input; the vertical and directional shaping functions were asymmetric to compensate for the comparative difficulty of exerting a downward versus an upward force and a right versus a left twist, respectively, on a right-hand sidestick controller. Control shaping implemented in the longitudinal axis is presented in Figure 4-5 as an example. This shaping function shows command in equivalent inches of conventional control displacement as a function of controller force input. Final response shaping functions for all control axes are given in Volume 3 - Simulation Results and Recommendations.

Derivative Rate Limiter

Rapid release of large control forces, which are common when using a force controller, often induce undesired high acceleration jerks in aircraft response. A derivative rate limiter (Figure 4-6) was implemented as part of the PFCS for Phase 2 simulation at NASA-Ames to limit the magnitude of initial acceleration response which the pilot can experience while performing rapid maneuvers and/or control reversals.

Experiments to develop the derivative rate limiter were conducted during the preliminary design phase of the ADOCS program. The derivative rate limiter characteristics were selected for each of the control axes by adjusting the network rate limit and time constant parameters to provide acceptable response characteristics for large maneuvers. The effect of the rate limit is to control the initial peak acceleration response to a step control input. As shown in Figure 4-7, an infinite rate limit passes a step input as a proportional path; a rate limit of zero produces a pure lag response with a time

LONGITUDINAL CONTROL RESPONSE SHAPING

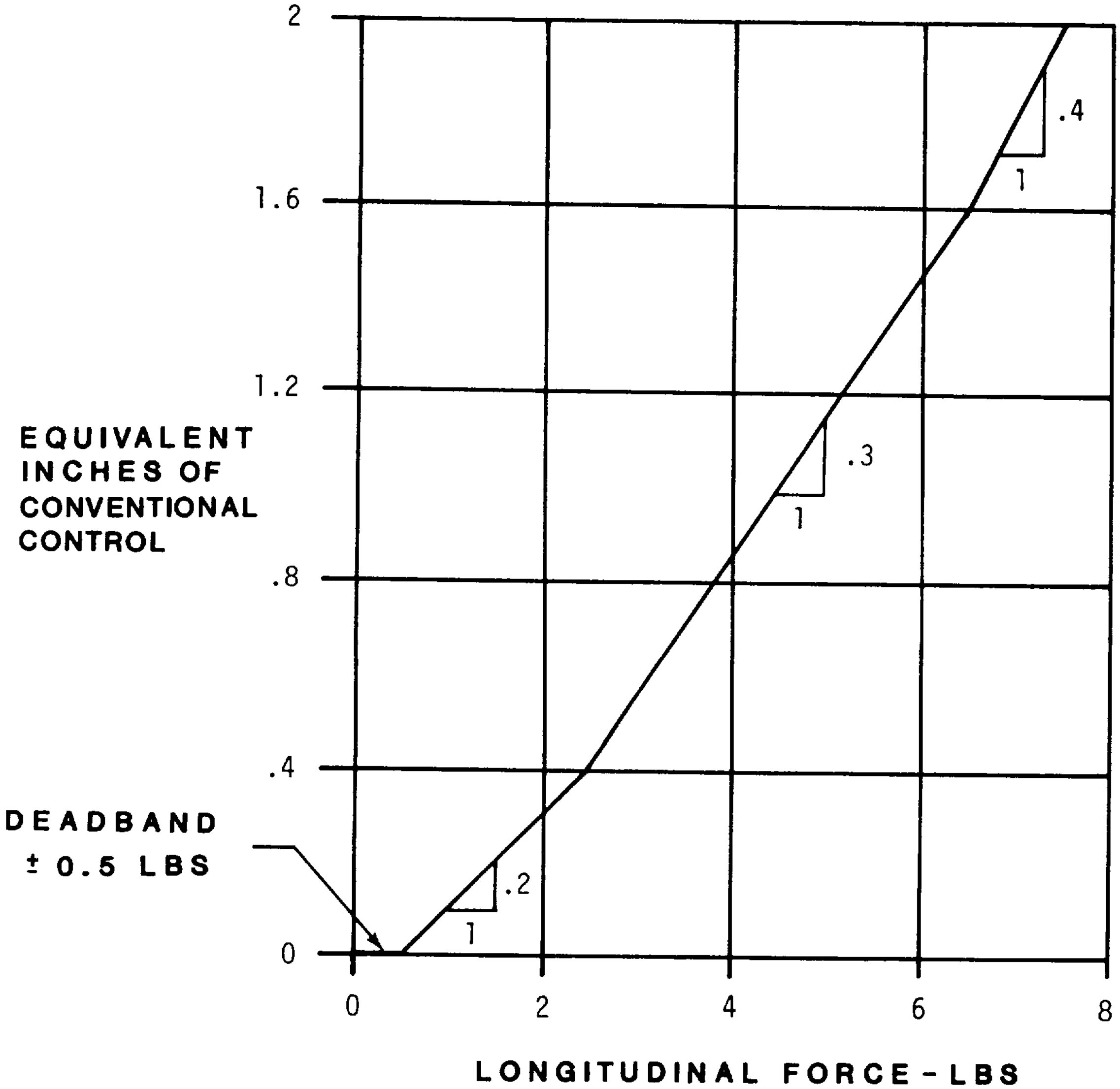


Figure 4-5

DERIVATIVE RATE LIMITER

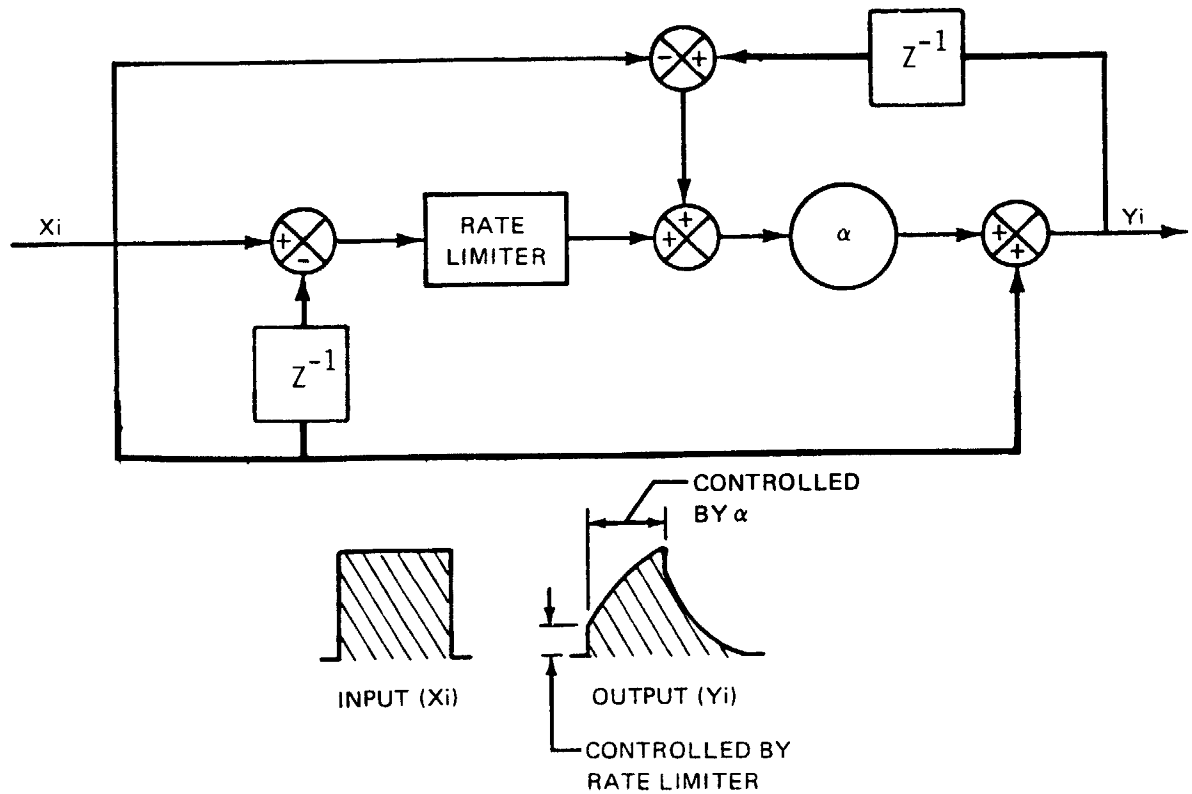


Figure 4-6

REDUCTION OF PEAK ACCELERATIONS WITH A DERIVATIVE RATE LIMITER

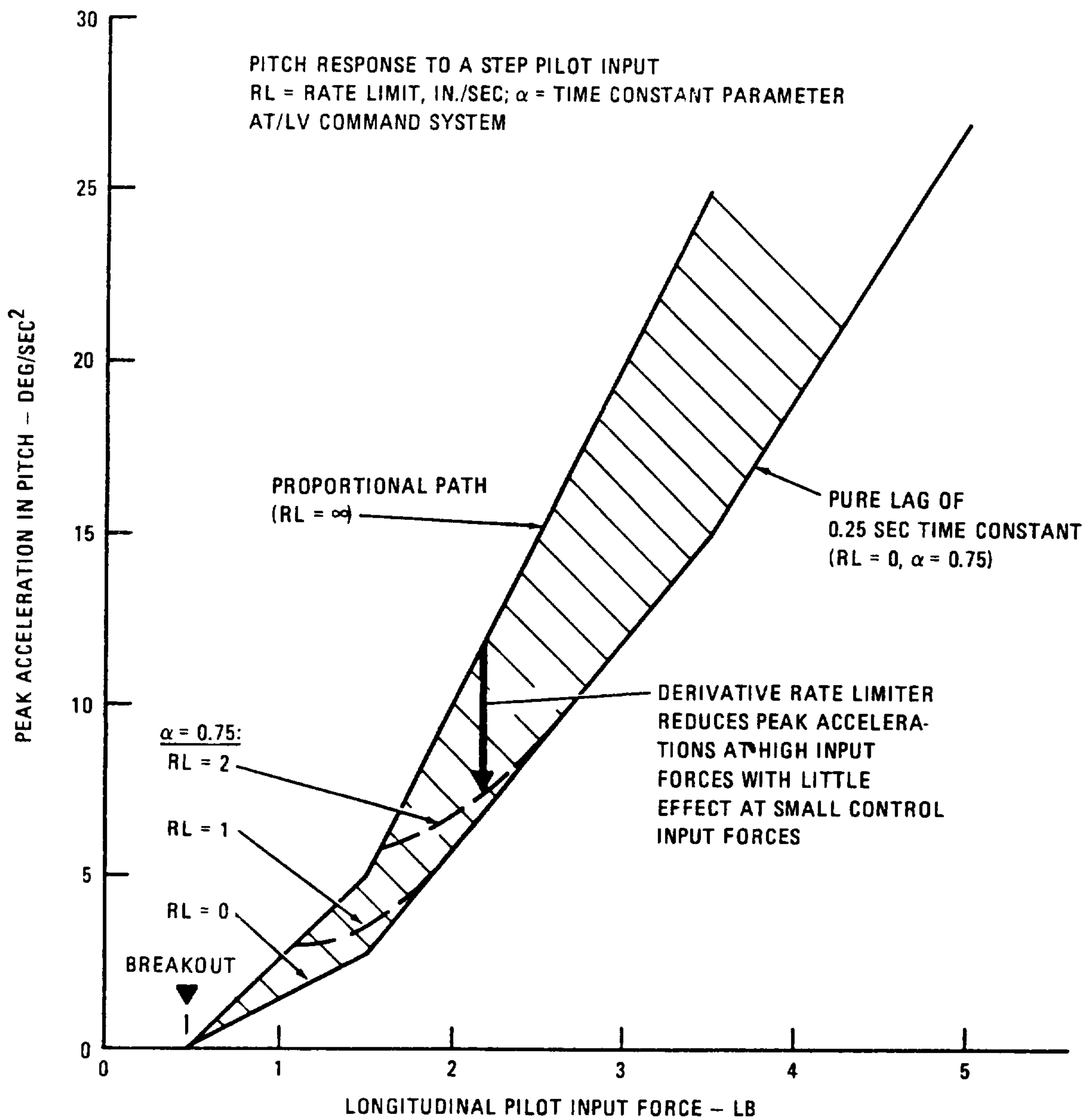


Figure 4-7

constant controlled by the network parameter α. A large variation of response characteristics is possible by changing the network rate limit (RL) and time constant (α) parameter values. A good control response balance is obtained when RL and α parameters are selected to limit peak accelerations for large control inputs without affecting control precision for small force inputs.

PFCS Shaping/Trim Functions

PFCS command signal shaping and trim functions are implemented as shown in Figure 4-8. Forward path lead-lag shaping is provided full-time for AFCS ON or AFCS OFF operation. Time constant values (τ_{LD} and τ_{LG}) are selected for AFCS OFF flight conditions to cancel inherent helicopter roots while substituting more desirable response mode characteristics. With AFCS ON the lead-lag shaping configuration supplements the AFCS command model, and yields a total command output to the helicopter that more closely matches the desired or actual response characteristics. Two benefits derived from implementation of lead-lag shaping in the PFCS are: (1) a balanced design that results in smaller transient AFCS output signals during dynamic maneuvers with AFCS ON, and (2) improved AFCS OFF response characteristics through the effect of control "quickening".

Based on redundancy management issues related to the ADOCS design, such as cross-channel equalization, powerup, power interrupt, and failure modes; it was decided to eliminate forward path open-loop integrators from the PFCS design. Open-loop integrators are still included within the AFCS command model for automatic force trimming with AFCS ON. In the PFCS however, high-gain, long-time constant lags are incorporated in place of open-loop integrators to provide comparable unaugmented handling qualities.

As shown in Figure 4-8, the high-gain, long-time constant lag path is activated during AFCS OFF flight by trim path engagement logic. A pilot trim switch is also included in the design to allow the pilot to trim forces to zero. Trim force requirements are slowly injected into the system through the long-time constant lag as shown. The pilot trim switch was only used during initial ACC/AFCS simulation studies investigating AFCS OFF flight, but was further evaluated as part of the ADOCS demonstrator program.

PFCS SHAPING/TRIM FUNCTIONS

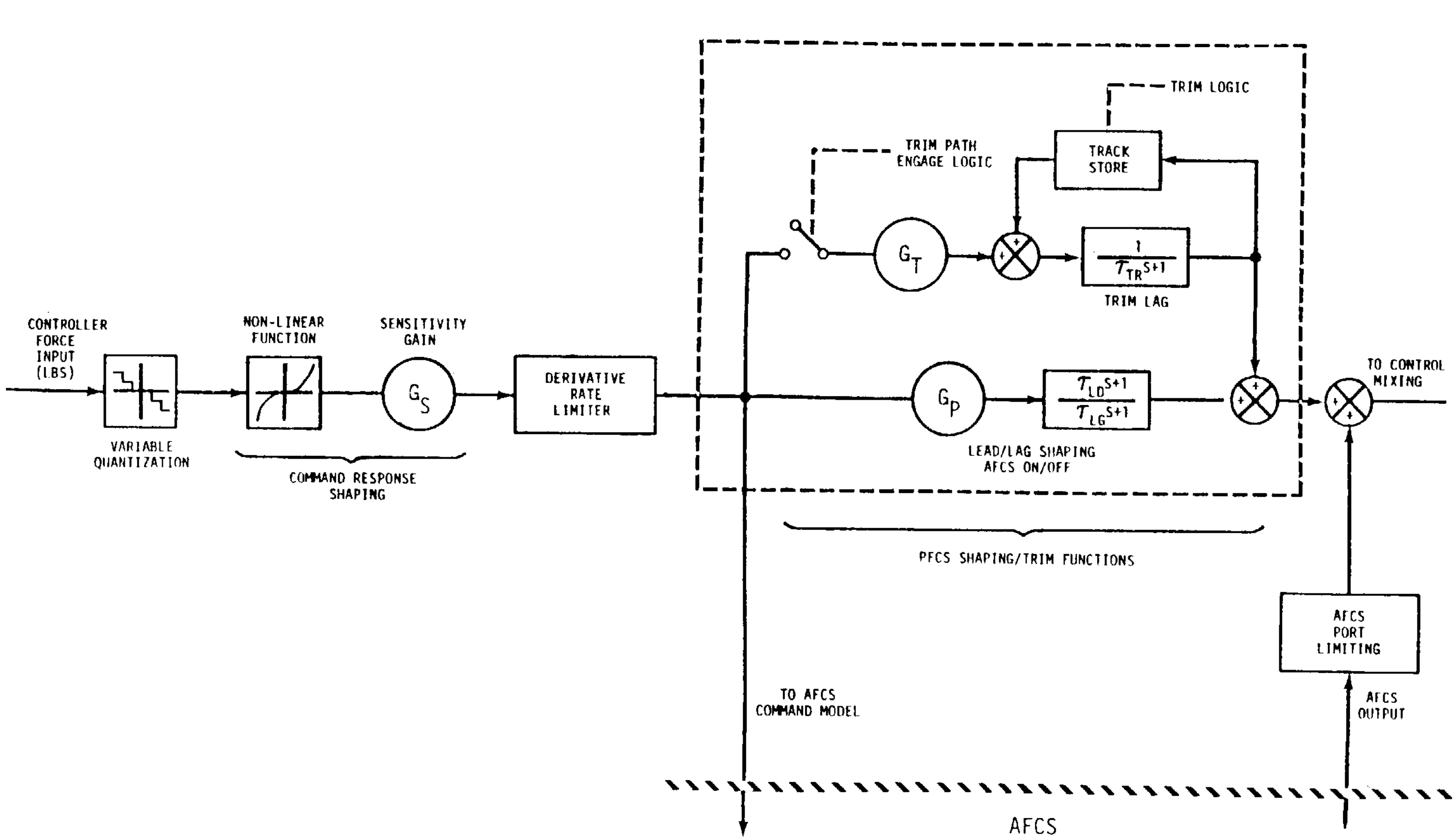


Figure 4-8

AFCS Port Limiting

The PFCS is designed to be active full-time with AFCS port limiting (Figure 4-9) providing a safeguard against AFCS hardover failures. All AFCS output signals pass through frequency-selection and limiting networks in the PFCS. The AFCS signals are split between a long-term trim and a high-frequency dynamic compensation path as shown in Figure 4-9. The trim path includes a high-authority limit and rate-limit for low-frequency trim signals such as directional or vertical control trim variations with airspeed. High-frequency stabilization signals pass through both authority limits with the lower limit dominating. A cross signal path from the rate limiter continually recenters the low-authority dynamic path. The interface network will ramp to zero after AFCS disengagement.

A sudden step transient into the system caused by an AFCS hardover is attenuated by the interface rate limit and low-authority limit. An example of the AFCS port limiter output response to a step input is also shown in Figure 4-9. Since hardover failures are introduced into the system in a controlled manner, adequate time is given to the pilot to take appropriate action.

As mentioned earlier, port limiting was not included in the ACC/AFCS simulation study to eliminate any possible effects of AFCS limiting on pilot ratings and system performance. Selection of limiting values was a task to be accomplished as part of the ADOCS demonstrator design effort, and no time was spent on this element of the PFCS design during the ACC/AFCS study.

4.2 AFCS DESIGN

The AFCS design permits investigation of a wide range of control laws with the complete flexibility required of an experimental system. AFCS configurations were analyzed using classical techniques with a pure time delay to account for digital computational effects. Based on the results of previous experimental studies (References 1, 18, and 26), various control system concepts were formulated to accomplish attack helicopter low speed/hover maneuvers. Prime Command/Stabilization (CMD/STAB) system candidates were designed for investigation during the ACC/AFCS study. Simulation data collected for the various CMD/STAB systems provide a substantiation for control system recommendations made for the ADOCS demonstrator aircraft. In addition, a data-base providing degraded-mode capabilities will be established and made available for future use.

The generic SCAS configurations chosen for evaluation are identified in Figure 4-10 in the form of a command response/stabilization (CMD/STAB) matrix. A simple system identification code (Figure 4-10) was established and is used extensively throughout all volumes of this report. The CMD/STAB notation first identifies the command response type and the STAB notation identifies the level of stability augmentation incorporated in

AFCS-PFCS INTERFACE LIMITER

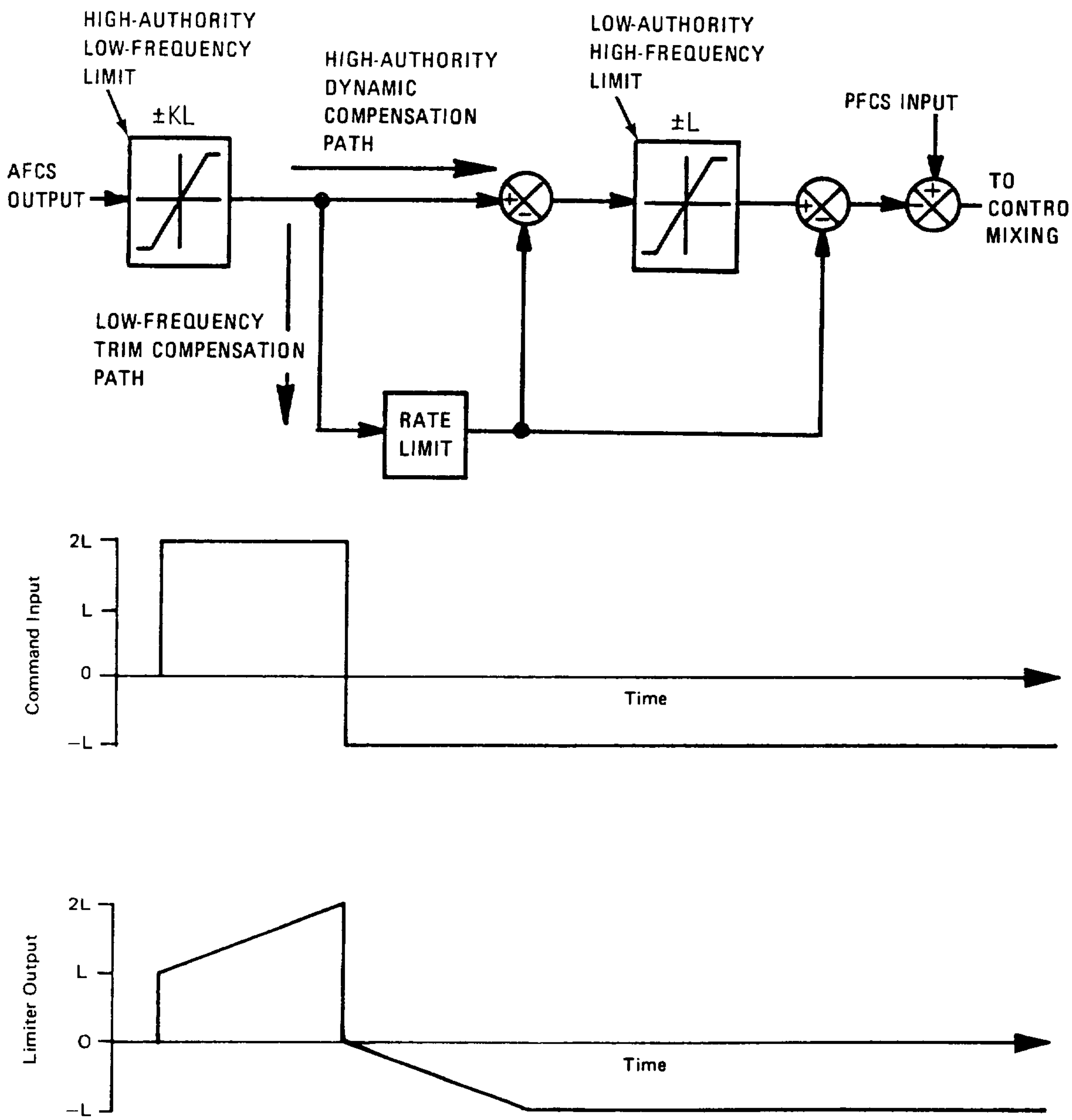


Figure 4-9

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 4-10

the control laws. Command response type refers to the steady-state response of the aircraft due to a step control input. For example, a system with angular rate command and attitude stabilization in pitch and roll was identified with the letter code RA/AT; a system having an attitude command response with velocity stabilization in pitch and roll was designated as an AT/LV system. Time history responses to a longitudinal control input are given in Figures 4-11, 4-12 and 4-13 for a rate, attitude, and velocity command system, respectively. Basic differences in the type of response provided each system can be easily seen. For instance, a rate command system exhibits a steady-state rate response proportional to applied force, and will return to zero rate when the control input is released thereby acquiring a new attitude trim condition. However, the attitude command system exhibits an attitude response proportional to input magnitude and returns to the original trim attitude condition when the control input is removed.

It should also be noted that the angular rate command system was designed to have identical control response characteristics for both the attitude and velocity stabilized systems, i.e. RA/AT and RA/LV. Similarly, the control response characteristics of the attitude command systems (AT/AT and AT/LV) were the same regardless of the level of stabilazation.

Initially all CMD/STAB systems identified by a shaded circle in Figure 4-10 were mechanized for evaluation, however some were found unacceptable during Phase 1 simulation and eliminated from evaluation during Phase 2 (See Volume 3 - Simulation Results and Recommendations, and Reference 11).

The design methodology used to synthesize the AFCS in its generic form is presented in the following sections. The discussion is divided according to the two main parts of the AFCS implementations:

(1) Stabilization Feedback Loops

(2) Feed-Forward Command Augmentation

4.2.1 Stabilization Loop Design

Because a variety of control laws are required to accomplish mission tasks defined for an attack helicopter, such as Nap-of-Earth flight, Precision Hover, and Bob-up) a full complement of stabilization levels was synthesized for simulation evaluation. Stabilization systems ranged in complexity from a simple, single-feedback, rate-damped system to a multi-feedback, complex position-hold system. A preliminary analysis effort described below was performed to define nominal gain values for each of the stabilization systems. Final data and results of the simulation are presented in Volume 3 to show the effect of stabilization level on handling qualities as measured by pilot Cooper-Harper ratings (Reference 23).

LONGITUDINAL RATE COMMAND SYSTEM RESPONSE

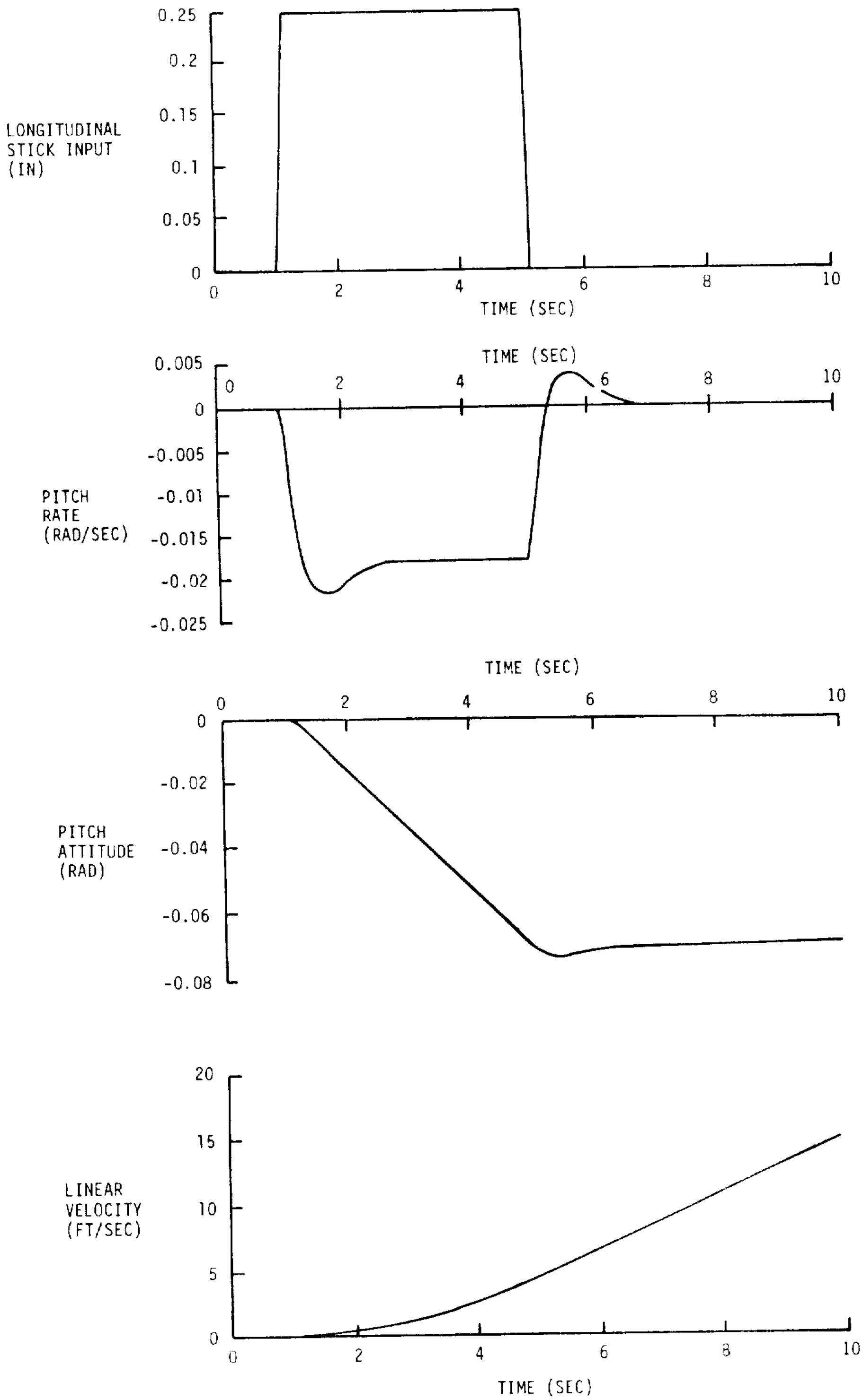


Figure 4-11

LONGITUDINAL ATTITUDE COMMAND SYSTEM RESPONSE

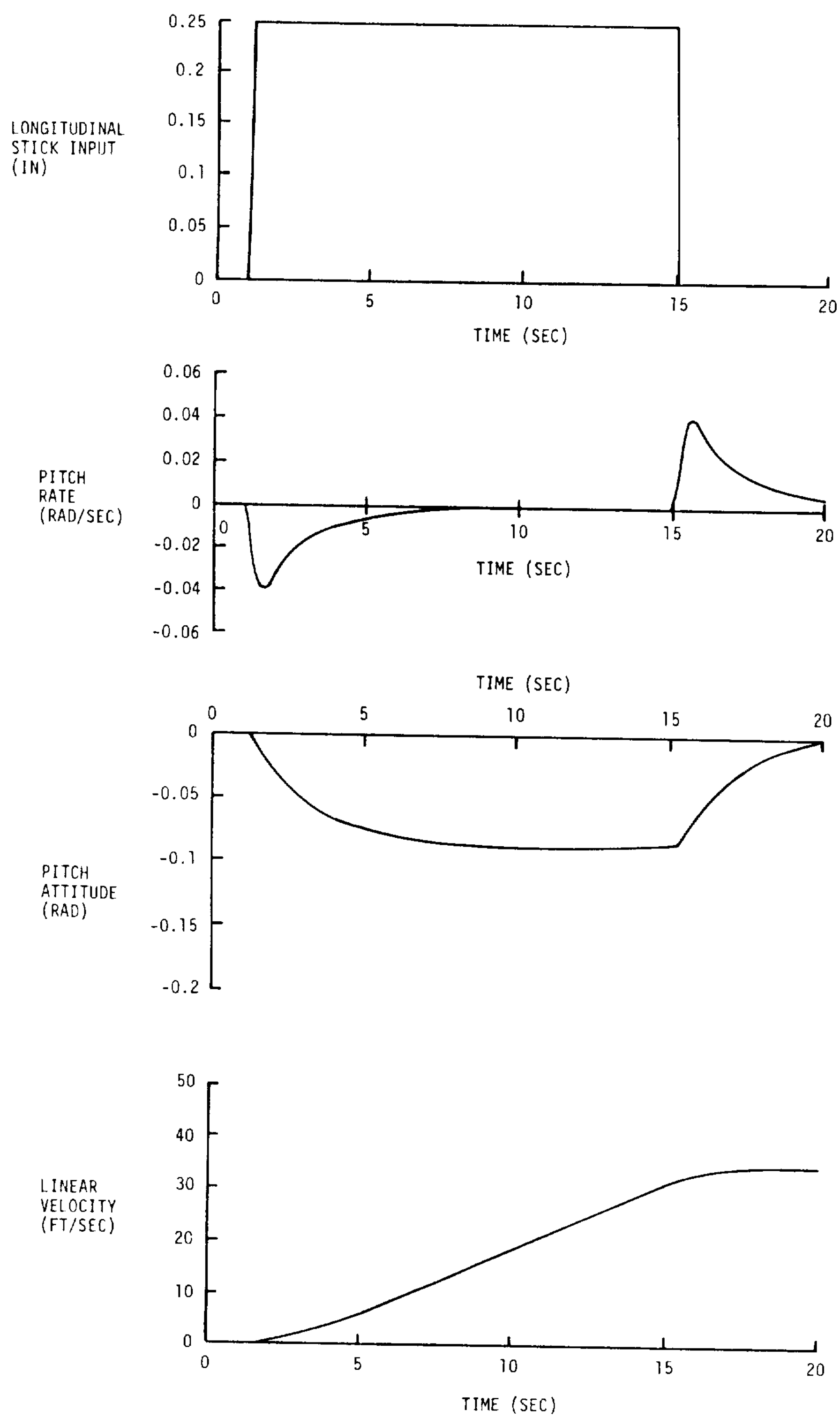


Figure 4-12

LONGITUDINAL LINEAR VELOCITY COMMAND SYSTEM RESPONSE

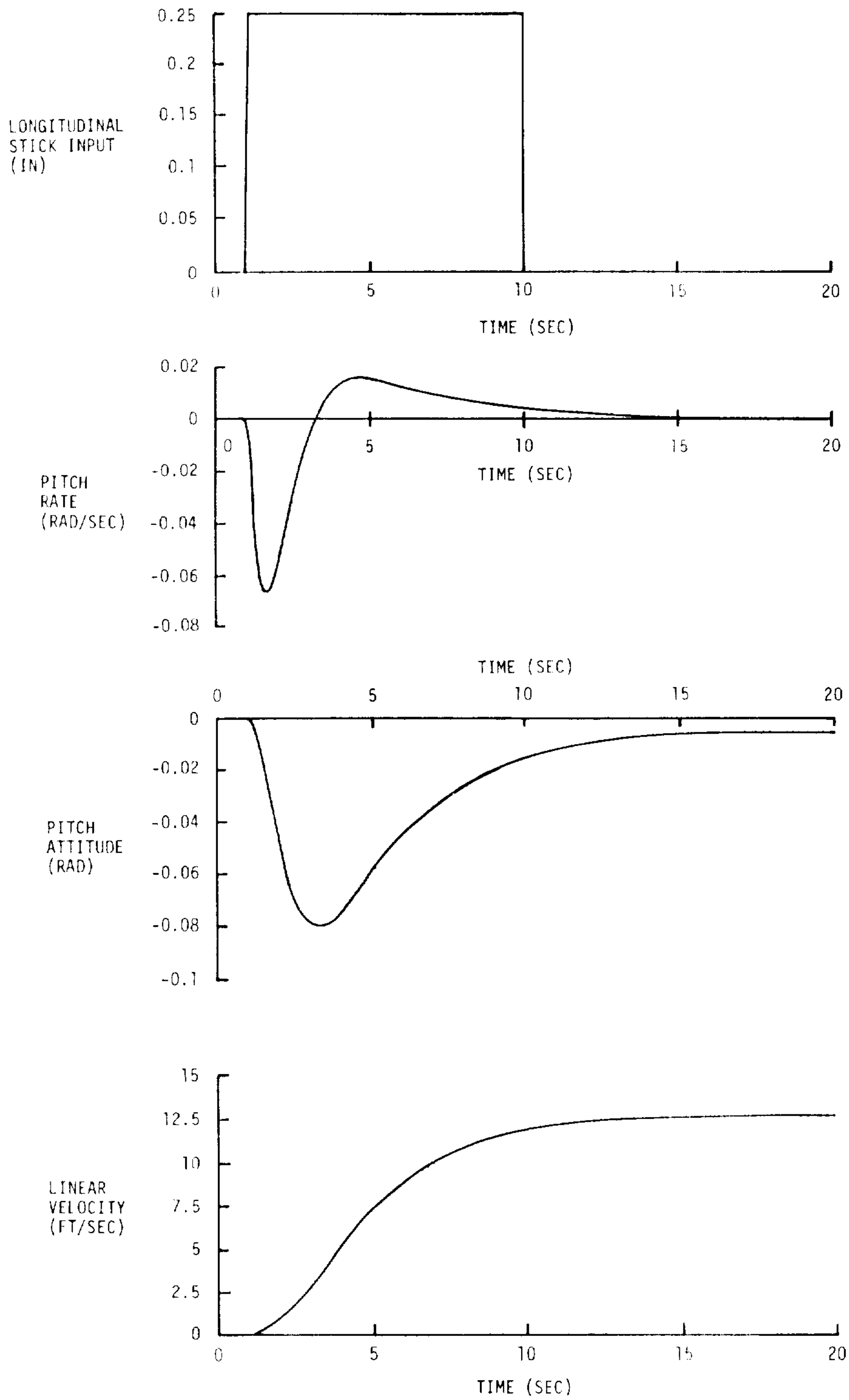


Figure 4-13

Stabilization loop requirements were determined through classical design methods such as root-locus, Bode plot and Nichols chart analyses. A response damping requirement to achieve good gust rejection characteristics was used as a design criteria to determine initial stabilization gain requirements. Based on experience gained from previous flight control programs (i.e. TAGS, HLH, and LAMPS), feedback gains were established to provide a nominal closed-loop damping ratio of 0.7, with 0.5 as a minimum acceptable value.

Figure 4-14 presents a block diagram of the aircraft model used in the preliminary determination of feedback gains for the various stabilization systems. This model is an uncoupled approximation which includes transfer functions for the ADOCS actuator, hydraulic upper-boost actuator, UH-60 rotor dynamics, and a computational cycle time delay. The fourth-order rotor model used represents flapping dynamics but does not account for inplane (lead-lag) mode effects; a detailed derivation of the rotor model can be found in Reference 24.

The UH-60A model used for this analysis has an open-loop frequency response as presented in Figures 4-15 and 4-16 (magnitude and phase respectively). The frequency response shown represents aircraft pitch rate response (q) for a commanded input δ_B. The following observations are made from these figures:

(1) For the open-loop (unaugmented) condition, a phase shift of more than 40 degrees exists at frequencies above 1 Hz (6.28 rad/sec). This significant phase shift may result in pilot induced oscillations (PIO) for high frequency control inputs and reversals.

(2) A computation time frame ranging from 50-70 milliseconds is inherent in the Boeing Vertol digital simulation of the UH-60A Blackhawk. The effects of rotor dynamics associated with blade flapping modes are also absent from the simulation. As shown in Figure 4-16, the phase shift attributed to rotor dynamics in the control frequency region is nearly equal to a 50 msec computational time delay. As shown in Figure 4-15, the rotor dynamics contribution to the response magnitude in the control frequency region is negligible. Therefore, the absence of the rotor dynamics in the ACC/AFCS simulation model is somewhat compensated for by the delay attributed to the computational time frame.

Open-loop eigenvalues for the longitudinal axis of the UH-60A are shown in Figure 4-17 with the origin of each root in the complex-plane identified. Feedback gains were determined primarily using Nichols Chart analysis techniques; however, results of the analysis are more clearly illustrated using root-locus plots as presented in the following discussion.

UH-60A AIRCRAFT MODEL USED FOR STABILITY ANALYSIS

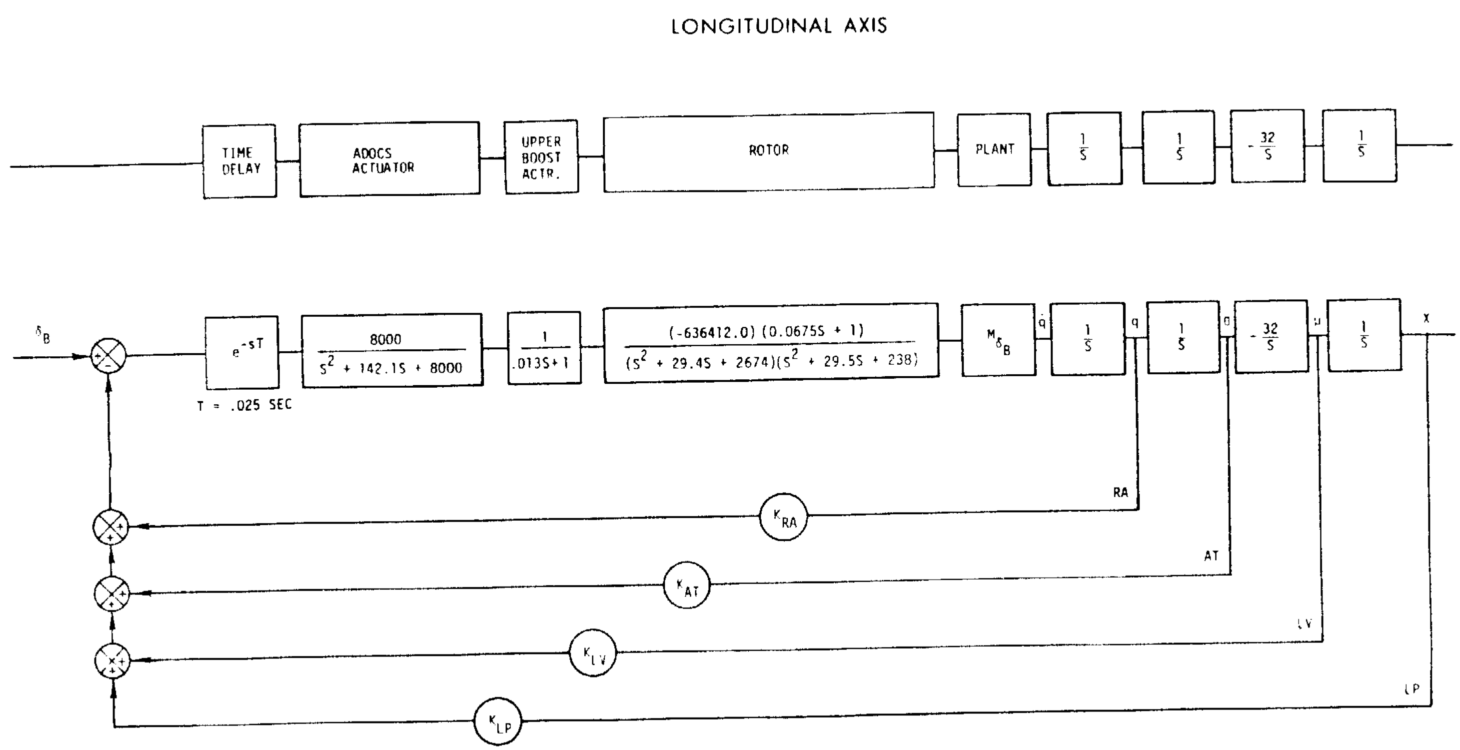


Figure 4-14

OPEN LOOP FREQUENCY RESPONSE
UH-60A SIMPLIFIED AIRCRAFT MODEL

- AMPLITUDE -

(BASED ON UNITY M_δ)
(q/δ_B)

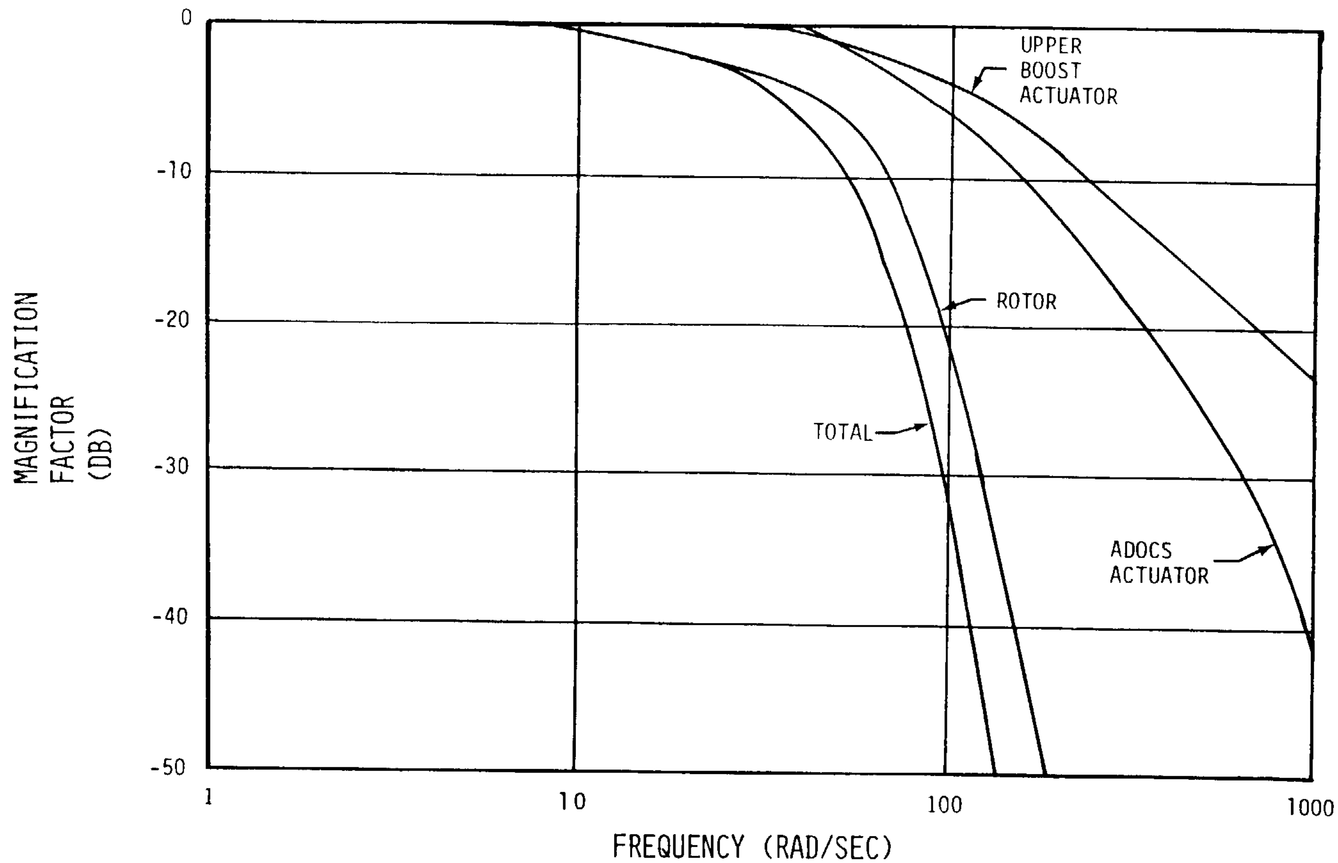


Figure 4-15

OPEN LOOP FREQUENCY RESPONSE
UH-60A SIMPLIFIED AIRCRAFT MODEL

- PHASE ANGLE -

(BASED ON UNITY M_δ)

(q/δ_B)

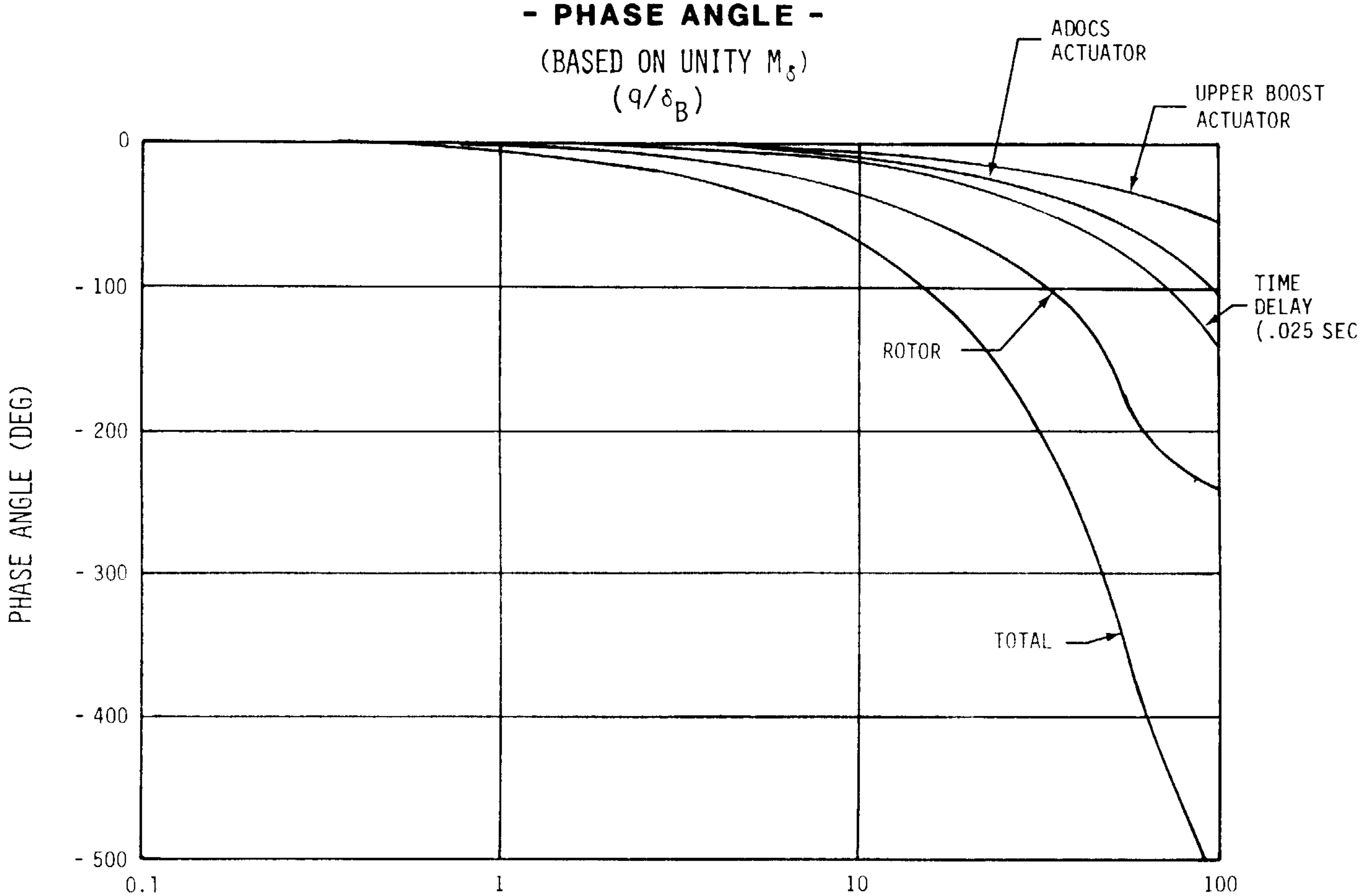


Figure 4-16

LONGITUDINAL AXIS-ROOT LOCUS VERSUS PITCH RATE GAIN

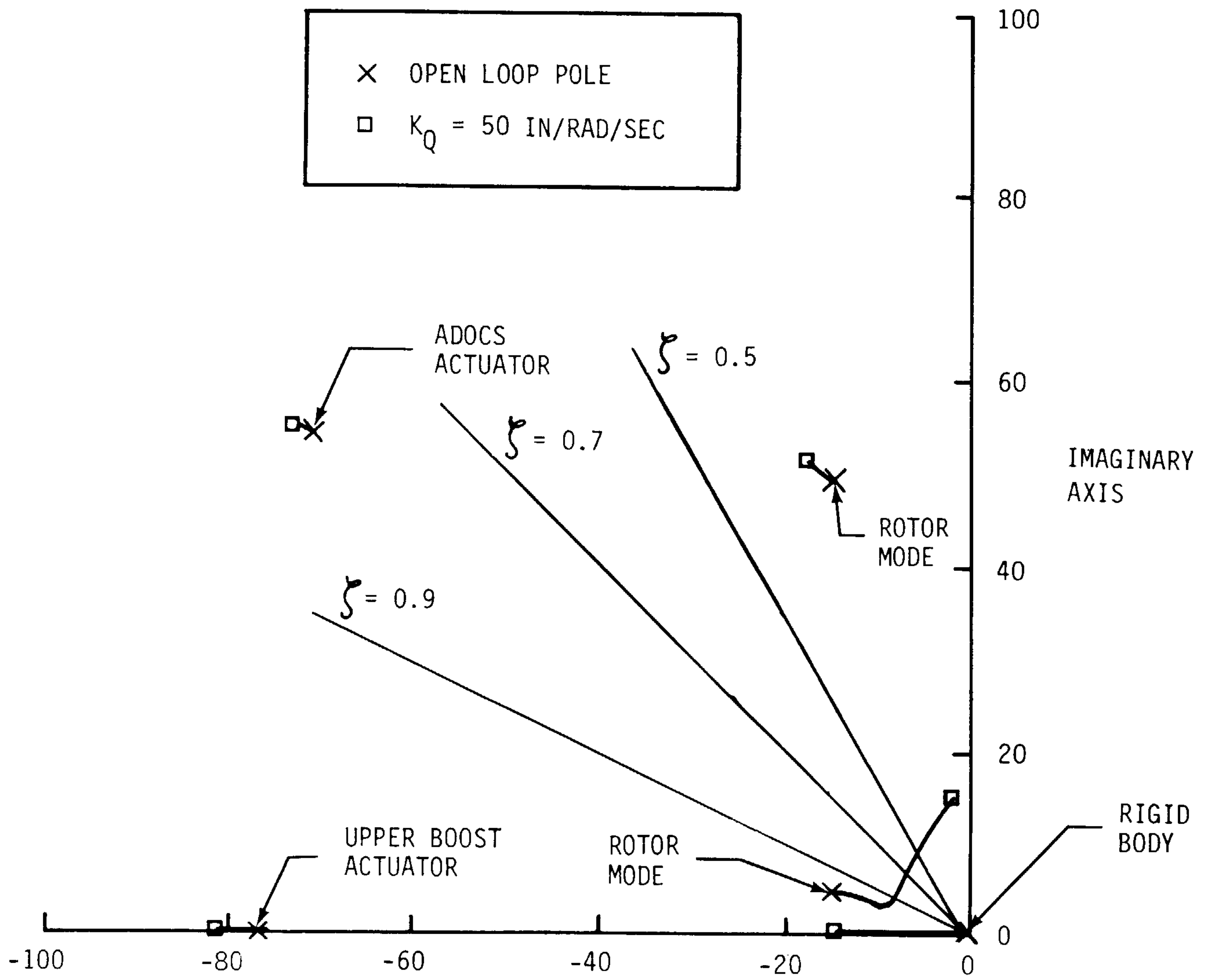


Figure 4-17

As previously stated, each feedback stabilization system was designed to exhibit a damping ratio of at least 0.7 in response to an external gust upset. Gains for each particular configuration were selected by closing one additional outer-loop feedback at a time; inner-loop stabilization gains were kept constant for each higher level of stabilization added. The rate feedback loop was closed first, then attitude, velocity and finally the position loop.

Figures 4-17 and 4-18 illustrate the effect of varying the rate feedback gain from 0.0 to 50 in/rad/sec. As expected, the actuator mode roots do not move significantly but the low-frequency, rotor mode root migrates toward the imaginary axis. A pitch-rate feedback gain of 16.0 in/rad/sec was selected to provide the desired damping ratio. A simulated time history of the aircraft response to a gust upset in the longitudinal axis is shown in Figure 4-19. With the selected gain of 16.0 in/rad/sec, the model exhibits a well-damped response characteristic.

With the rate gain defined, a root-locus plot was generated by varying pitch attitude gain from 0.0 to 50.0 in/rad (Figure 4-20). As this figure indicates, gains up to 35.0 in/rad lower the mode response frequency with little change in damping ratio. An attitude feedback gain of 34 in/rad was selected. With both the rate and attitude feedbacks active, a smaller pitch attitude perturbation results when a gust disturbance is simulated. (Figure 4-21).

Root-locus analysis of a velocity stabilized configuration is shown in Figure 4-22. A velocity feedback gain of -1.0 in/ft/sec represents a compromise between the damping ratio of the two low-frequency control response modes. Both control mode roots show a damping ratio between 0.65 and 0.75. Figure 4-23 presents the simulated longitudinal response of the aircraft to a gust upset with the rate, attitude and velocity feedback loops active. The return to original trim velocity after the disturbance input takes about 2 seconds.

Feedback stabilization gains for the remaining control axes were defined in the same manner as outlined for the pitch axis. Resulting gains from this analysis are presented in Table 4-2.

Figure 4-24 compares the gust response characteristics of the stability augmentation system defined for this study to two other cases -- (1) the basic helicopter without stability augmentation, and (2) the production UH-60A SCAS configuration. The stabilization system developed for the ACC/AFCS study provides a significant improvement in gust rejection characteristics as measured by power spectral density.

Gains selected for the ACC/AFCS stabilization loops are compared to corresponding gains which were successfully flown in the HLH/Model 347 and TAGS aircraft in Figures 4-25 and 4-26. Longitudinal gains used for the ACC/AFCS simulations match very

LONGITUDINAL AXIS-ROOT LOCUS VERSUS PITCH RATE GAIN

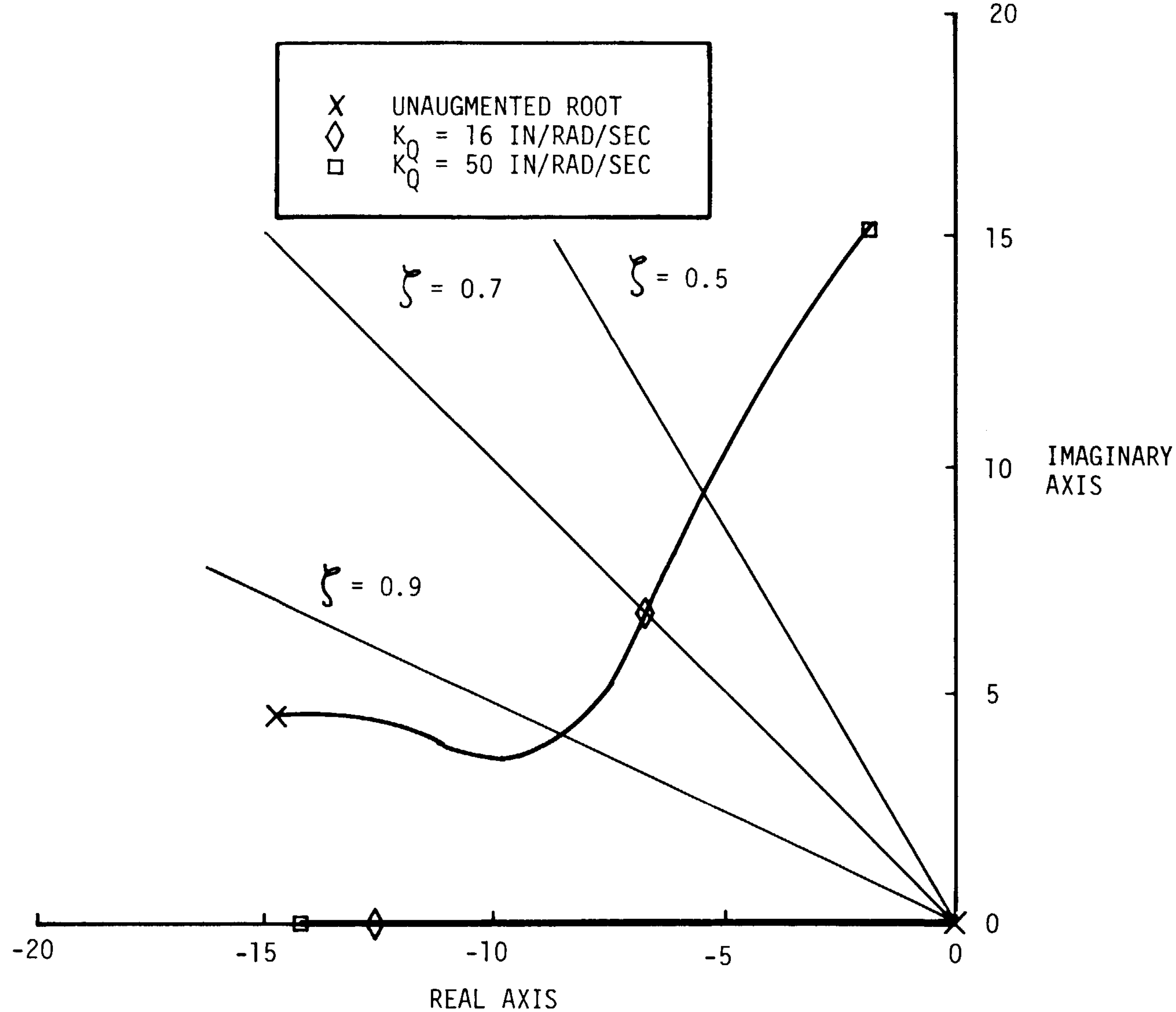


Figure 4-18

SIMULATED RESPONSE TO GUST UPSET
PITCH RATE FEEDBACK ONLY

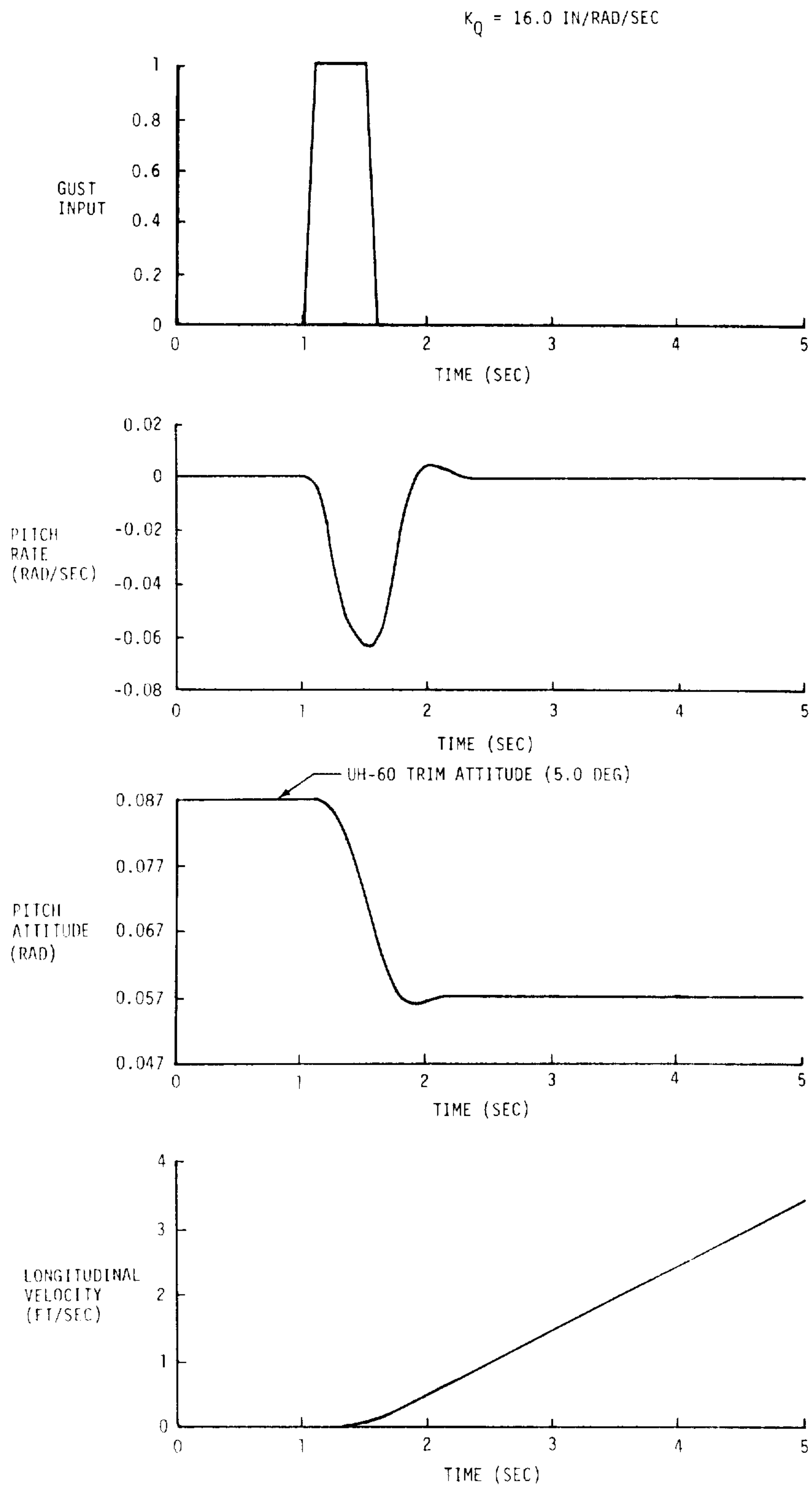


Figure 4-19

LONGITUDINAL AXIS-ROOT LOCUS VERSUS PITCH ATTITUDE GAIN

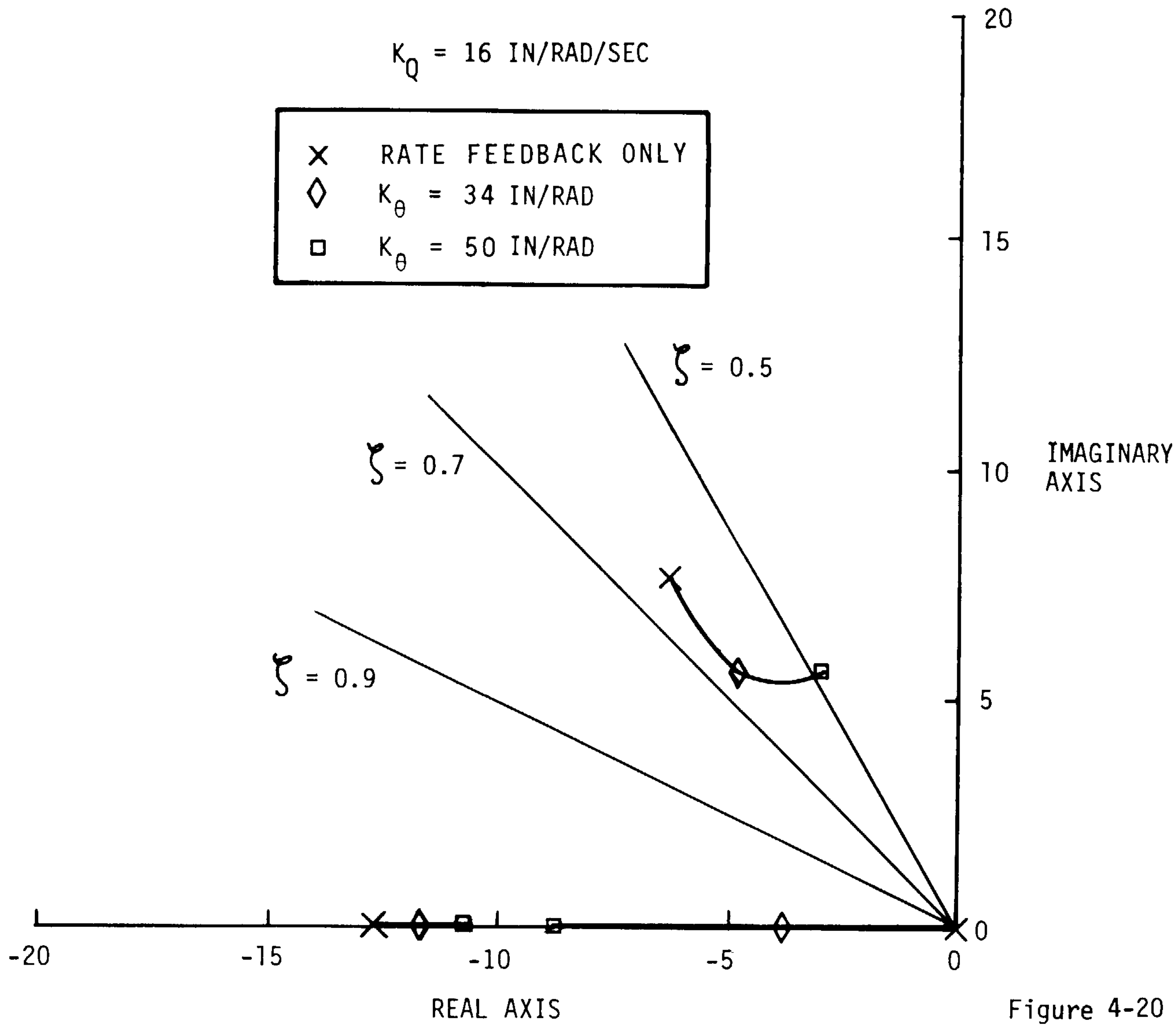


Figure 4-20

SIMULATED RESPONSE TO GUST UPSET
PITCH ATTITUDE AND RATE FEEDBACK

K_Q = 16 IN/RAD/SEC

K_θ = 34 IN/RAD

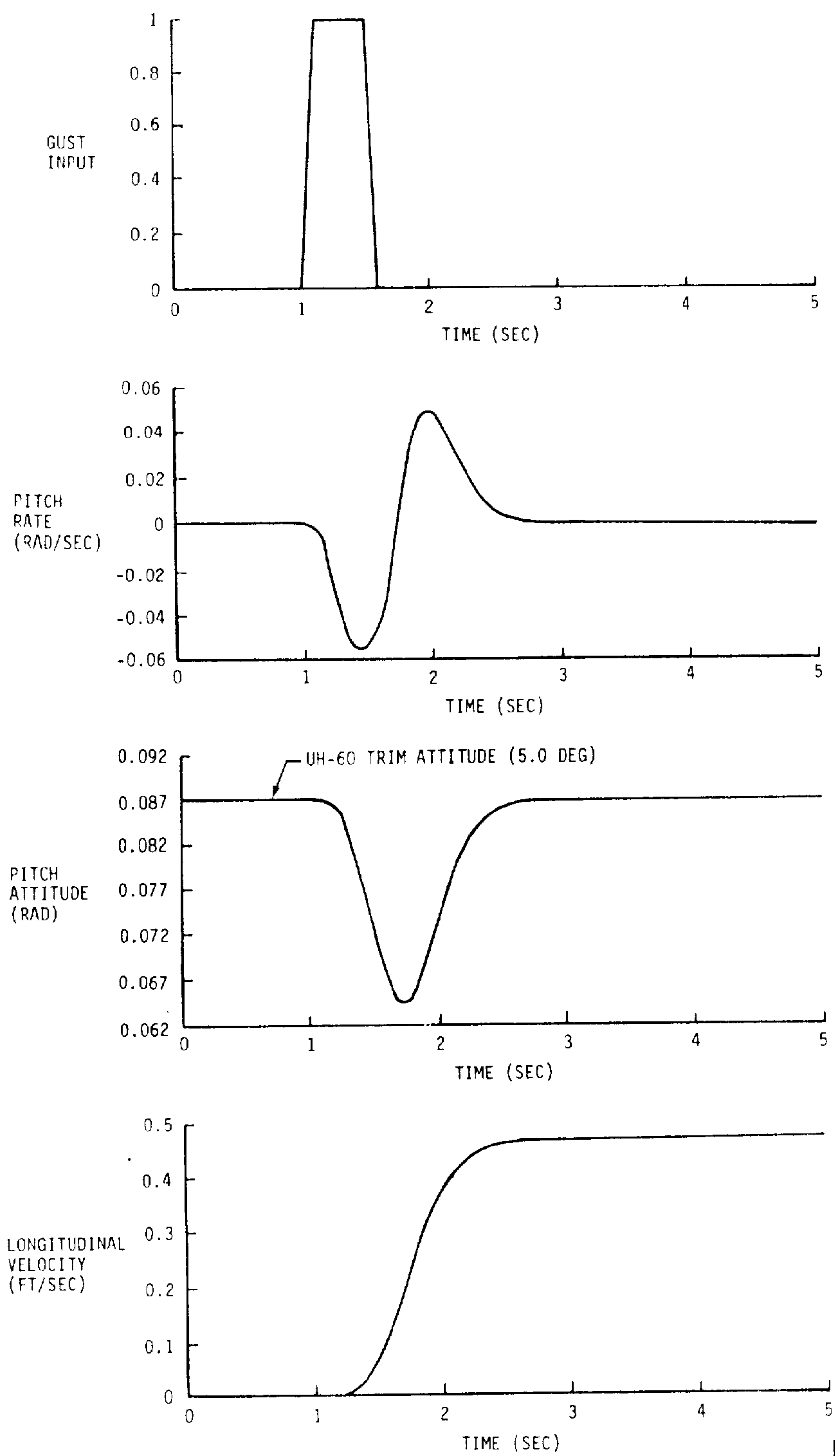


Figure 4-21

LONGITUDINAL AXIS-ROOT LOCUS VERSUS VELOCITY FEEDBACK GAIN

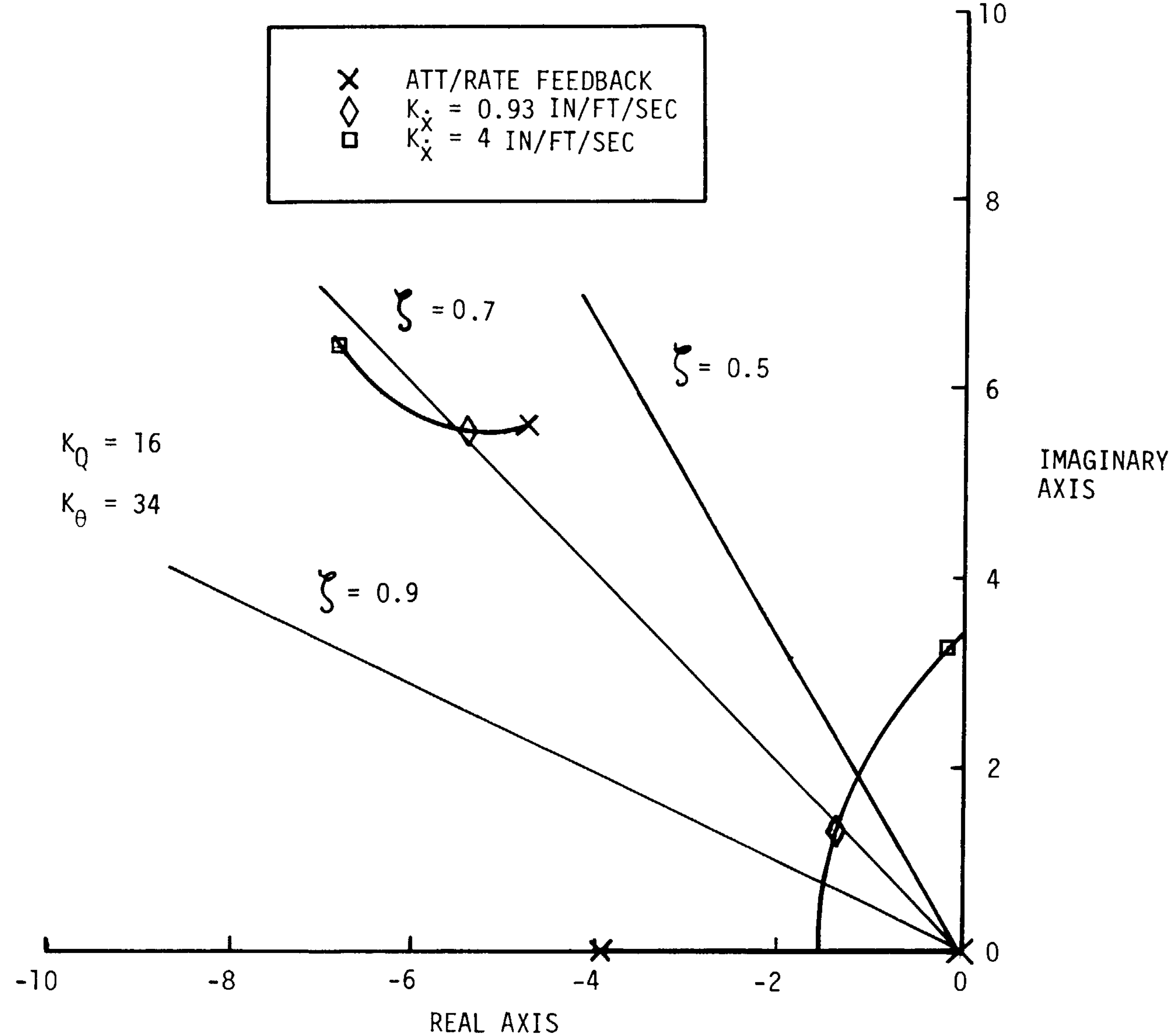


Figure 4-22

SIMULATED RESPONSE TO GUST UPSET
PITCH RATE, ATTITUDE, AND VELOCITY FEEDBACK

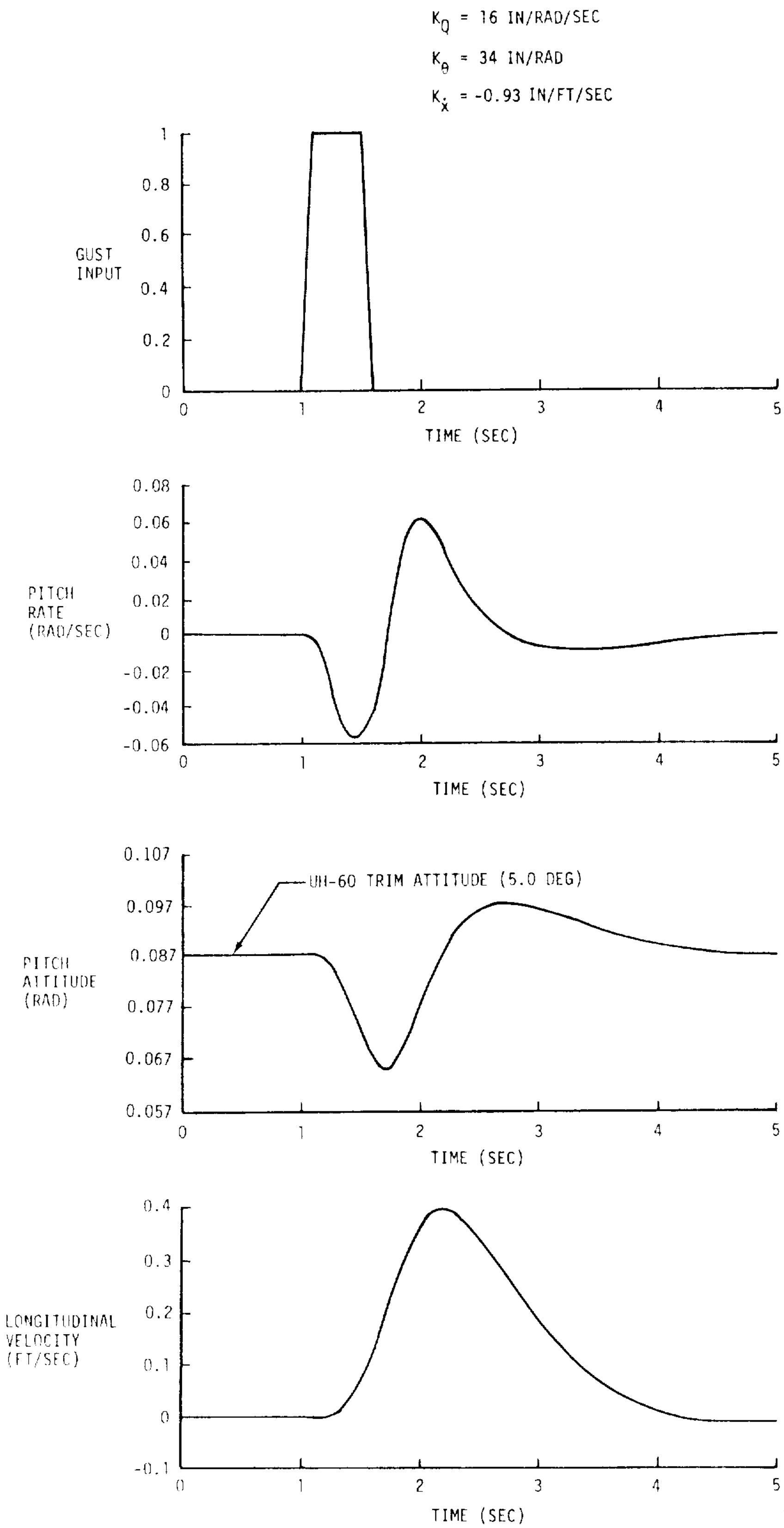


Figure 4-23

ACC/AFCS SIMULATION FEEDBACK GAINS

<table>
<tr><th rowspan="2">AXIS</th><th rowspan="2">FEEDBACK PARAMETER</th><th rowspan="2">SELECTED GAIN</th><th colspan="7">CMD/STAB SYSTEM</th></tr>
<tr><th>AC/RA</th><th>RA/AT</th><th>RA/LV</th><th>AT/AT</th><th>AT/LV</th><th>LV/LV</th><th>LV/PH</th></tr>
<tr><td rowspan="4">LONGITUDINAL</td><td>RATE</td><td>16 IN/RAD/SEC</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>ATTITUDE</td><td>34 IN/RAD</td><td>–</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>VELOCITY</td><td>0.93 IN/FT/SEC</td><td>–</td><td>–</td><td>X</td><td>–</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>POSITION</td><td>0.4 IN/FT</td><td>–</td><td>–</td><td>–</td><td>–</td><td>–</td><td>–</td><td>X</td></tr>
<tr><td rowspan="4">LATERAL</td><td>RATE</td><td>6.0 IN/RAD/SEC</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>ATTITUDE</td><td>20.0 IN/RAD</td><td>–</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>VELOCITY</td><td>0.25 IN/FT/SEC</td><td>–</td><td>–</td><td>X</td><td>–</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>POSITION</td><td>0.4 IN/FT</td><td>–</td><td>–</td><td>–</td><td>–</td><td>–</td><td>–</td><td>X</td></tr>
<tr><td rowspan="3">DIRECTIONAL</td><td></td><td></td><td colspan="2">$\ddot{\psi}/\dot{\psi}$</td><td colspan="3">$\ddot{\psi}/\psi_H$</td><td colspan="2">$\dot{\psi}/\psi_H$</td></tr>
<tr><td>RATE</td><td>7.19 IN/RAD/SEC</td><td colspan="2">X</td><td colspan="3">X</td><td colspan="2">X</td></tr>
<tr><td>HEADING</td><td>7.7 IN/RAD</td><td colspan="2">–</td><td colspan="3">X</td><td colspan="2">X</td></tr>
<tr><td rowspan="3">VERTICAL</td><td></td><td></td><td colspan="2">$\ddot{h}/\dot{h}$</td><td colspan="3">$\ddot{h}/h_H$</td><td colspan="2">$\dot{h}/h_H$</td></tr>
<tr><td>RATE</td><td>0.35 IN/FT/SEC</td><td colspan="2">X</td><td colspan="3">X</td><td colspan="2">X</td></tr>
<tr><td>ALTITUDE</td><td>0.35 IN/FT</td><td colspan="2">–</td><td colspan="3">X</td><td colspan="2">X</td></tr>
</table>

Table 4-2

UH-60A GUST RESPONSE COMPARISON *

PITCH AXIS

$\frac{\dot{\theta}}{u_{GUST}}$

HOVER CASE

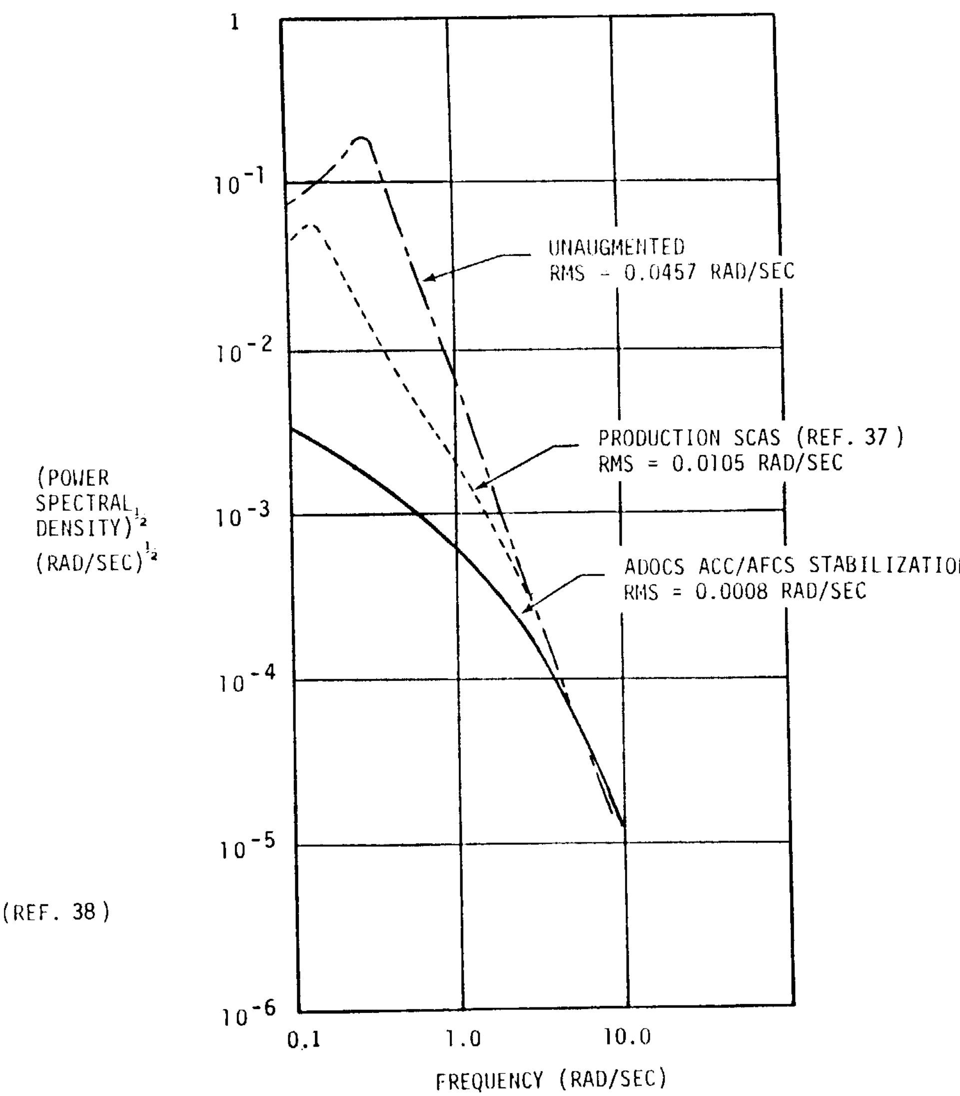
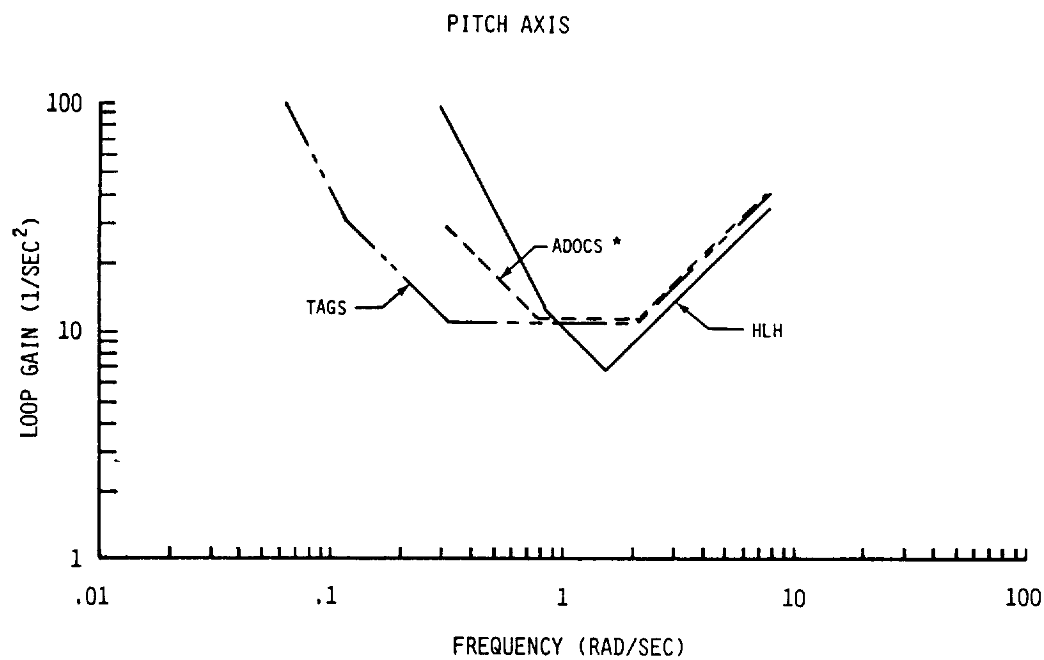


Figure 4-24

*DATA BASED ON
DRYDEN GUST MODEL (REF. 38)
H = 1000 FT
σ = 7.8

STABILIZATION LOOP GAIN COMPARISON



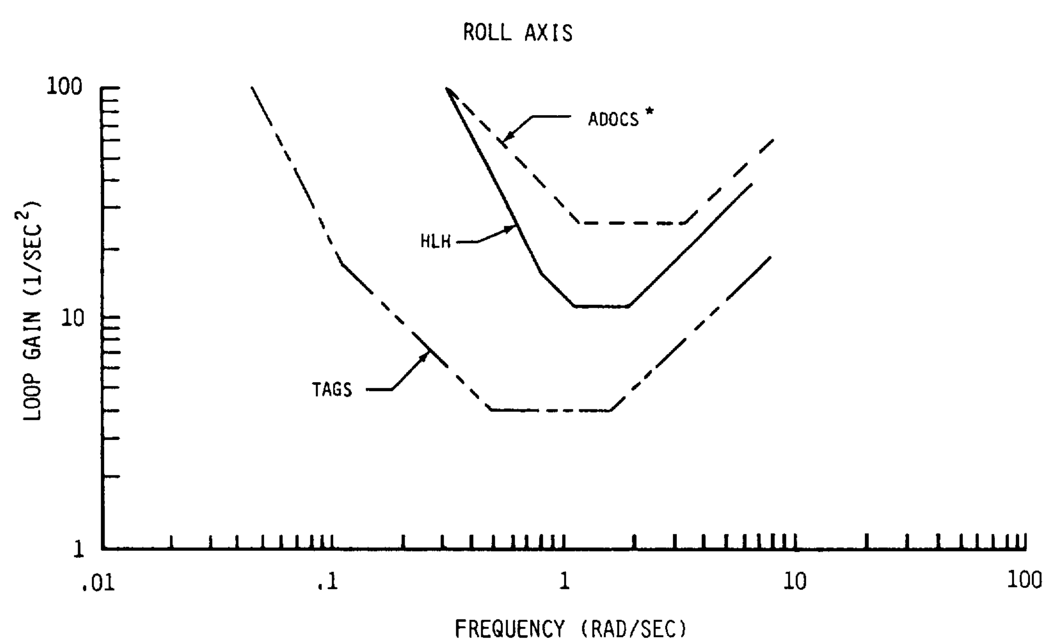


Figure 4-25

* ADOCS SIMULATION GAINS

STABILIZATION LOOP GAIN COMPARISON

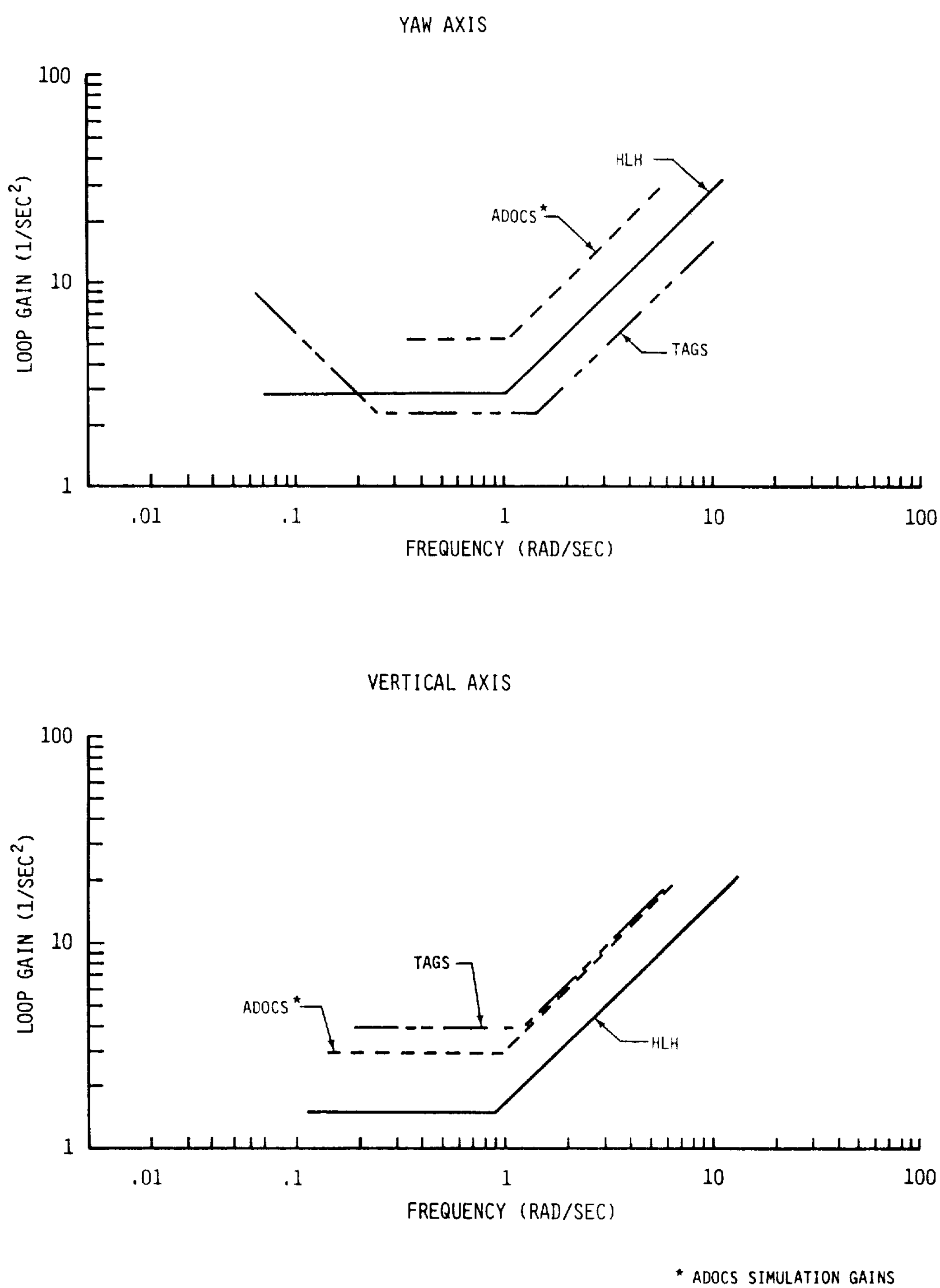


Figure 4-26

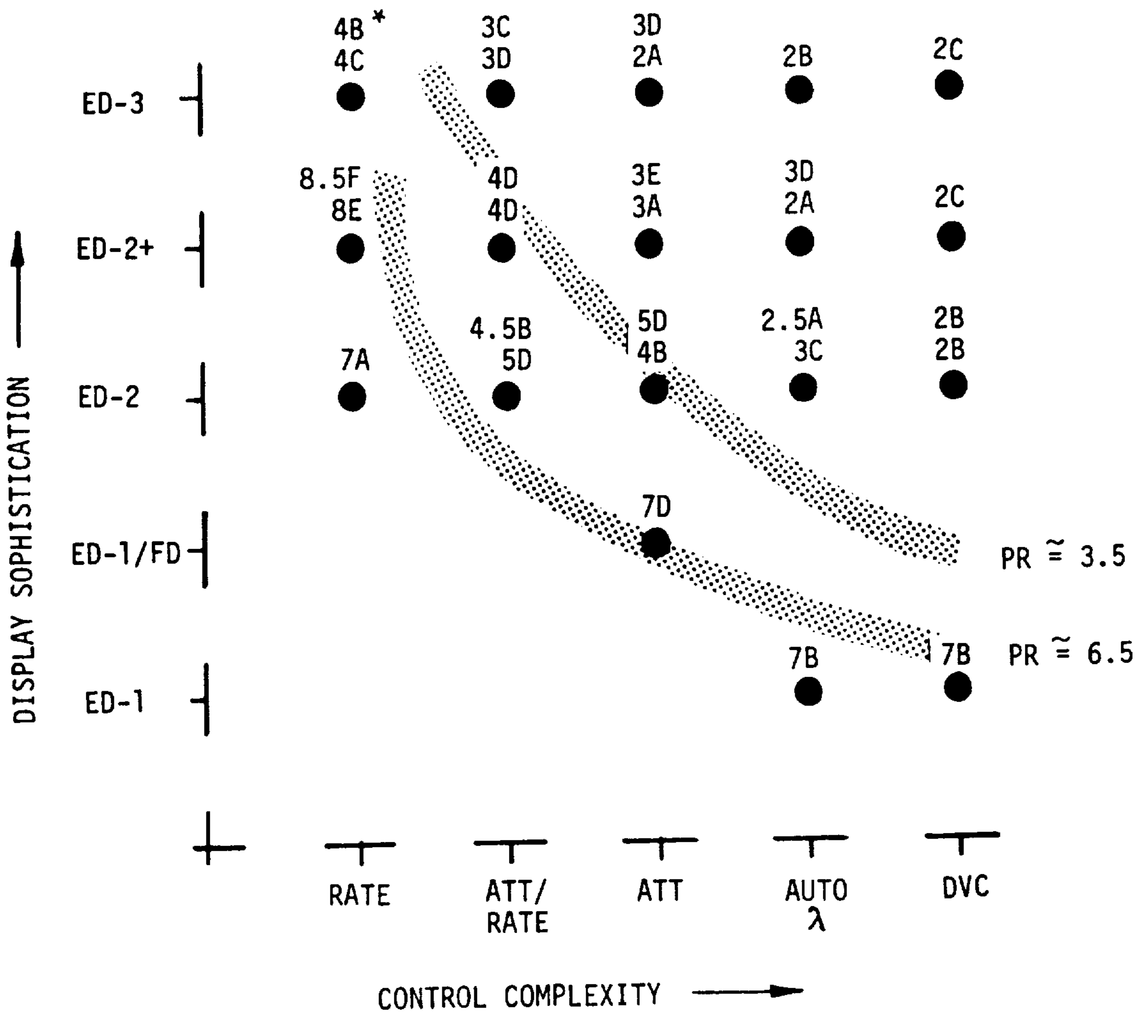
closely with those selected for the TAGS design as shown in Figure 4-25. Lateral gains, however, when compared to HLH and TAGS system are substantially higher. As a result of subsequent analysis, roll gains were lowered for implementation on the ADOCS demonstrator after the ACC/AFCS simulations had been completed. The directional axis gains (Figure 4-26) used for the ACC/AFCS study are slightly higher than those of the other programs but did not result in negative effects. As shown in Figure 4-26, vertical axis loop gains appear between those used for HLH and TAGS thus no inflight problems arising in this axis were predicted.

4.2.2 Command Model Design

A stability augmented helicopter does not necessarily possess desirable response characteristics to control inputs. Appropriate design of feed-forward command shaping loops or modification of feed-back control laws is necessary to achieve the control response characteristic desired for a chosen stabilization level and/or pilot control task. The benefits associated with higher levels of command or stabilization have been documented in Reference 25 by Aiken and Lebacqz, the HLH final report, (Reference 22), as well as numerous other studies. Aiken and Lebacqz found that, for a given task, a tradeoff exists between the level of control complexity and display sophistication. Figure 4-27 from Reference 25 illustrates the benefits of increased levels of stability and control augmentation on pilot handling quality ratings. Hoh and Ashkenas (Reference 27) found that rate and attitude command systems may be adequate for partial IMC conditions, but a translational rate command system is required for low speed flight and hover in zero visibility. Capability was required during the ACC/AFCS simulation to explore a wide range of generic command systems in an efficient manner. The method selected to accomplish this task is described in the following discussion.

Control of the command response characteristics can be achieved through a variety of methods including two well known techniques commonly referred to as model following and response-feedback modification. The HLH (Reference 22) mechanization of control laws used the latter method whereby appropriate feedback loops are synchronized during periods when the pilot is in-the-control-loop. Control response time constants are controlled by this method through feed-forward dynamic shaping. Model-following, which was preferred in Reference 19 over the alternative method, was also applied in the design of the control laws for TAGS (Reference 6). The model-following technique allows full-time engagement of stabilization loops, thereby reducing gust sensitivity during maneuvers and eliminating feedback loop switching transients associated with engagement/disengagement of stability augmentation signals. This advantage resulted in improved pilot Cooper-Harper Ratings (CHR) of half a point as reported in References 19 and 27. In addition, command model signals can directly provide inter-axis

EFFECT OF CONTROL SYSTEM/DISPLAY SYSTEM ON PILOT RATINGS



*Numbers are Cooper-Harper pilot ratings, letters are turbulence effect ratings. Two ratings indicates two separate evaluations of a configuration.

FIGURE FROM REF. 25

Figure 4-27

control requirements for compensation of inherent aircraft cross-axis coupling or automatic turn coordination. Direct control compensation from the command model reduces or eliminates the demand on feedback stabilization signals to accomplish these functions. Because of the above benefits, as demonstrated by results of the TAGS flight demonstration program, control laws for the ACC/AFCS study and ADOCS demonstrator aircraft were implemented using the model-following design technique.

4.2.2.1 Model Following Concept

The model following technique has an advantage over alternate control response methods since command model output predicts actual aircraft responses, thereby closely negating stabilization signals from the feedback loops. This results in a minimal feedback control usage during dynamic control maneuvers. Control law mechanization using the model-follower concepts is illustrated in Figure 4-28. The basic principle of the design concept is evident from the transfer matrix R(s)/B(s) which can be expressed as I, the identity matrix. More specifically, the combination of $P^{-1}(s)$ and H(s) formed in the command model ideally cancel out the augmented aircraft dynamics. Producing the unity transfer matrix allows the control law designer to obtain any desired response type through manipulation of the transfer matrix, D(s), in the forward control path. Attack helicopter control laws will be required to change as a function of flight regime and/or pilot task. Therefore, desired control responses characteristics can be easily altered by varying the transfer matrix, D(s).

In theory, a full complement of equations of motion would be required within the command model to accurately predict aircraft responses. Practically, the time to calculate these fully coupled responses in the flight control computer would be prohibitively high for real time operation. This problem is resolved due to the fact that the high-gain stabilization loops dominate over the inherent aircraft response characteristics and provide nearly decoupled responses in each axis. The command model can then be based on a first-, second-, or third-order response model as required, making calculations simpler and much more time efficient. Simulations have shown that responses produced by the simplified command model are adequate. Figure 4-29 compares the simulated aircraft response using a six degree-of-freedom model with the output of a command model based on a first-order approximation.

4.2.2.2 Command Response Characteristics

Response characteristics selected for each candidate command system were initially defined based on data collected during the literature review, as well as experience gained by Boeing Vertol during the TAGS, HLH, and ASH programs (Reference 6, 22

MODEL FOLLOWING COMMAND SHAPING

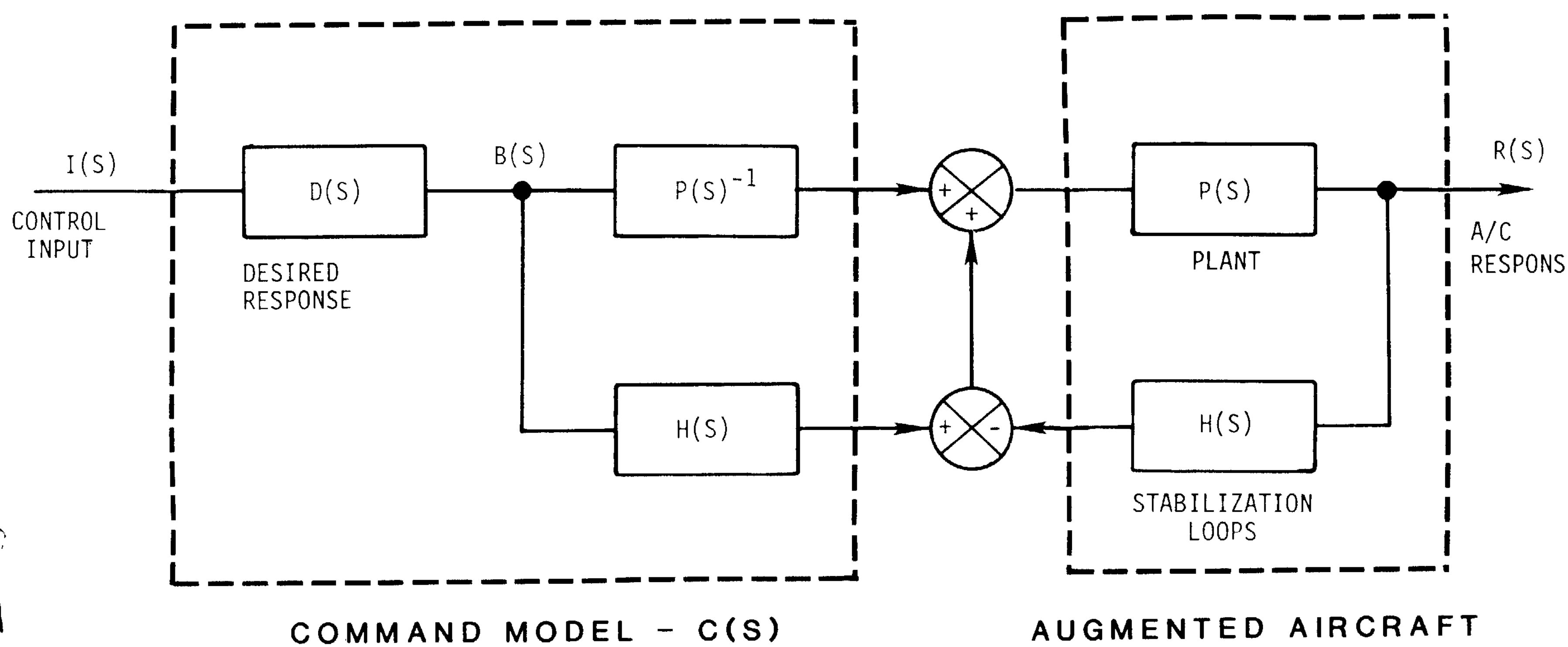
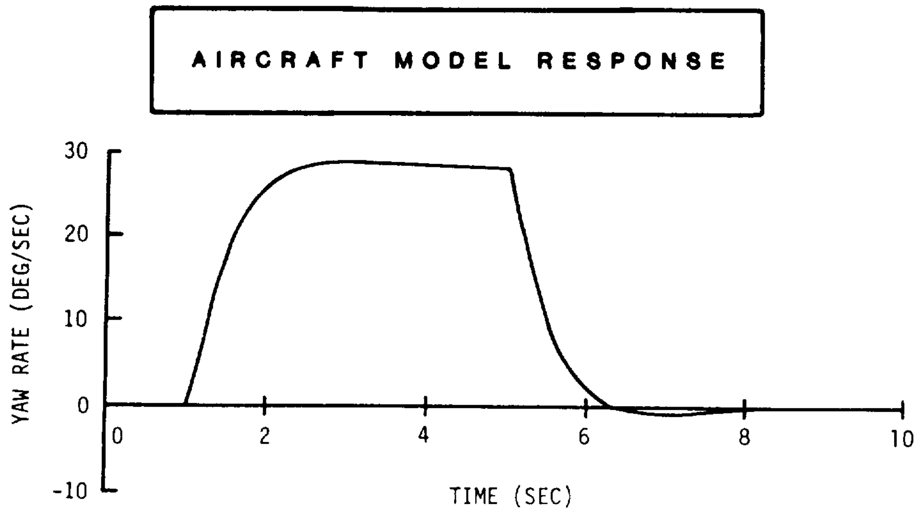


Figure 4-28

YAW RATE RESPONSE COMPARISON
COMMANDED VS ACTUAL

SIX DEGREE-OF-FREEDOM AIRCRAFT MODEL
- HOVER -



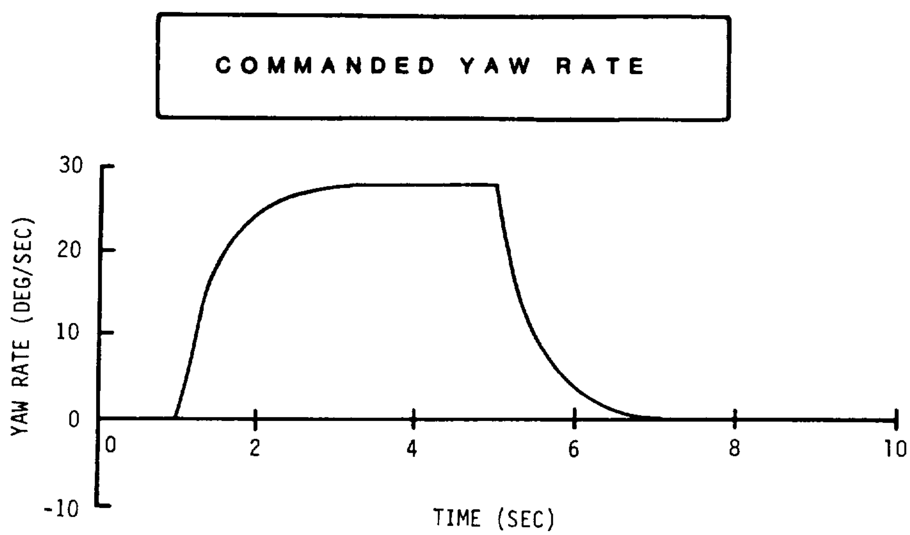


Figure 4-29

C-2

and 8 respectively). Available data were examined primarily for recommended response time-constants and sensitivities.

The importance of defining an appropriate response time constant is illustrated for a translational rate (i.e. velocity) command system in Figure 4-30 from Reference 26. Pilot ratings are presented as a function of response time constant ($\tau_{\dot{x}}$) of a first order equivalent velocity response system. Other data from the TAGS, HLH and ASH studies are also shown for comparison. Best pilot ratings were achieved for the longitudinal velocity command system with a response time constant between 2 and 5 seconds. The HLH program achieved Level 1 pilot ratings without an external sling load with a time constant of 6 seconds for the velocity command system; however, the TAGS design, which also incorporated a 6 second time constant received Level 2 pilot ratings. These results, however, are highly dependent on the task performed.

Pilot rating data as a function of control response sensitivity are presented for a rate command system in Figure 4-31 and an attitude command system in Figure 4-32. A similar trend is evident from the data, i.e. variation in sensitivities resulted in a desired range of sensitivity as indicated by a "bucket" in pilot ratings. Minimum or best pilot ratings were achieved with a roll rate response sensitivity of approximately 10.0 deg/sec/inch and a roll attitude response sensitivity of about 5.7 deg/inch.

Much of the available data as described above was generated for various type tasks utilizing conventional center-stick controllers, or side-arm controller configuration with relatively large-displacement (i.e. HLH and TAGS). Obviously, care has to be taken in relating recommended response sensitivities for a large-displacement center-stick or side-arm controller to requirements for a small-deflection force controller. A major factor which complicates the direct transfer of desired response characteristics is the need for non-linear force/response shaping with a side-stick force controller. It was decided to describe response sensitivity characteristics for the side-stick controller in terms of the initial sensitivity about the zero force reference position, i.e. the first linear shape of the response shaping function.

A summary of the information gathered from the literature review is presented in Table 4-3. Desired response characteristics (sensitivity and time constant) are given for various command system types including acceleration, rate, attitude, and linear velocity command systems. All sources of data are indicated by a document reference number. Where controller force/deflection information was available, response sensitivities are presented in terms of steady-state aircraft response per unit pound of force input rather than units of controller displacement (inches). The following is a discussion of the data presented in Table 4-3.

EFFECT OF TIME CONSTANT OF VELOCITY COMMAND SYSTEM ON PILOT RATING

- Path response well approximated by

$$\frac{\dot{x}}{\delta_{stk}} = \frac{K_{\dot{x}_c}}{T_{\dot{x}_{eg}} s + 1}$$

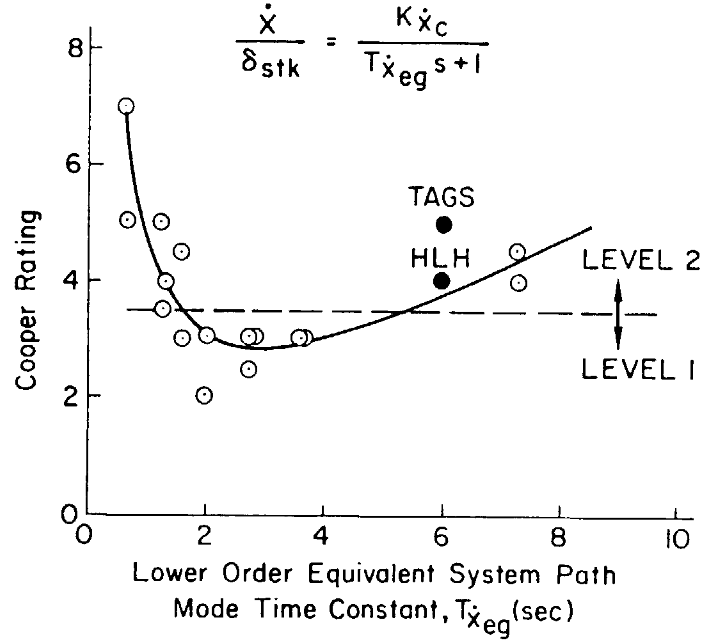


FIGURE FROM REF. 26

Figure 4-30

EFFECT OF ROLL RATE COMMAND SENSITIVITY ON PILOT RATING

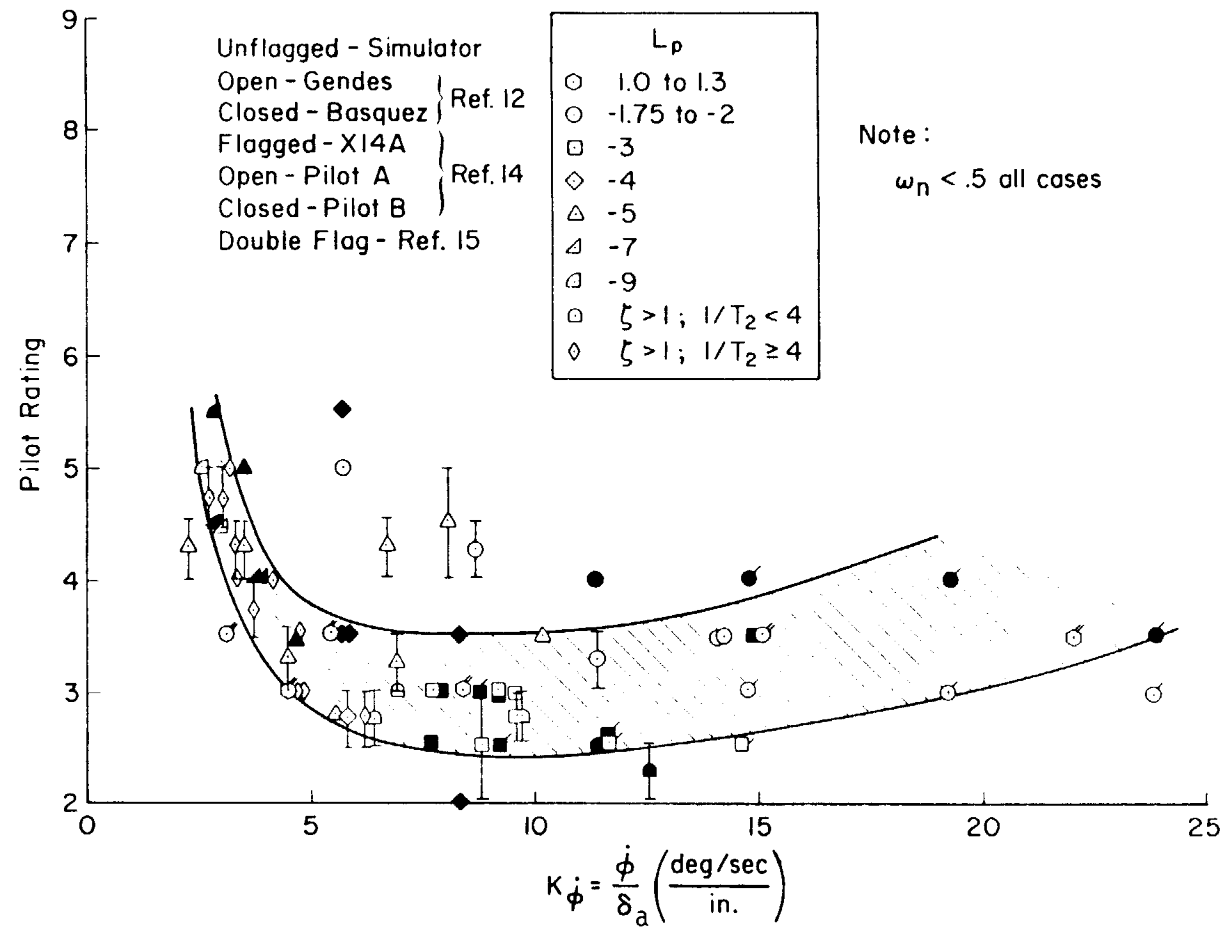


FIGURE FROM REF. 26

Figure 4-31

EFFECT OF ROLL ATTITUDE COMMAND SENSITIVITY ON PILOT RATING

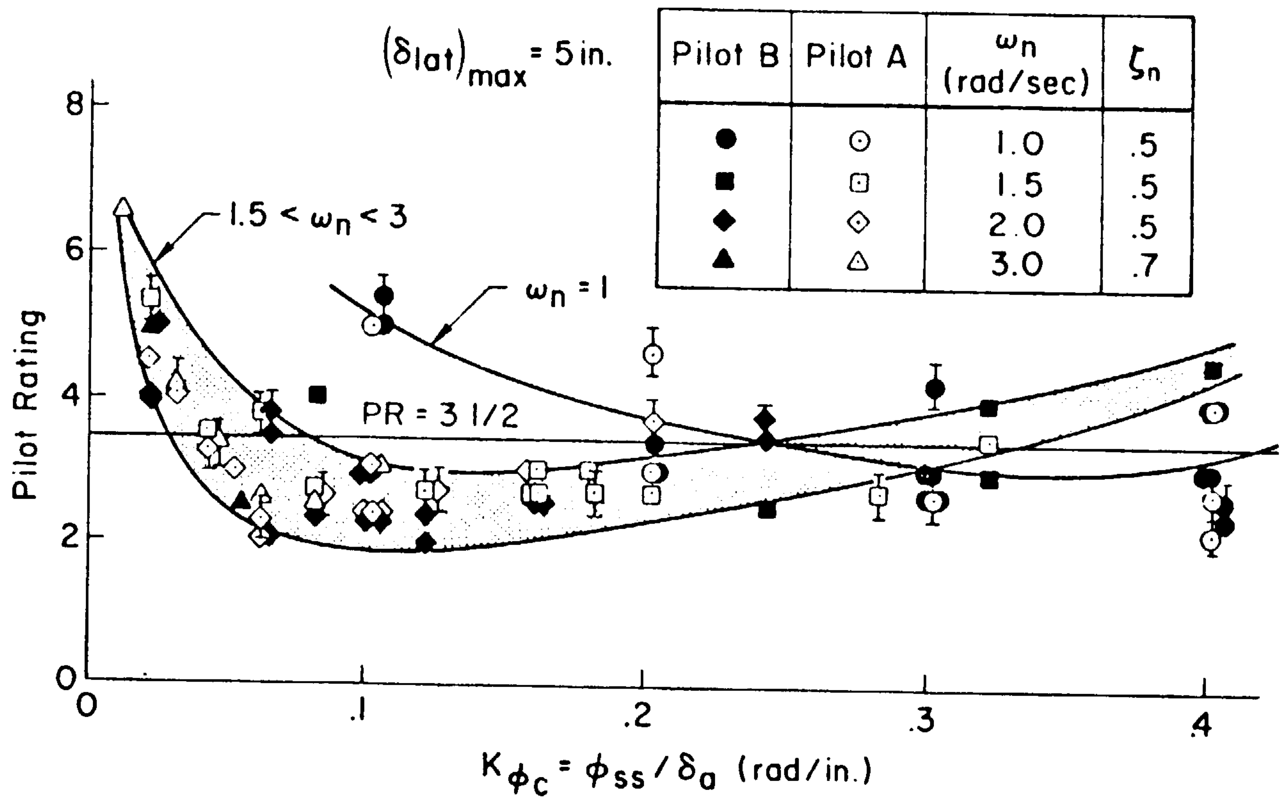


FIGURE FROM REF. 26

Figure 4-32

RESPONSE CHARACTERISTICS FROM LITERATURE REVIEW

AXIS	RESPONSE PARAMETER	COMMAND SYSTEM			
		ACCELERATION	RATE	ATTITUDE	LINEAR VELOCITY
LONGITUDINAL	SENSITIVITY	16.0 $DEG/SEC^2/LB$ (19)	8.0 DEG/SEC/LB (19)	4.0 DEG/SEC/LB (19)	3.0 TO 16.0 FT/SEC/LB * (28) 30.0 FT/SEC/LB (1) 3.0 FT/SEC/LB (19)
	TIME CONSTANT		0.25 TO 0.4 SEC (29) 0.30 SEC (19)		2.0 TO 5.0 SEC (26) 2.0 SEC (1)
LATERAL	SENSITIVITY	20.0 $DEG/SEC^2/LB$ (19)	5.0 DEG/SEC/LB (8) 8.0 DEG/SEC/LB (19) 5.0 TO 11.0 DEG/SEC/IN (26)	5.0 DEG/LB (8) 4.0 DEG/LB (19) 4.5 TO 11.5 DEG/IN (26)	5.0 TO 10.0 FT/SEC/LB* (8) 5.0 TO 25.0 FT/SEC/LB* (28) 40.0 FT/SEC/LB (1) 3.0 FT/SEC/LB (19)
	TIME CONSTANT		0.25 TO 0.4 SEC (29) 0.30 SEC (19)		2.0 TO 5.0 SEC (26) 2.0 SEC (1) 3.0 SEC (8)
DIRECTIONAL	SENSITIVITY		3.0 TO 12.0 DEG/SEC / (IN-LB) * (28) 19.0 DEG/SEC/IN (1)	NA	NA
	TIME CONSTANT		0.5 SEC (1)		
VERTICAL	SENSITIVITY		1.1 TO 8.5 FT/SEC/LB* 13.0 FT/SEC/IN (30) 16.0 FT/SEC/IN (1)	NA	NA
	TIME CONSTANT		1.0 SEC (30) 2.0 SEC (1)		

NOTE: SOURCE OF DATA IS INDICATED BY REFERENCE DOCUMENT NUMBER (#)

* - NON-LINEAR SHAPING EMPLOYED

Table 4-3

Longitudinal/Lateral

Reference 26 contains recommended response time constants and steady-state sensitivity requirements for low-speed and hover flight under reduced visibility conditions. Requirements are specified for a linear velocity command system and a roll rate and attitude command system in the lateral axis. Figure 4-30, from Reference 26, shows that the longitudinal/lateral velocity response time constant should range from 2.0 to 5.0 seconds to achieve Level 1 pilot ratings. ASH simulation studies (Reference 8) also defined a velocity response time constant well within the desired range (i.e. 3.0 seconds) with the Hover Hold Mode engaged. Response time constants for a velocity command system implemented on the HLH and TAGS program were at the high end of the range. i.e. 6.0 seconds. Low speed maneuvering tasks evaluated during the simulator study of Reference 1 resulted in a recommended time constant at the low end of the range, i.e. 2.0 seconds.

Recommended steady-state response sensitivities for a linear velocity command system ranged from 3.0 to 30.0 ft/sec/lb for the pitch axis and from 3.0 to 40.0 ft/sec/lb for the roll axis. The requirement for Precision Hover Tasks and low-speed maneuvering resulted in non-linear response shaping for the HLH load controlling crewman controller (Reference 28). Therefore, Table 4-3 specifies a minimum and maximum response sensitivity to define the HLH non-linear shaping function. Hovering tasks evaluated in the simulation studies reported in Reference 19 defined relatively low response sensitivities of 3.0 ft/sec/lb for both longitudinal and lateral, as did the ASH studies of Reference 8 which defined a desired range of 5.0 to 10.0 ft/sec/lb for the Hover Hold Mode.

A simulation investigation of the effect of various control system types on attack helicopter handling qualities was conducted at NASA-Ames (Reference 26). Low-speed tasks including approach to hover and acceleration/deceleration maneuvers were performed using a conventional center-stick controller. A hover and low-speed velocity command system was implemented using response sensitivities of 30.0 ft/sec/lb for longitudinal and 40.0 ft/sec/lb for lateral.

Specific response time constant values for an attitude command system were not found in the literature review. Requirements for system response characteristics are generally specified in terms of system damping and natural frequency. A response sensitivity of 4.0 deg/lb for a pitch and roll attitude command system was recommended in Reference 19. A comparable value of 5.0 deg/lb was defined for the inital sensitivity slope of the ASH lateral response/force shaping function (Reference 8). Reference provided an additional source of information on desired roll attitude response sensitivity, although the data were presented in terms of controller displacement. A sensitivity range of 4.5 to 11.5 deg/inch was recommended. Assuming a typical force gradient of 1.0 lb/inch, this range of attitude sensitivity from Reference is consistent with the data from References 8 and 19.

Recommended response characteristics for a rate command system are contained in Reference 19 and 29. Response time constants ranging from 0.25 to 0.4 seconds were desired. A nominal pitch and roll rate response sensitivity of 8.0 deg/sec/lb was specified in Reference 19. ASH studies (Reference 8) used a rate response sensitivity of 5 deg/sec/lb with a stiff side-stick controller, whereas a range of response sensitivity from 5.0 to 11.0 deg/sec/inch was recommmended in Reference 1. All the data reviewed for a pitch/roll rate response command system was consistent and indicated a nominal sensitivity value of 8.0 deg/sec/lb with a minimum-maximum range from 5.0 to 11.0 deg/sec/lb.

Directional

A yaw rate command/heading hold system was included in the control system evaluated by Aiken and Merrill in Reference 1. A variety of low speed/hover task under IMC were evaluated using a yaw rate command system having a time constant of 0.5 seconds and a steady-state response sensitivity of 19.5 deg/sec per inch of pedal deflection.

The HLH employed directional control effected through a side-stick controller at the load controlling crewman's station for precision maneuvers. A non-linear shaping function used in this program varied from 3.0 to 12.0 (deg/sec/in-lb).

Vertical

Vertical velocity command systems were implemented for two studies using a conventional collective lever for vertical control. Therefore, sensitivity values are defined in aircraft response per inch of collective lever motion. A response time constant of 1.0 second was used for the simulation study reported in Reference 1. The effect of variations in vertical response time constant were evaluated in flight test and documented in Reference 30 where a time constant of 2.0 seconds was recommended. A vertical response sensitivity of 16.0 ft/sec/inch was used for the Reference 1 simulation, and a sensitivity of 13.0 ft/sec/inch was recommended in Reference 30.

For precision hover and load-handling tasks of the HLH, sensitivities of 1.11 to 8.5 ft/sec/lb were desired (Reference 28). Vertical control was implemented on the right-hand 4-axis side-stick controller and non-linear shaping of response sensitivity was required.

Before the effect of controller configuration on handling qualities could be evaluated by piloted simulation, it was necessary to define a set of "best" control response characteristics for the four control axes and the generic system types identified previously (Figure 4-10). The ACC/AFCS simulation test plan was prepared to include a sufficient amount of preliminary testing to determine satisfactory response characteristics for each of the controller configurations. During the initial Phase 1A simulation activity at Boeing Vertol, a series of mini-experiments was conducted. Results of these experiments are presented in Table 4-4 (Reference 11). Values presented in Table 4-4 are based on the initial slope of the non-linear shaping function used in each axis. A comparison between the results of the Phase 1A mini-experiments and the results of the studies reviewed in Table 4-3 shows good correlation between the two. Because of the non-linear shaping used in the ACC/AFCS simulation, some sensitivities appear low but would agree more closely with the values used in other studies if second or third slope values were compared.

4.2.2.3 Command Model Analysis

The procedure followed in designing the command model for each generic command/stabilization (CMD/STAB) system is described in this section. As previously discussed, the command model characteristics are influenced by three main factors including the unaugmented response characteristics of the aircraft, stabilization feedback loops employed, and desired control response characteristics. An example of the derivation of command model characteristics is presented for a yaw rate command/heading hold ($\dot{\psi}/\psi_H$) system.

<u>Yaw Rate Command/Heading Hold System</u>

The desired response of a yaw rate command system is shown in Figure 4-33 where a directional control step input produces a constant yaw rate with a response time constant of 0.5 seconds. When the control input is removed, yaw rate decays to zero and the aircraft attains and holds a new heading. The desired yaw rate response transfer function is expressed as a first-order system in Equation 1.

$$D_{(S)} = \frac{r}{\delta_R} = \frac{K_{ss}}{\tau_1 s + 1} \qquad (1)$$

Where:

$\frac{r}{\delta_R}$ = Yaw rate due to directional control input (rad/sec/in)

K_{ss} = Steady-state response sensitivity (rad/sec/in)

τ_1 = Desired time constant (sec)

A block diagram that defines the simplified model used to represent the directional control system is given in Figure 4-34.

SELECTED CONTROL RESPONSE CHARACTERISTICS

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

		ANGULAR RESPONSE						LINEAR RESPONSE			
		ACCEL (AC)		RATE (RA)		ATTITUDE (AT)		ACCEL (AC)		VELOCITY (LV)	
AXIS	CONTROLLER	INITIAL SENSITIVITY (deg/sec^2)	STEADY STATE SENSITIVITY (deg/sec^2)	SENSITIVITY (deg/sec)	TC (sec)	SENS (deg)	TC (sec)	INITIAL SENSI-TIVITY (ft/sec^2)	STEADY STATE SENSI-TIVITY (ft/sec^2)	SENSI-TIVITY (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	2.4	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 4-4

DESIRED YAW RATE RESPONSE TO STEP INPUT

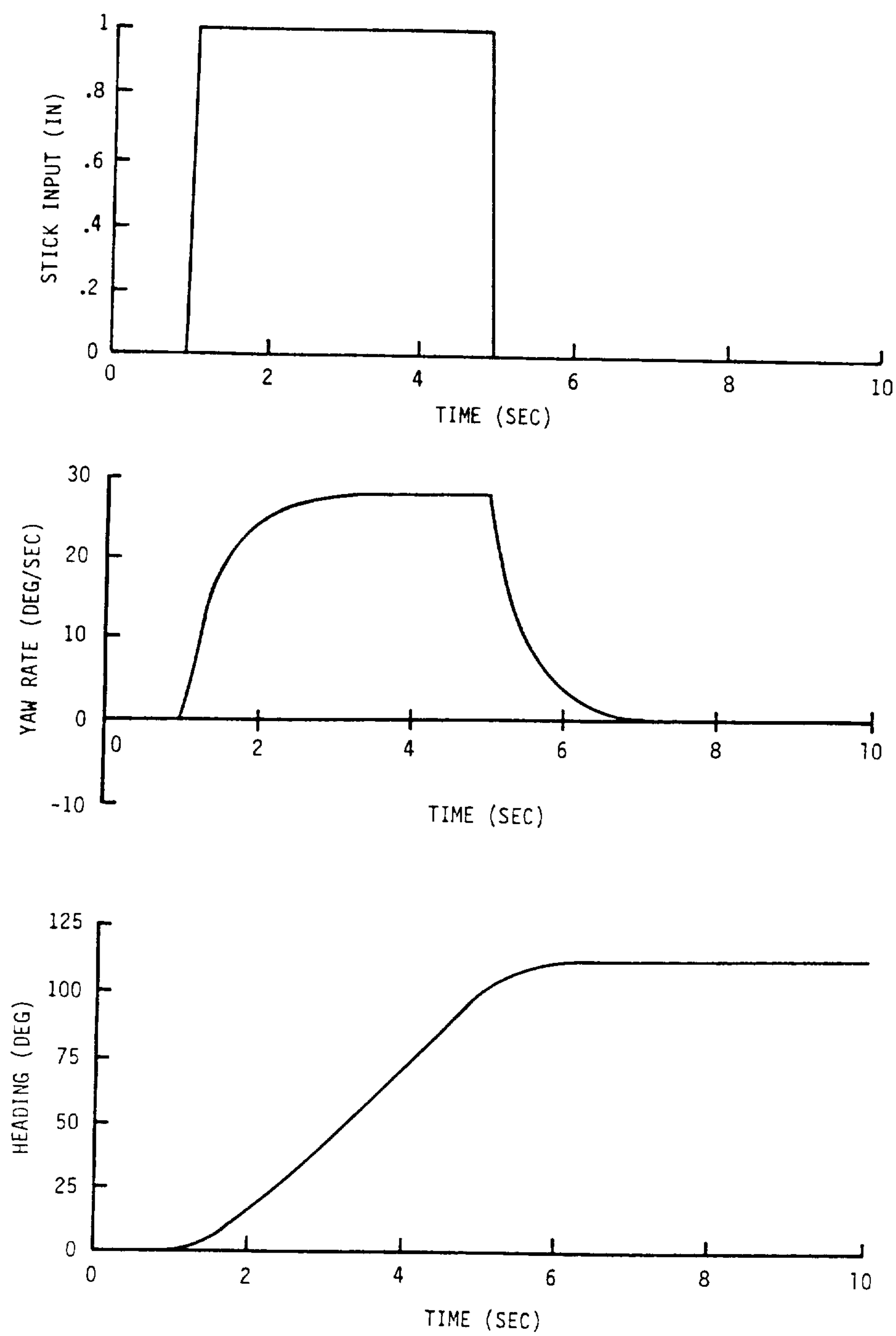


Figure 4-33

SIMPLIFIED AIRCRAFT MODEL - DIRECTIONAL AXIS

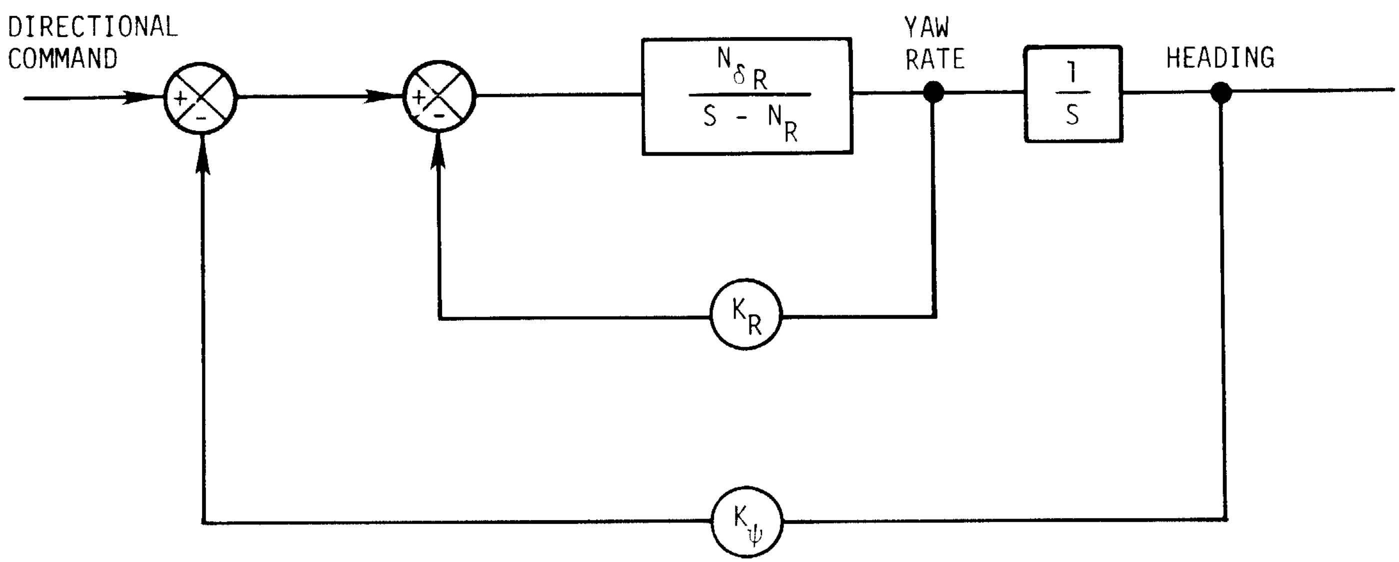


Figure 4-34

The command model, C(S), required to produce the desired response, D(S), is a function of the stabilization loops, H(S), employed. The unaugmented aircraft transfer function, P (s), in a decoupled, simplified form can be expressed as:

$$P(s) = \frac{N_{\delta_R}}{s - N_r} \qquad (2)$$

The stabilization feedback loops can be expressed by the transfer function, H(s):

$$H(s) = K_r + \frac{K_\psi}{s} \qquad (3)$$

A desired response, D(s) (Equation 1), can be calculated by using the relationship:

$$D_{(s)} = C(s) \frac{P(s)}{1 + P(s)\ H(s)} \text{, or}$$

$$C(s) = D(s) \left(\frac{P(s)}{1 + P(s)\ H(s)}\right)^{-1}$$

This relationship shows that the command model C(s) contains the desired response in the numerator and the aircraft inherent augmented response characteristics in its denominator. Therefore, the inherent response is "cancelled" and the desired response becomes dominant.

Solving for C(s):

$$C(s) = \frac{K_{ss}}{N_{\delta_R}} \cdot \frac{s^2 + (N_{\delta r}K_r - N_r)s + N_{\delta r}K_\psi}{s(\tau_1 s + 1)} \qquad (4)$$

Where:
$N_{\delta R}$ = 0.69 (rad/sec^2/in)
N_r = -0.28 (1/sec)
K_{ss} = 0.56 (rad/sec/in)
K_r = 7.7 (in/rad/sec)
K_ψ = 7.19 (in/rad)

This command model transfer function can be realized in a number of ways. Because of design requirements for unaugmented flight as described in Section 4.1, the mechanization shown in Figure 4-35 was selected. This mechanization provides a PFCS path with shaping that operates during both augmented and unaugmented flight, AFCS ON and OFF, respectively. In general, the command model gains used in the PFCS feed-forward path are smaller than these in the AFCS, thereby causing the AFCS loops to dominate the response characteristics throughout the entire flight regime. This in turn eliminates the need for tuning the command model for different flight conditions.

DIRECTIONAL AXIS COMMAND MODEL
YAW RATE COMMAND/HEADING HOLD

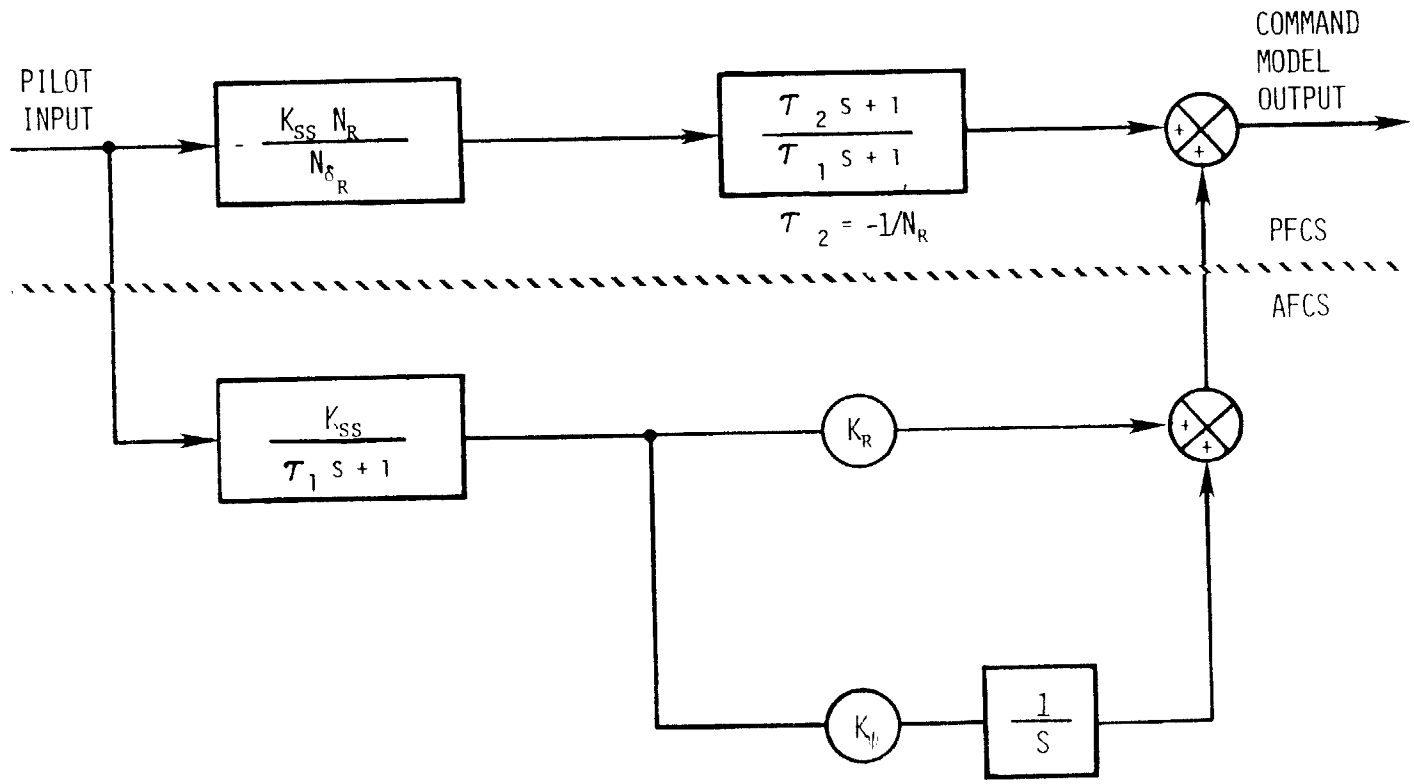


Figure 4-35

The yaw command model was not implemented exactly as predicted by the above analysis because of pilot comments received during initial simulations. With AFCS OFF, the lead-lag path in the PFCS tended to be "too quick," providing responses which were considered too sharp. The sensitivity for unaugmented yaw control was also noted to be too low, requiring the pilot to apply undesirably high torques to the side-stick controller. As a result of the initial simulations, the PFCS path in the directional axis was modified, incorporating a lower time constant in the numerator (0.82 sec vs. 3.5 sec) and a higher steady-state gain (0.61 vs. 0.23). These two changed produced a lower high frequency gain and a higher DC gain as desired. The AFCS portion of the command model was not altered as augmented responses were judged adequate by test pilots.

Figure 4-36 compares the modeled response of the augmented directional axis to a step input of the analytically chosen command model, and the modified command model. As seen in Figure 4-36, both rate responses are very similar with the modified PFCS exhibiting a slight initial overshoot in the response. Pilot comments do not indicate that this overshoot is noticeable, probably because sharp step inputs are rarely applied in flight.

4.2.2.4 Generic AFCS Implementation

Generic AFCS configurations for each axis are presented in Figures 4-37 through 4-40. Similarities in mechanization between the longitudinal and lateral AFCS design can be noted. Likewise, the structure of the Vertical and Directional AFCS configurations are similiar. Each axis of the AFCS contains a command model on the left implemented in a canonical form, and the various levels of feedback stabilization loops shown on the right half of the diagram. Together, these loops provide the desired response and stabilization characteristics. Important aspects of the AFCS design for each axis are discussed in the following paragraphs.

Longitudinal

Longitudinal AFCS (Figure 4-37) inner stabilization feedback loops include body-axis pitch rate feedback for damping and a correction term ($r_c \tan \phi$) to remove the steady pitch rate component in turning flight. Outer loops include attitude and velocity stabilization as well as a ground reference position feedback loop available as a selectable option for Precision Hover Tasks when the Hover Hold mode was engaged.

A groundspeed stabilization signal was provided for long-term velocity hold at low speeds less than 40 knots. For evaluation of forward flight characteristics during Phase 2 at NASA-Ames, an airmass reference velocity feedback signal was provided for long-term airspeed hold. A "complementary airspeed" signal using a combination of pitot static airspeed and pitch attitude

YAW AXIS RESPONSE COMPARISON

YAW RATE RESPONSE TO STEP INPUT

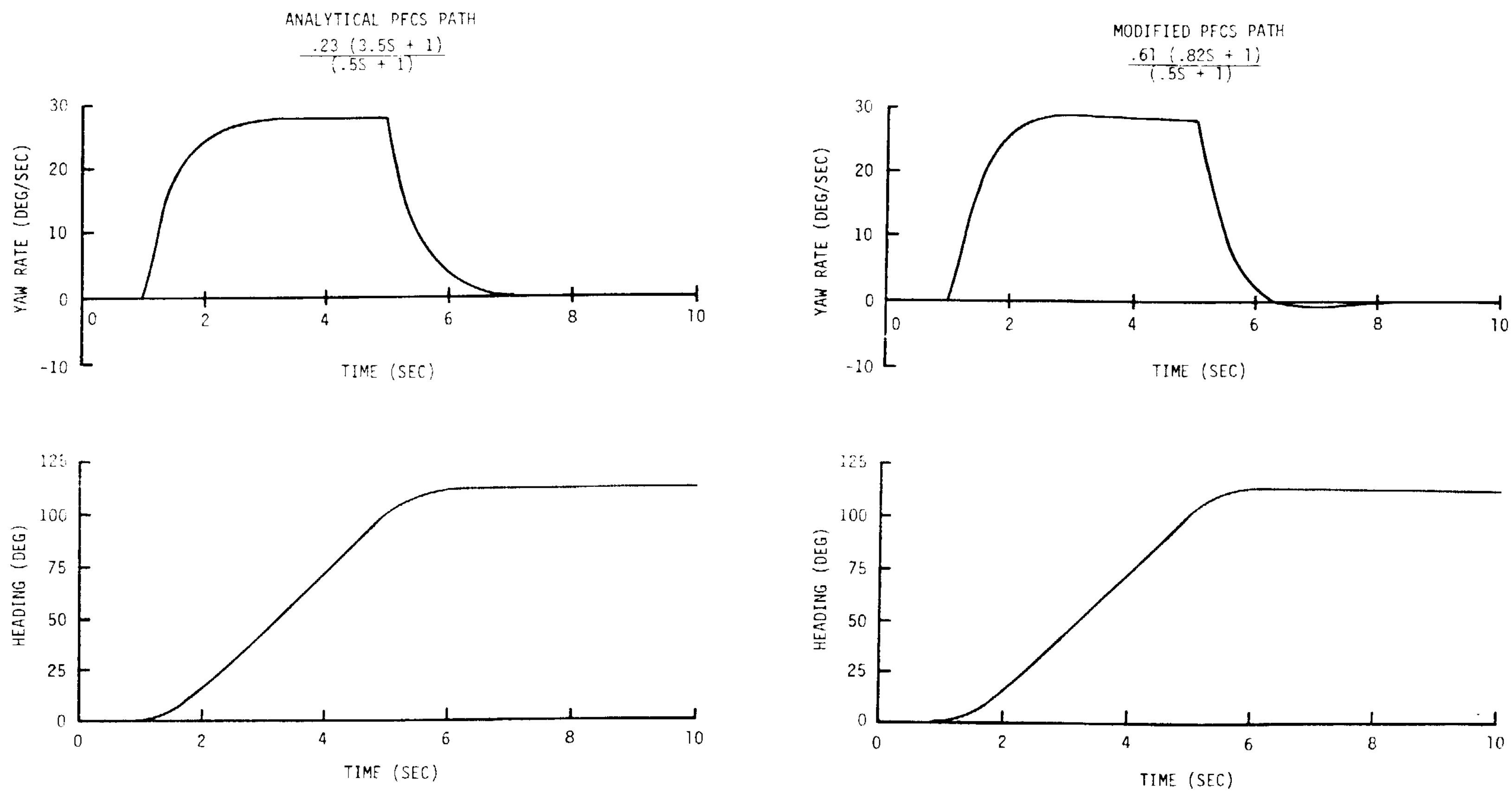
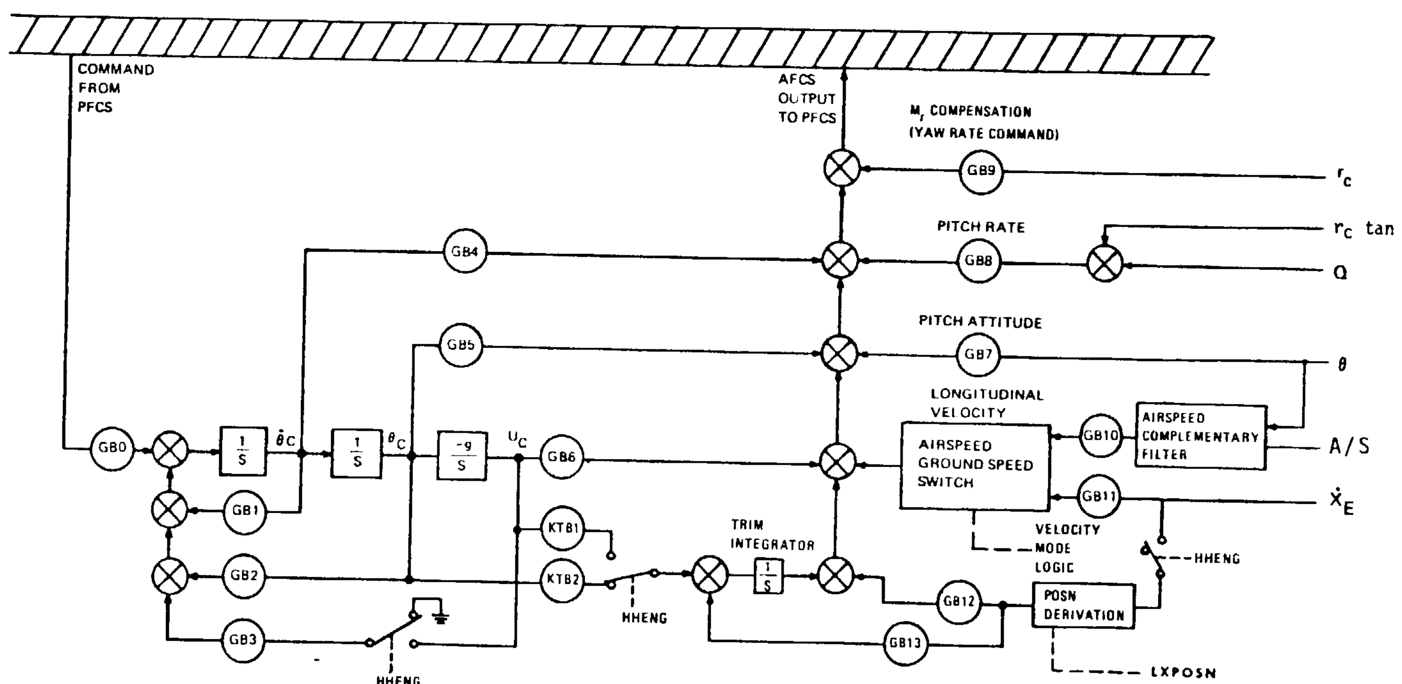


Figure 4-36

AFCS-LONGITUDINAL AXIS



NOTE: HHENG = 1 IF HOVER HOLD IS SELECTED ON. THIS RESULTS IN LINEAR VELOCITY COMMAND SYSTEM.

Figure 4-37

AFCS-LATERAL AXIS

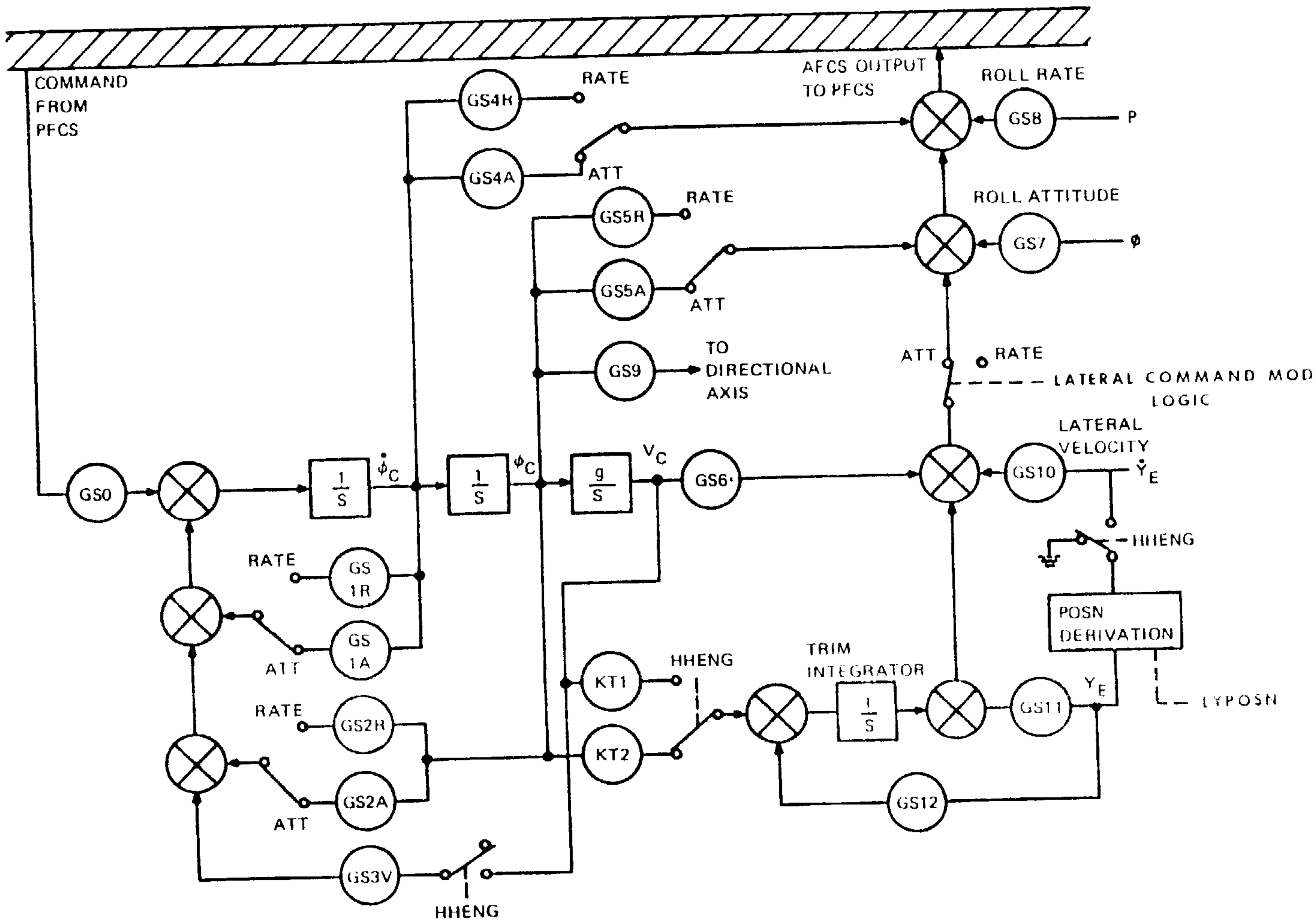


Figure 4-38

AFCS-DIRECTIONAL AXIS

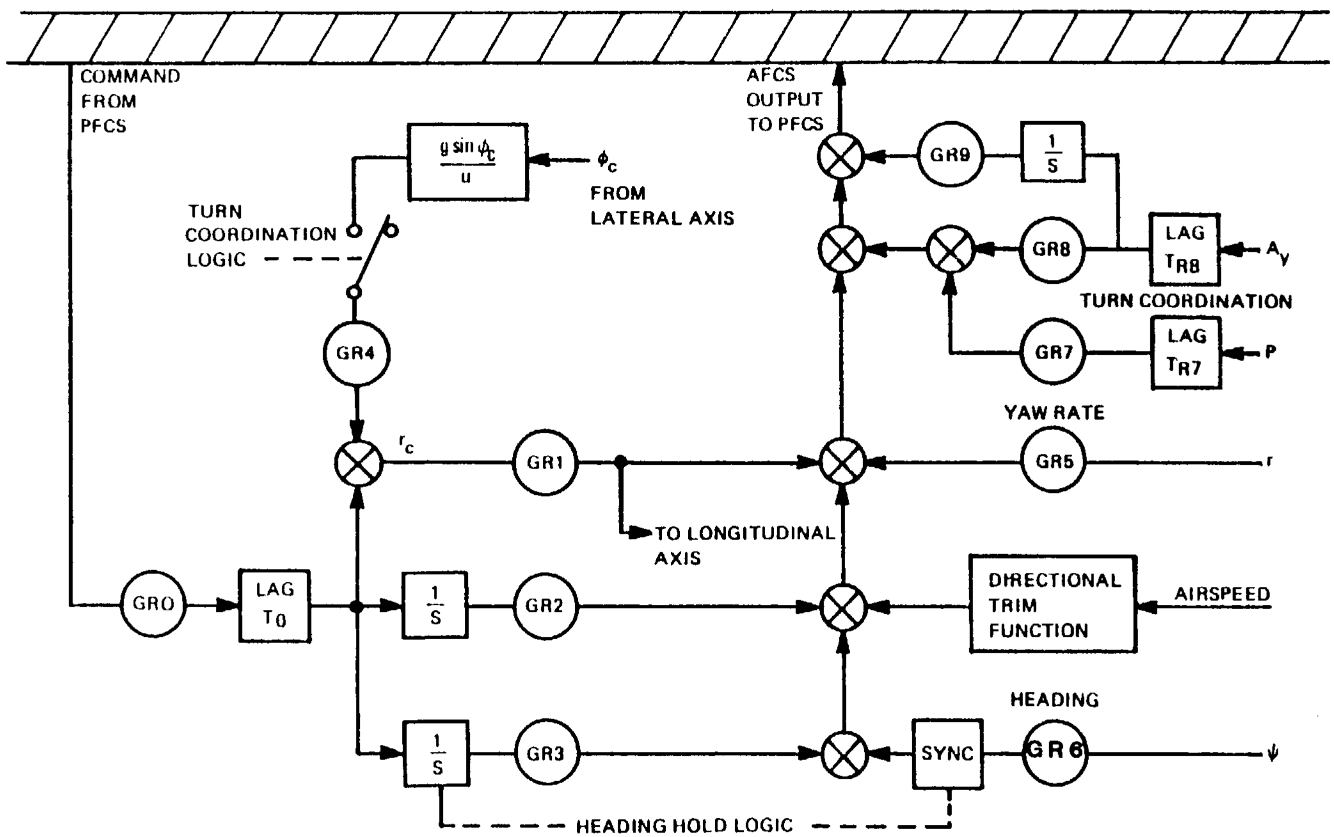


Figure 4-39

AFCS-VERTICAL AXIS

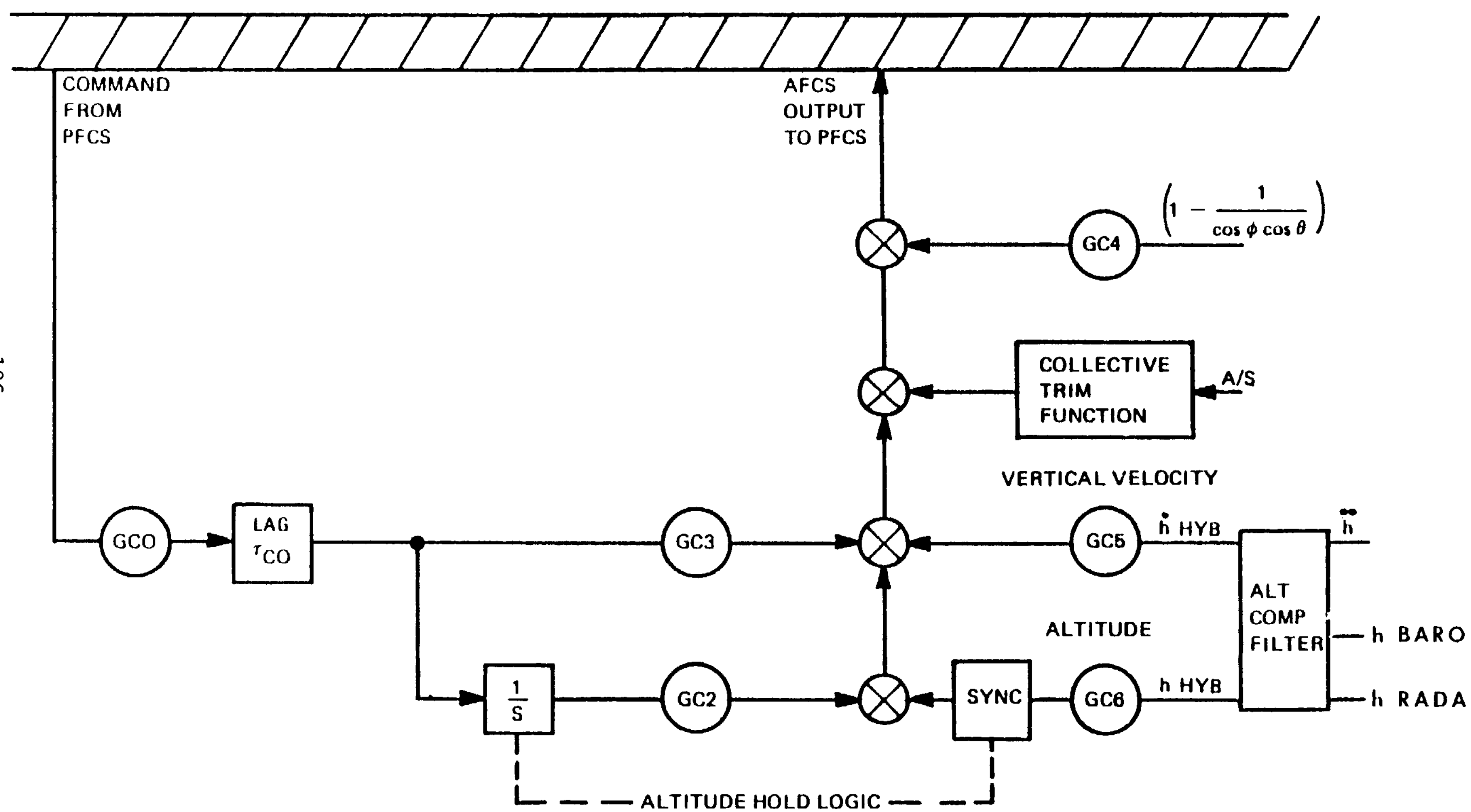


Figure 4-40

(Equation (5)) was implemented to eliminate the effects of high-frequency wind gust and shear upsets. A velocity mode transfer switch was also incorporated for the Phase 2 simulation to automatically switch transient-free between airspeed and ground-speed signals.

$$\text{complementary airspeed} = \frac{(K_1K_3+K_2K_3s)}{(s^2+K_2K_3s+K_1K_2)}\,u - \frac{K_4s}{(s^2+K_2K_3s+K_1K_2)}\,\theta \qquad (5)$$

where:

K_1, K_2, K_3, K_4 are gains selected for appropriate frequency response of filter

u is measured pitot static airspeed (knots)

θ is measured pitch attitude (rad)

The UH-60 has a non-symmetric pitch moment coupling in turn maneuvers. In forward flight the aircraft tends to pitch nose down in a right turn (gain airspeed) and pitch nose up in a left turn (lose airspeed). This characteristic is much stronger at low airspeeds (60 to 80 knots), and can be described as pitch moment due to yaw rate (M_r) coupling. A cross-axis control loop was incorporated to provide the necessary longitudinal control input to cancel the effect of the M_r stability derivative. Commanded turn rate (R_c) from the directional axis command model is used instead of measured aircraft yaw rate for stability reasons.

The longitudinal command model provides either a rate command system or an attitude command system. Response sensitivities for both the rate and attitude command systems were constant as a function of airspeed. A Hover Hold Mode was provided to select a velocity command system with either high gain velocity or position feedback. This mode is designed for use during the Precision Hover or the Bob-up Task.

Lateral

The lateral AFCS (Figure 4-38) uses body-axis roll rate feedback to obtain roll damping. A roll attitude feedback is included for full-time attitude stabilization at all airspeeds. Lateral velocity stabilization was provided to improve gust rejection as well as maneuvering characteristics at speeds less than 40 knots. Outer-loop position feedback was implemented in a manner similar to the longitudinal axis and was an option available with the Hover Hold Mode engaged.

A roll rate command or roll attitude command system could be selected in the lateral command model through appropriate gains. For Phase 2 simulation of full-envelope control laws, switches were incorporated in the lateral command model to provide automatic switching of control laws during transition from low-speed to forward flight and vice versa. For example, the lateral axis was implemented to provide an attitude command/ velocity stabilization system below 40 knots and an angular rate command/attitude stabilization system for high speed flight. Control law transfer was accomplished smoothly by use of transient-free switches and appropriate design of the lateral command mode logic as described in Volume 3-Simulation Results and Recommendations.

As in the longitudinal AFCS, the selectable Hover Hold Mode for Precision Hover Tasks adjusted appropriate gains in the lateral command model to provide a velocity command system. Capability to evaluate high-gain ground speed or position feedback stabilization with the same velocity command response characteristic was provided for the Hover Hold Mode.

In order to provide coordinated turn capability for forward flight evaluation during Phase 2 simulations, a cross-axis command path from the lateral to directional axis was included in the design. Commanded bank angle was fed to the directional axis to calculate a turn rate command as a function of airspeed.

Directional

Yaw rate feedback in the directional axis (Figure 4-39) provides yaw damping for directional stabilization. A trim function was programmed to automatically compensate for the basic helicopter directional trim requirement as a function of airspeed. Long-term Heading Hold stabilization was a selectable mode function operated by Heading Hold Mode logic.

For the Phase 2 simulation which included evaluation of forward flight handling qualities, automatic Turn Coordination was incorporated for airspeeds above 50 knots. Turn Coordination control loops included lateral acceleration through a proportional and integral path, and roll rate to improve initial turn entry coordination.

The Turn Coordination and Heading Hold control logic implemented for Phase 2 simulation operates automatically as a function of airspeed and aircraft flight condition. Turn Coordination is activated when airspeed exceeds 50 knots and a roll rate or turn condition is commanded, i.e., when lateral controller force command exceeds the force deadzone by 0.5 lbs. With Turn Coordination operating, the Heading Hold function is automatically disengaged while in turning flight. Turn Coordination remains On and Heading Hold Off until the aircraft is commanded to a near level roll attitude flight condition.

Synchronization of heading feedback and initialization of the command model heading integrator signal are controlled by the Heading Hold Mode logic. The directional command model forms a yaw rate command (r_c) using a lagged signal from the directional PFCS, and a turn-rate command signal activated by turn coordination logic. The turn rate signal is formed using roll attitude command from the lateral axis, i.e., $r_c = \frac{g \sin \phi_c}{\mu}$.

As air speed increases, the bank angle required to maintain a constant turn rate increases. Thus, the directional AFCS commands a heading rate such that a coordinated turn can be achieved throughout the forward speed range with zero directional controller force input. The yaw rate command signal is also fed to the longitudinal AFCS to compensate for the M_r stability derivative.

Vertical

Vertical axis (Figure 4-40) control laws were implemented to provide vertical height stabilization and altitude hold based on either a radar or barometric altitude reference. Vertical damping is obtained from a hybrid vertical velocity feedback signal that augments the inherent basic aircraft damping. The hybrid altitude and vertical velocity signals were formed with a complementary filter circuit using a vertical accelerometer and either a radar or barometric altimeter.

Altitude Hold Mode logic controls an altitude feedback synchronizer and command model integrator to initialize the system to a desired reference. High stabilization gains are provided for tight radar altitude hold for Precision Hover Tasks, and lower gains for Barometric Altitude Hold during high speed maneuvering.

A feedback control path which is a function of roll and pitch attitude is included to compensate for thrust-vector orientation changes. This compensation path is provided at all airspeeds and significantly reduces deviations in altitude while performing longitudinal and lateral maneuvers in hover and bank angle turns in forward flight.

A vertical trim function is also provided to compensate for the helicopter collective trim required as a function of airspeed. This reduces altitude hold excursions during acceleration/deceleration maneuvers.

The command model was implemented to provide a vertical rate response due to controller force inputs with Altitude Hold On. A command input from the PFCS was shaped by a lag filter to give an appropriate response time constant. Command model gains are changed as a function of airspeed to give the desired vertical rate response sensitivity for either Altitude Hold system (radar or baro).

The generic gains specified on each of the AFCS diagrams (Figure 4-37 through 4-40) determine the stabilization and response characteristics of each type of CMD/STAB system. Sets of gains used for each generic system evaluated during both simulation phases are presented in Tables 4-5 to 4-8. Transfer functions for each command response type have been calculated and are also presented in Laplace Transform notation in Tables 4-9 to 4-11.

Transfer functions presented in this report were calculated using EASY5 (Reference 31), a Boeing Company dynamic analysis program. The model utilizied by EASY5 was a 6 DOF small perturbation model based on the hover stability derivatives presented in Table 4-12. Command model and stabilization characteristics were incorporated in the transfer function analysis for each CMD/STAB system. The transfer functions contained herein are a simplified version of the transfer functions produced by EASY 5; that is, higher frequency terms and off axis, non-dominant roots were not included.

Appendix A contains time histories for the various command/ stabilization systems studies during Phase 2 simulations. Time histories shown were generated using EASY5, programmed with a command model and stabilization loops corresponding to the implementation at the NASA-Ames VMS. Non-linear shaping in the command path was not included, only the gain associated with the first slope of the shaping function was utilized.

Responses to a unit step input are shown. As discussed earlier (RA/AT) in Section 3.2, a rate/attitude command/stabilization system results in a constant rate being commanded and an attitude hold function when the input is released. Responses are also shown for attitude, velocity, and acceleration systems.

LONGITUDINAL AXIS SYSTEM GAINS

GAIN	CMD/STAB SYSTEM						
	AC/RA	RA/AT	AT/AT	AT/LV	AT/AS	LV/LV	LV/PH
GB0	1.6	0.8	0.8	0.8	0.8	0.8	0.8
GB1	4.0	4.0	5.0	5.0	5.0	6.0	6.0
GB2	0.0	.008	2.0	2.0	2.0	9.0	9.0
GB3	0.0	0.0	0.0	0.0	0.0	.03	.03
GB4	6.76	6.76	16.9	16.9	16.9	39.3	39.3
GB5	1.36	12.24	30.6	30.6	30.6	87.8	87.8
GB6	0.0	0.0	0.0	0.0	0.0	1.0	1.0
GB7	0.0	34.0	34.0	34.0	34.0	34.0	34.0
GB8	16.0	16.0	16.0	16.0	16.0	16.0	16.0
GB9	1.5	1.5	1.5	1.5	1.5	1.5	1.5
GB10	0.0	0.0	0.0	0.0	0.1	0.0	0.0
GB11	0.0	0.0	0.0	0.93	0.0	0.93	0.93
GB12	0.0	0.0	0.0	0.0	0.0	0.0	0.37
GB13	0.0	0.0	0.0	0.0	0.0	0.0	0.02
KTB1	0.0	0.0	0.0	0.0	0.0	0.1	0.1
KTB2	0.0	0.0	0.0	.1	.6	0.0	0.0

Note : See figure 4-37 for AFCS diagram.

Table 4-5

LATERAL AXIS SYSTEM GAINS

GAIN	CMD/STAB SYSTEM					
	AC/RA	RA/AT	AT/AT	AT/LV	LV/LV	LV/PH
GS0	1.6	1.6	1.6	1.6	2.2	2.2
GS1R	5.0	2.5	0.0	0.0	0.0	0.0
GS1A	0.0	0.0	3.5	3.5	4.4	4.4
GS2R	0.0	0.0	0.0	0.0	0.0	0.0
GS2A	0.0	0.0	3.0	3.0	6.2	6.2
GS3V	0.0	0.0	0.0	0.0	.044	.044
GS4R	3.36	1.68	0.0	0.0	0.0	0.0
GS4A	0.0	0.0	3.515	3.515	3.515	3.515
GS5R	0.68	4.56	0.0	0.0	0.0	0.0
GS5A	0.0	0.0	11.78	11.78	11.78	11.73
GS6	0.0	0.0	0.0	0.0	.15	.15
GS7	0.0	20.0	20.0	20.0	20.0	20.0
GS8	6.0	6.0	6.0	6.0	6.0	6.0
GS9	0.0	.242	.242	.242	.242	.242
GS10	0.0	0.0	0.0	.25	.25	.25
GS11	0.0	0.0	0.0	0.0	0.0	.1
GS12	0.0	0.0	0.0	0.0	0.0	.005
KTS1	0.0	0.0	0.0	0.0	.025	.025
KTS2	0.0	0.0	0.0	.15	0.0	0.0

Note : See figure 4-38 for AFCS diagram.

Table 4-6

DIRECTIONAL AXIS SYSTEM GAINS

CMD/STAB SYSTEM		
GAIN OR TIME CONSTANT	$\ddot{\psi}/\dot{\psi}$	$\dot{\psi}/\psi_H$
GR0	0.56	0.56
GR1	7.19	7.19
GR2	7.0	0.0
GR3	0.0	7.7
GR4	0.0	1.0
GR5	7.19	7.19
GR6	0.0	7.7
GR7	0.0	0.93
GR8	0.0	0.2
GR9	0.0	0.05
τ_O	0.5	0.5
τ_{R7}	0.0	0.5
τ_{R8}	0.0	0.8

Note : See figure 4-39 for AFCS diagram.

Table 4-7

VERTICAL AXIS SYSTEM GAINS

CMD/STAB SYSTEM		
GAIN OR TIME CONSTANT	$\ddot{h}/\dot{h}$	$\dot{h}/h_H$
GC0	2.0-2.85	4.0-5.7
GC2	1.5	.07-.35
GC3	.15-.35	.15-.35
GC4	2.9	2.9
GC5	0.0	.07-.35
GC6	.15-.35	.15-.35
τ_{CO}	.25	.25

Note : Gains varied as a linear function of airspeed as shown. See figure 4-40 for AFCS diagram.

Table 4-8

LONGITUDINAL AXIS TRANSFER FUNCTIONS *

CMD SYSTEM	TRANSFER FUNCTION
RA/AT	$\frac{q}{\delta_B} = \frac{.308(S+2.7)(S+8.6)(S^2+3.12S+2.85)}{(S+2)(S+3.7)(S+4)(S^2+5.6S+9.9)}$
AT/AT	$\frac{\theta}{\delta_B} = \frac{6.17(S+2.7)(S^2+3.5S+3.4)}{(S+0.44)(S+2)(S+3.8)(S+4.56)(S^2+5.8S+10)}$
AT/LV	$\frac{\theta}{\delta_B} = \frac{5.88(S+1.33)}{(S+0.44)(S+1.24)(S+4.56)(S+6.9)}$
LV/LV	$\frac{\dot{X}}{\delta_B} = \frac{65.7(S+1.8)(S+2.3)(S^2+.09S+6)(S^2+2.23S+1.57)}{(S+2)(S+2.2)(S+6.9)(S+5.7)(S^2+.835+.19)(S^2+1.7S+1.8)}$

* PHASE 2 SIMULATION

Table 4-9

LATERAL AXIS TRANSFER FUNCTIONS*

CMD/STAB SYSTEM	TRANSFER FUNCTION
RA/AT	$\frac{P}{\delta_S} = \frac{0.19(S+2)(S+5)(S+6.67)}{(S+2.5)(S+3.73)(S^2+5.65S+9.9)}$
AT/AT	$\frac{\phi}{\delta_S} = \frac{2.18(S+3.16)(S+5.3)}{(S+1.5)(S+2)(S+3.8)(S^2+5.8S+10)}$
AT/LV	$\frac{\phi}{\delta_S} = \frac{.15(S+.43)(S+5.4)(S+7.3)(S^2+3.62S+3.4)(S^2+5.2S+6.8)}{(S+.56)(S+1.5)(S+2)(S+2.2)(S+2.5)(S+6.9)(S^2+3.4S+3.1)}$
LV/LV	$\frac{\dot{Y}}{\delta_S} = \frac{515.0(S^2+4.6S+5.3)}{(S+.25)(S+2.2)(S+2.5)(S^2+4S+7.6)(S+6.87)}$

* PHASE 2 SIMULATION

Table 4-10

DIRECTIONAL AND VERTICAL AXES TRANSFER FUNCTIONS

CMD SYSTEM / AXIS	DIRECTIONAL AXIS	VERTICAL AXIS
RATE COMMAND	$\frac{R}{\delta_R} = \frac{.77(S+1.04)(S+8.2)^2(S+14)}{(S+1.24)(S+2)(S+6.9)(S^2+17.4S+82.8)}$	$\frac{\dot{h}}{\delta_C} = \frac{3.83(S+.86)(S+1.92)(S+23.1)}{(S+2.18)(S+4)(S^2+3.4S+3.11)}$
ACCELERATION COMMAND	$\frac{\dot{R}}{\delta_R} = \frac{.77(S+.94)(S+8.2)^2(S+14)}{(S+2)(S+7.4)(S^2+18.2S+94)}$	$\frac{\ddot{h}}{\delta_C} = \frac{3.89(S+4.5)(S+9.5)}{(S+3.73)(S+4)}$

Table 4-11

UH-60A STABILITY DERIVATIVES - HOVER CASE

G.W. =	16824.91	LBS	VEL. =	.50	KTS	ALT. =	25.00 FT
C.G. =	-9.20	IN	R/C =	.00	FPM	TEMP =	59.00 DEG

	L/IXX	M/IYY	N/IZZ	X/M	Y/M	Z/M
DELB	-.0627	-.3286	-.0021	1.7041	-.0845	.1134
DELS	1.3118	-.0051	.0266	.0478	.9664	.0036
DELR	-.9313	.0411	.7153	1.1265	-1.7151	.6799
DELC	-.0620	-.0183	.0665	1.0893	.2289	-8.5827
P	-3.3484	.2938	-.1856	-1.6106	-1.5152	-.1703
Q	-1.6917	-.5193	-.4165	1.3499	-1.4242	.1135
R	.2119	-.0687	-.2879	-.3497	.4485	2.0788
U	.0386	.0005	.0018	-.0150	.0168	-.0050
V	-.0260	.0085	.0081	-.0092	-.0465	-.0097
W	.0024	.0021	-.0010	.0212	.0038	-.2748
IHT	.0000	.0009	.0000	-.0009	.0000	.0024

Table 4-12

5.0 VISUAL DISPLAY SYSTEMS FOR IMC

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 of the pilot's night vision aids on the aircraft handling qualities. A review of pertinent literature revealed numerous systems designed to allow flight operations in an IMC environment. These systems ranged in sophistication and ideology from a kinesthetic tactual display system (Reference 32) to a fully developed flight director system (Reference 33). Literature also emphasized that the design of display dynamics, and in fact control law development, depends upon the type of display used -- panel mounted, heads-up (HUD), or helmet mounted (HMD). After consideration of alternate approaches, one display system was felt to be uniquely suited for use during the ACC/AFCS simulation program. The Integrated Helmet and Display Sight System (IHADSS) developed for the Army YAH-64 Advanced Attack Helicopter (AAH) was selected.

For this simulation program, it was assumed that the pilot is provided with the AH-64 Pilot Night Vision System (PNVS) and associated avionics (Reference 34) which includes a helmet mounted display system. The PNVS evolved directly from the Advanced Attack Helicopter (AAH) mission requirements and is specifically designed to allow a pilot to perform a mission using terrain flying techniques at night or under any other form of IMC.

The PNVS incorporates a forward-looking infared (FLIR) sensor to provide a limited field-of-view monochromic image of the outside world that is slaved to the pilot's helmet movement. The FLIR field-of-view is 30 degrees by 40 degrees and can be rotated ±90 degrees in azimuth and +20 to -45 degrees of elevation. A symbology generator is employed to superimpose flight control and fire control symbology upon the image.

The Honeywell IHADSS was selected for simulation of the IMC mission. 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.

Using IHADSS, the pilot is able to:

- o Fly the aircraft at night by pointing a night vision sensor with natural head movements only, using the HMS, and then viewing the imagery with the HMD as though he were scanning the terrain under daylight conditions;

- Point weapons simply by looking at the target through his HMD;
- Point the target acquisition designation system (TADS) with his HMS, and
- View critical flight control, navigation, and fire control information on the HMD, day or night, without shifting his line-of-sight from the target to look down into the cockpit at control panel instruments.

Flight Control Symbology

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 35. Baseline display laws and information format used for this investigation were defined based on the AH-64 Pilot Night Vision System (PNVS) described in Reference 34.

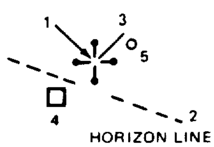
Figure 5-1 presents the display mode symbology divided into three categories - central, peripheral, and weapon delivery/ fire control symbology. The characteristics of each symbol are described and the symbols which appear for the four-mission modes are identified. The selectable display modes, which are used to meet the operational requirements for various AAH mission tasks, are:

CRUISE MODE (Figure 5-2). This mode is intended for high-speed level flight and normal maneuvering enroute to the forward edge of the battle area. Data presented include indicated airspeed, heading, radar altitude, instantaneous rate of climb, engine torque, line of sight, and an artificial horizon reference. Gains and time constants are adjusted for forward flight conditions.

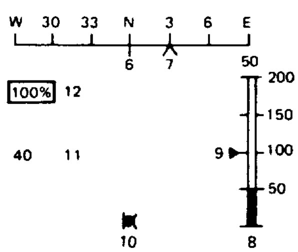
TRANSITION MODE (Figure 5-3). This mode is recommended for low speed NOE flight including dash, quick stop, and sideward flight maneuvers. Velocity and acceleration symbols are presented in addition to the aircraft-state data provided for the cruise mode. Aircraft velocity is presented as a vector and acceleration is indicated as the displacement of a ball relative to the end of the velocity vector.

HOVER MODE (Figure 5-4). This mode is used to maintain a stable hover with minimum drift. Major differences between this mode and the transition mode are the sensitivities of the velocity vector and the acceleration cue. Because this mode is intended for use at low speeds around hover, velocity and acceleration gains are increased to provide higher sensitivity and better resolution. In this mode, a position reference symbol is also added but remains stationary at a center position until activated by the Bob-Up mode.

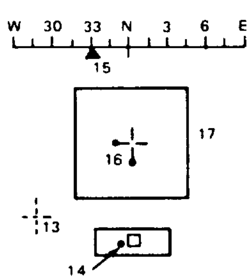
IHADSS SYMBOLOGY



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 5-1

IHADSS CRUISE MODE SYMBOLOGY

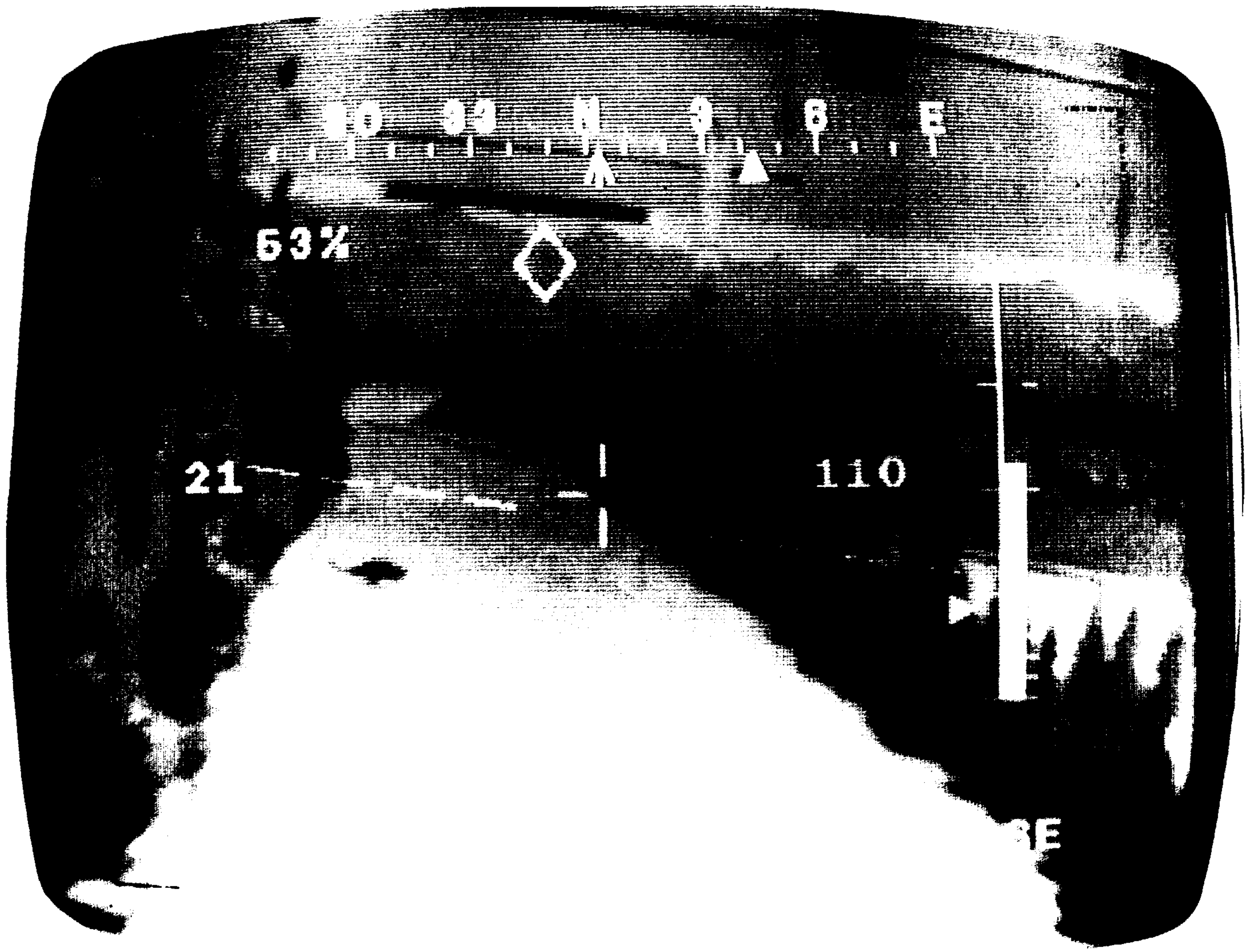


Figure 5-2

IHADSS TRANSITION MODE SYMBOLOGY

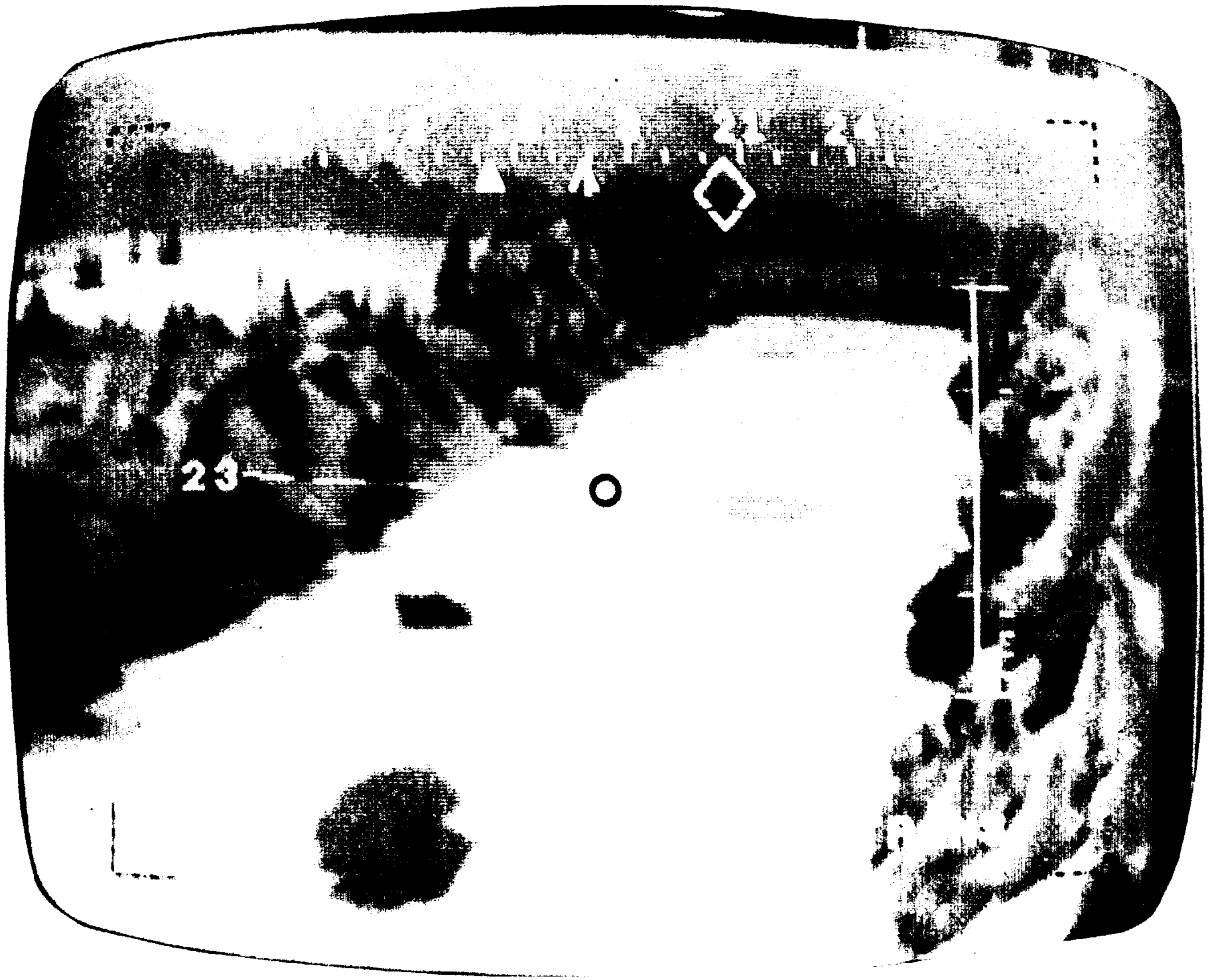


Figure 5-3

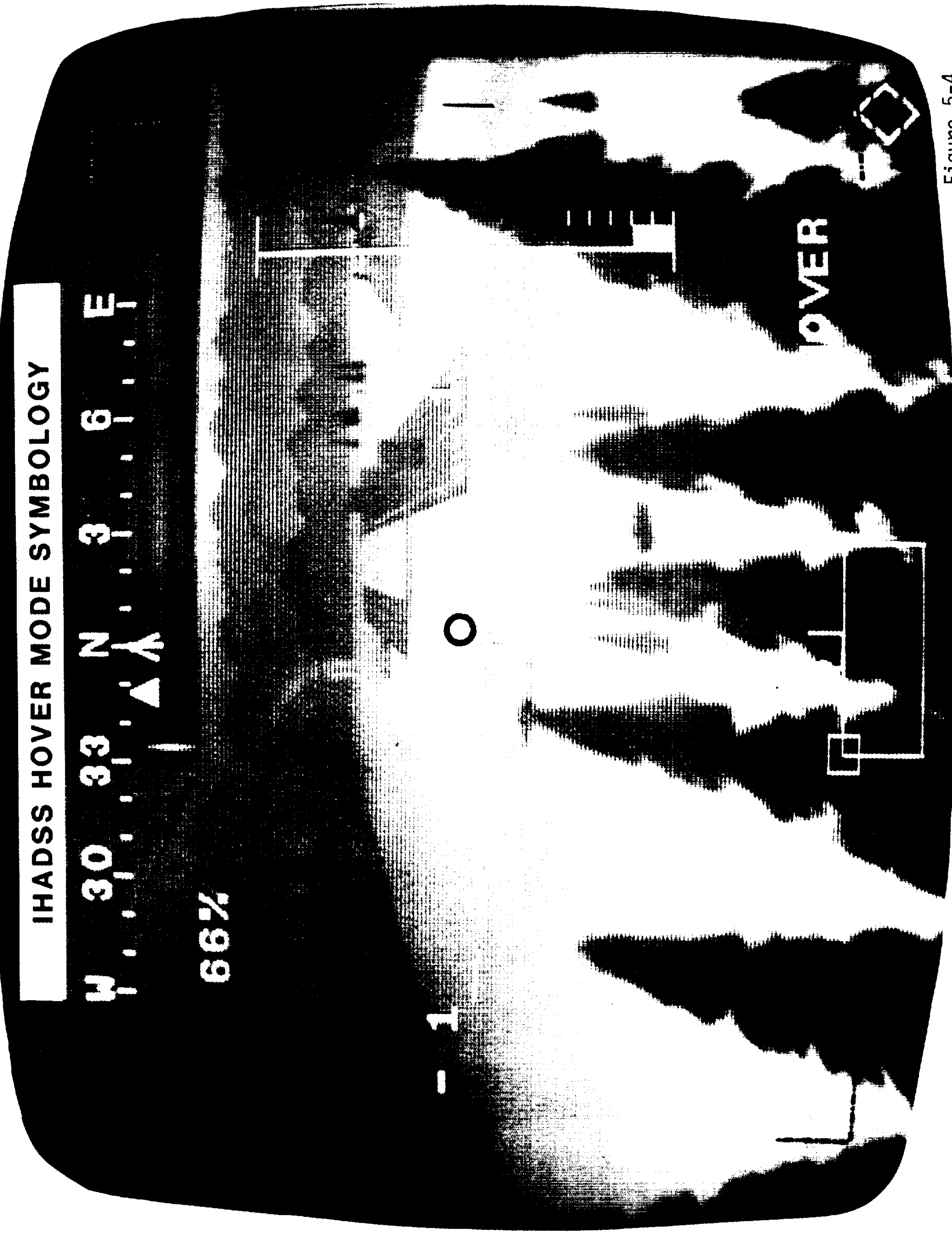


Figure 5-4

BOB-UP MODE (Figure 5-5). The Bob-up Task includes unmask, target acquisition, and remask maneuvers over a desired ground position. Symbology for the Bob-up includes a position reference symbol to provide information as to deviation from the initial hover location. The artificial horizon is removed in this mode because cyclic cues are provided for by the acceleration ball relative to the position indicator.

Display Dynamics

Various simulation studies (References 1, 22, and 35) have been performed to define display requirements and associated display dynamics for NOE flight. In a simulator investigation of a night-time attack helicopter mission which included a head-up display of the PNVS symbology (Reference 22), 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.

During preliminary Phase 1 simulations, variations to the baseline AH-64 symbology were made based on Reference 22 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 Phase 1 IHADSS check-out, 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,

IHADSS BOB-UP MODE SYMBOLOGY

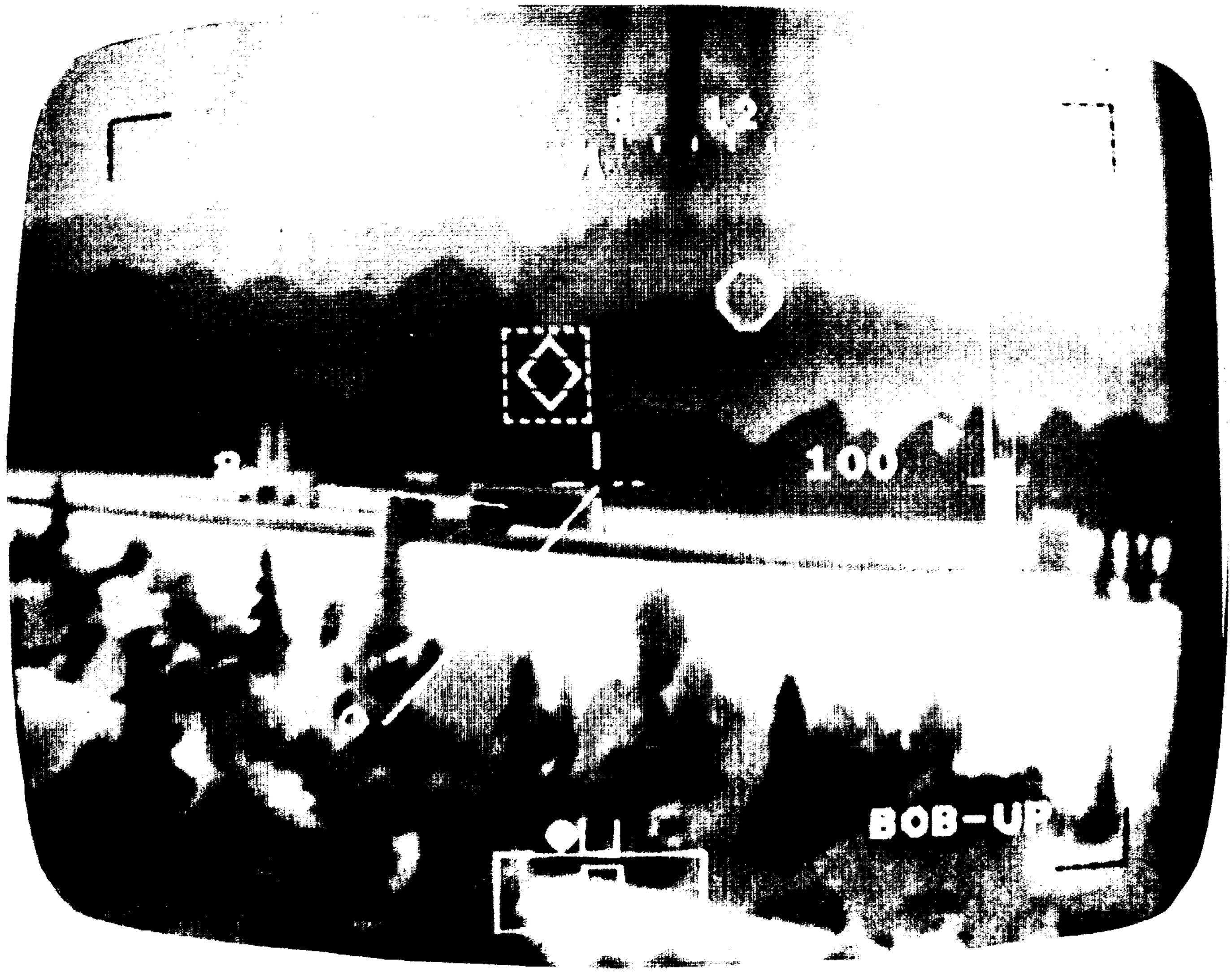


Figure 5-5

i.e., rate, attitude, or velocity. Values were established in the same manner discussed in Reference 1.

Table 5-1 summarizes the sensitivities and time constants selected for the display symbology. The above changes to display dynamics were implemented for all IMC simulations conducted during Phase 1 and Phase 2.

Prior to the Phase 2B simulation at NASA Ames, the IHADSS symbology was altered based on pilot comments received during Phase 1 Simulations. A complete description of these changes is included in Section 6 of Volume 3.

SELECTED SCALING FOR IHADSS SYSTEM

MODE	VELOCITY VECTOR SENSITIVITY FT/SEC-FULL SCALE	HOVER POSITION SENSITIVITY FT-FULL SCALE	LONGITUDINAL ACCELERATION		LATERAL ACCELERATION	
			SENSITIVITY DEG-FULL SCALE	TIME CONSTANT (SEC)	SENSITIVITY DEG-FULL SCALE	TIME CONSTANT (SEC)
BOB-UP	20 15**	88*	75	3	75	3
HOVER	20 15**	—	75	3	75	3
TRANSITION	202 160**	—	15	50	30	10
CRUISE	202 160**	—	15	50	30	10

* NON LINEAR SCALING USED FOR PHASE 2B
** VALUES USED FOR PHASE 2B

Table 5-1

6.0 CONCLUDING REMARKS

The literature review and preliminary analysis of Phase 1 guided the design of all ACC/AFCS simulation experiments and test plans as follows.

Side-stick controller characteristics were defined based on a recommended region of force/deflection characteristics resulting from AFFDL testing. Three candidate 4-axis controllers, one with variable force/deflection characteristics, were selected to bracket the AFFDL recommended region. A simulation test plan was written to conduct a comprehensive evaluation of controller force/deflection characteristics during the first simulation phase at Boeing Vertol.

Proper response/force sensitivities are critical to the successful implementation of a side-stick controller. Studies showed that the range of acceptable response sensitivity varies as a function of force/deflection gradient. Because of the criticality of choosing proper control response sensitivity values for a SSC, initial Phase 1 simulation experiments were designed to define acceptable response sensitivity values for each 4-axis controller. These tests were necessary before the various side-stick controller configurations described below could be evaluated.

Integration of four axes of control onto a single, right-hand SSC was demonstrated by both the HLH and Canadian NAE flight research programs. Four candidate controller configurations were chosen for evaluation in order to collect data on the interaction of controller configuration, SCAS (control response type and level of stabilization), and visual display system (VMC versus IMC). The four configurations selected include:

(1) <u>(4+0)</u>: All control axes (pitch, roll, yaw, and vertical) on the right-hand side-stick controller,

(2) <u>3+1 (Collective)</u>: 3-axis side-stick for pitch, roll, and yaw control, and a separate left-hand controller for vertical control,

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

(4) <u>(2+1+1)</u>: 2-axis side-stick for pitch and roll control, with separate left-hand controller for vertical control, and pedals for directional control.

The importance of SSC orientation with respect to the pilot seat was emphasized in literature. Therefore, the installation of all controllers included an adjustable mounting bracket allowing for changes in forward tilt, lateral tilt, and twist about the controller's vertical axis. An adjustable armrest was also provided to increase pilot comfort and minimize inter-axis coupling.

Activation of switches located on a small-deflection or stiff SSC can easily cause inadvertent control inputs. Low-force switches having a breakout of less than half the force breakout in any particular control axis were recommended. Switch location on the SSC grip was found to be extremely important as well; switches should be located within one inch of the pilot's thumb with his hand normally placed on the grip.

The achievement of Level 1 handling qualities ratings depends on the interaction of the three primary elements of the ACC/AFCS study. For instance, the relationship between display system and SCAS configuration has been reported in detail. To achieve satisfactory handling qualities ratings, a tradeoff exists between the required pilot visual aids for degraded visual conditions and/or level of command/stabilization augmentation. An objective of the ACC/AFCS study was to define the combinations of display, SCAS, and controller configuration which provide Level 1, 2 and 3 ratings. Various command/stabilization systems were designed using a generic SCAS implementation which allowed control response characteristics to be easily altered through command model gains. The simulation test plan was formulated to evaluate a large matrix of SCAS/controller configuration combinations for both VMC and IMC tasks, with IMC simulated using IHADSS. Variations in the standard AH-64 symbology were included based on the results and recommendations of previous studies. Simulation results are presented in Volume 3 of this report.

REFERENCES

1. Aiken, Edwin W. and Merrill, Lt. Col. Robert K.; "Results of a Simulator Investigation of Control System and Display Variations for an Attack Helicopter Mission". AHS Preprint No. 80-28, May 1980.

2. Sjoberg, S.A.; Russell, W.R.; and Alford W.L.: "Flight Investigation of a Small Side-Located Control Stick Used With Electronic Control Systems in a Fighter Airplane". NACA RM L56L28A, 1957.

3. Staten, K.E. and Theurer, B.: "F-104D Side Stick Control System". Presented at 14th Annual SETP Symposium, Beverly Hills, CA, Sept. 1970.

4. Kemmerling, P.; Cronbury, J.G.; and Thorburn, D.E.: "A Comparison of Pilot Performance Using a Center Stick vs. Sidearm Control Configuration". ASD-TR-70-39, Nov. 1970.

5. Deardorff, J.C.; Friesner, A.L.; and Albion, N.: "Flight Test Development of the Tactical Aircraft Guidance System". AHS Preprint No. 761, May 1973.

6. Tactical Aircraft Guidance System Advanced Development Program Flight Test Report; Volumes 1 and 2, Boeing Vertol Company, Philadelphia, PA, Document No. D214-40006-1, -2; June 1972.

7. McManus, Bruce L.: "Fly-By-Wire for Vertical Lift". AHS Preprint No. 78-15, presented at the 34th Annual National Forum of the AHS, Washington, DC; May 1978.

8. Advanced Scout Helicopter (ASH) Fly-By-Wire Flight Control System Preliminary Design; Volume I, Boeing Vertol Company, Philadelphia, PA, Document No. D210-11560-1, October 1980.

9. Padfield, G.D.; Tomlinson, B.N.; and Wells, P.M.: "Simulation Studies of Helicopter Agility and Other Topics". RAE Technical Memorandum, 1978.

10. Sinclair, M. and Morgan M.: "An Investigation of Multi-Axis Isometric Side-Arm Controllers in a Variable Stability Helicopter". National Research Council Canada LR-606, NRC #19629, Aug. 1981.

11. Landis, K. and Aiken, E., "An Assessment of Various Side-Stick Controller/Stability and Control Augmentation Systems for Night Nap-of-the-Earth Flight", Helicopter Handling Qualities, NASA CP-2219, April 1982.

12. Black, G.T. and Moorhouse, D.J.: "Flying Qualities Design Requirements for Sidestick Controllers". AFFDL-TR-79-3126, Oct 1979.

13. Smith, S.B.: "Limited Flight Evaluation of Side Stick Force-Deflection Characteristics on Aircraft Handling Qualities". AFFTC-TR-77-34, Nov. 1977.

14. Smith, S.B. and Miller, C.M.: "An Evaluation of Sidestick Force/Deflection Characteristics on Aircraft Handling Qualities". AFFDL-TR-78-171, Oct. 1978.

15. Hall, G.W. and Smith, R.E.: "Flight Investigation of Fighter Side-Stick Force-Deflection Characteristics". AFFDL-TR-75-39, May 1975.

16. Landis, K., Aiken, E., Dunford, P., and Hilbert, K., "A Piloted Simulator Investigation of Side-Stick Controller/ Stability and Control Augmentation System Requirements for Helicopter Visual Flight Tasks," Presented at the 39th Annual Forum of the American Helicopter Society, Paper A-83-39-59-4000, St. Louis, Mo., May, 1983.

17. Landis, K.H.; Glusman, S.I.; Aiken, E.W.; and Hilbert, K.B.; "An Investigation of Side-Stick-Controller/Stability and Control-Augmentation System Requirements for Helicopter Terrain Flight Under Reduced Visibility Conditions." Presented at the 22nd Aerospace Sciences Meeting, AIAA-84-0235, January 1984.

18. Greif, R.K.; Fry, E.B.; Gerdes, R.M.; and Gossett, T.D.: "Effects of Stabilization on VTOL Aircraft in Hovering Flight". NASA TND-6900, Aug. 1972.

19. Corliss, L.; Greif, R.K.; and Gerdes, R.M.; "Comparison of Ground-Based and In-Flight Simulation of VTOL Hover Control Concepts". J. Guidance and Control, Volume 1, Number 3, May-June, 1978.

20. Corliss, L.D. and Dugan, D.C., "A VTOL Translational Rate Control System Study on a Six-Degree-of-Freedom Motion Simulator, "NASA TX X-62,194, Oct. 1972.

21. <u>Advanced Technology Component Program Flight Control System - Task 1 - Summary Report</u>; Boeing Vertol Company, Philadelphia, PA, Document No. D301-10095-1, December 1971.

22. <u>Heavy Lift Helicopter Flight Control System</u>; Volume III - Automatic Flight Control System Development and Feasibility Demonstration. Boeing Vertol Company, Document No. USAAMRDL-TR-77-400, September 1977.

23. Cooper, G.E. and Harper, R.P., Jr., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," NASA TN D-5153, 1969.

24. Bramwell, A.R.S.; Helicopter Dynamics, Edward Arnold, Ltd.; 1976.

25. Lebacqz, J.V.; and E.W. Aiken: "A Flight Investigation of Control, Display and Guidance Requirements for Decelerating Descending VTOL Instrument Transitions Using the X-22A Variable Stability Aircraft." Calspan Report No. AK-5336-F-1, September 1975.

26. Hoh, Roger H. and Ashkenas, Irving L.; "Handling Quality and Display Requirements for Low Speed and Hover in Reduced Flight Visibility". AHS preprint No. 79-29, May 1979.

27. Merrick & Gerdes, R.M.; "Design and Piloted Simulation of a VTOL Flight-Control System." J. Guidance and Control, Vo. 1, No. 3, May-June, 1978.

28. Davis, J.M.; Landis, K.H.; and Leet, J.R.: "Development of Heavy Lift Helicopter Handling Qualities for Precision Cargo Operations." AHS Preprint No. 940, Presented at the 31st Annual National Forum of the AHS, Washington, DC; May 1975.

29. Lebacaz, J. Victor: "Survey of Helicopter Control/Display Investigations for Instrument Decelerating Approach." NASA TM 78565, 1978.

30. Kelly, James R.; Neissen Frank R.; Yenni, Kenneth R.; and Person, Lee H.; "Flight Investigations of a Vertical-Velocity Command System for VTOL Aircraft. NASA TND-8480, July 1977.

31. EASY5 Dynamic Analysis System User's Guide; Boeing Company, 1980.

32. Gilson, R.D.; Dunn, R.S.; and Sun, P.: "A Kinesthetic - Tactual Display Concept for Helicopter - Pilot Workload Reduction." AHS Preprint No. 77.33-22, Presented at the 33rd Annual National Forum of the AHS, Washington, D.C.; May 1977.

33. Kelly, J.R.; Niessen, F.R.; Thibodeaux, J.J.; Yenni, K.R.; and Garren, J.F., "Flight Investigation of Manual and Automatic VTOL Decelerating Instrument Approaches and Landing." NASA TND-7524, July 1974.

34. Tsoubanos, C.M. and Kelly, M.B.: "Pilot Night Vision System (PNVS) for Advanced Attack Helicopter (AAH)". AHS

Preprint No. 78-16, Presented at the 34th Annual National Forum of the AHS, Washington, DC; May 1978.

35. Keane, William P.; et al: "A Versatile Display System for NOE Operations." AHS Preprint No. 77.33-24, Presented at the 33rd Annual National Forum of the AHS, Washington, DC; May 1977.

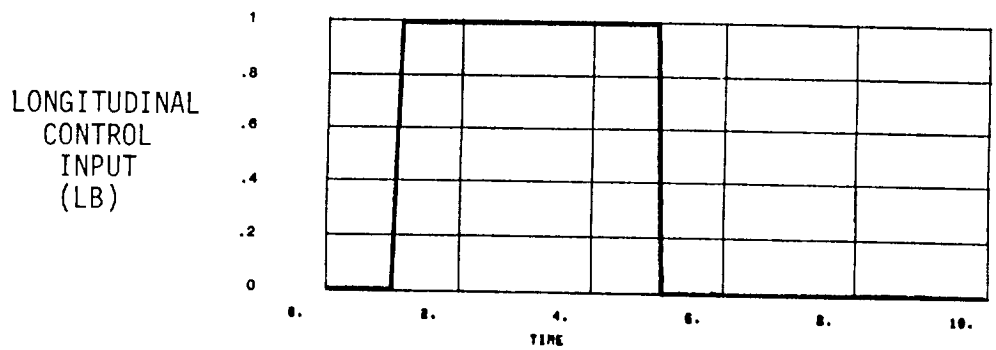
36. Pape, James K. and Garland, Michael P.; F-16 A/B Flying Qualities Full Scale Development Test and Evaluation. AFFTC-TR-79-10, September 1979.

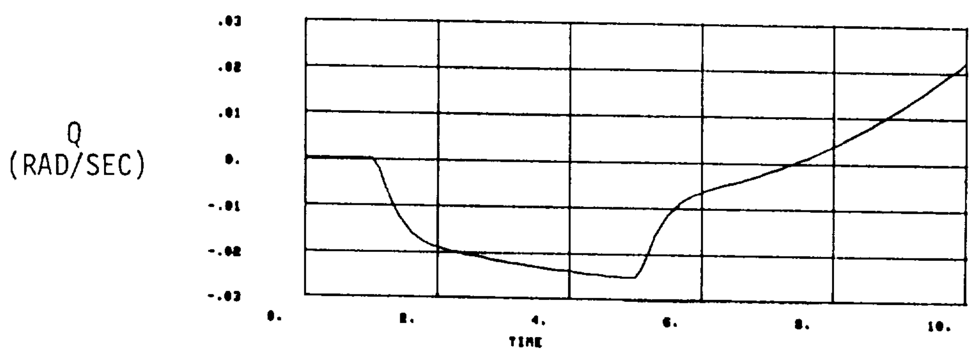
37. "Air Vehicle Technical Description Data Report - UH60A Input Data for C-81 Rotorcraft Simulation Program" SER-70189 dated 2 March 1977.

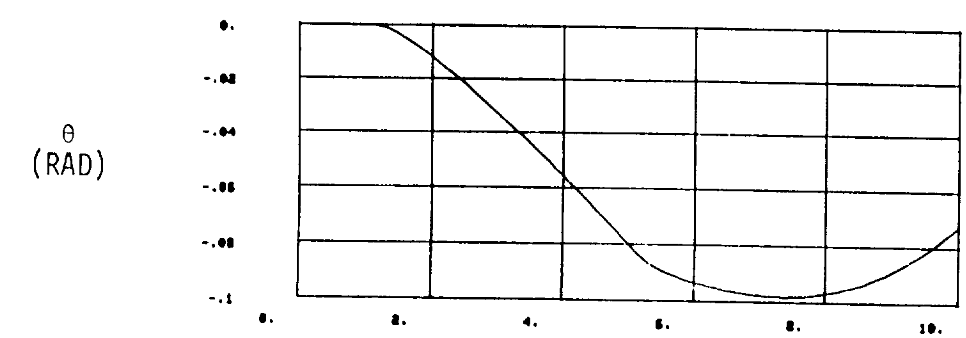
38. Anon, "Military Specification, Flying Qualities of Piloted Airplanes", MIL-F-8785B (ASG), 7 August 1969.

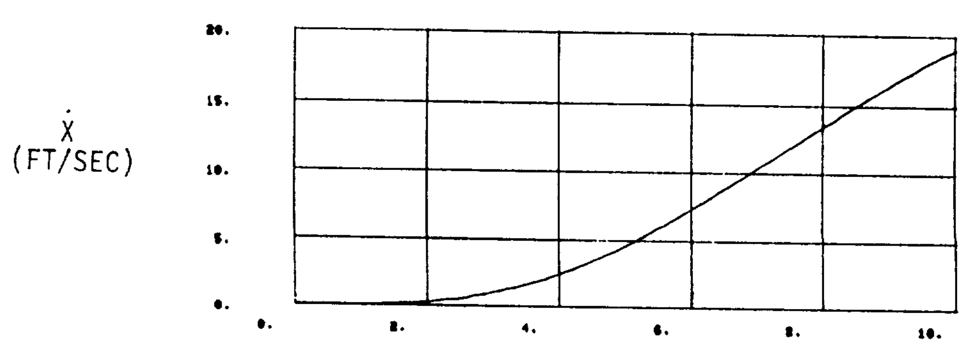
APPENDIX A

LONGITUDINAL AXIS - AC/RA SYSTEM

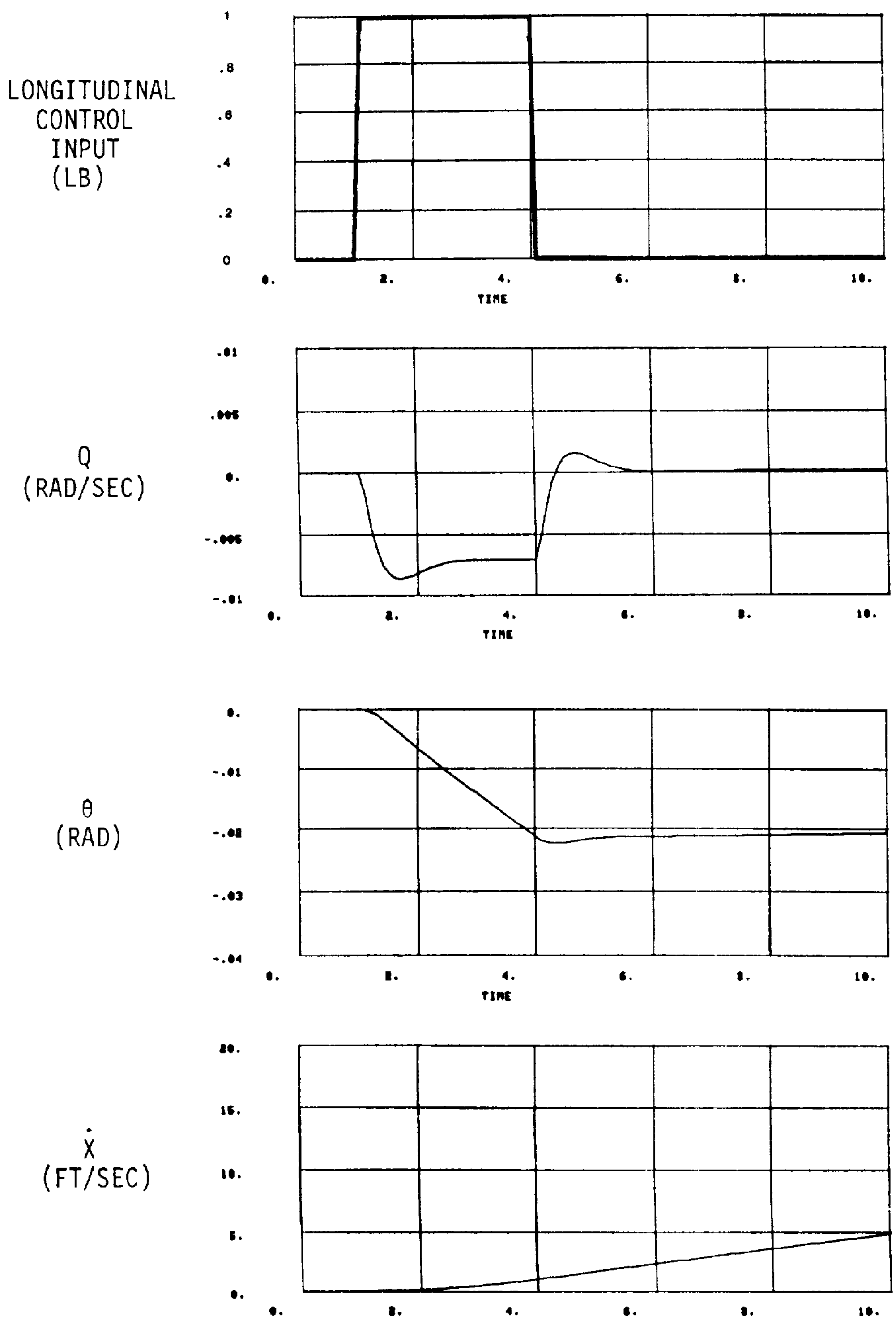




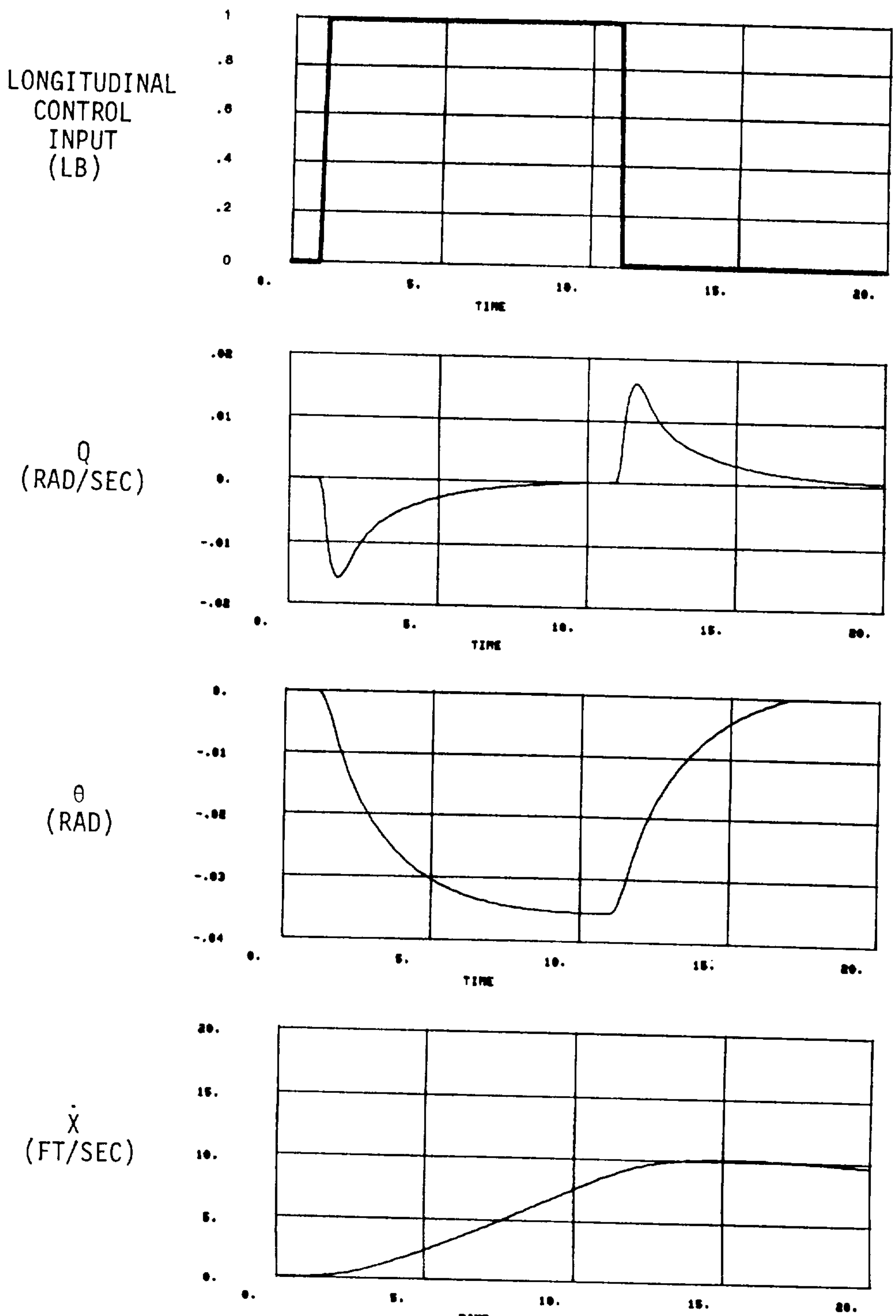




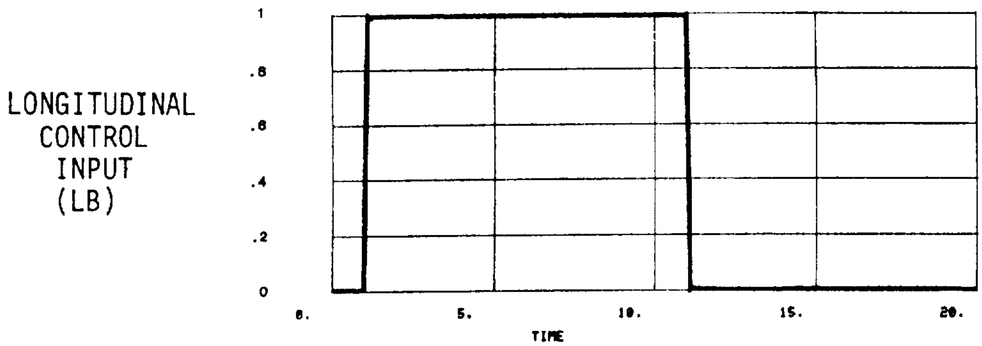
LONGITUDINAL AXIS - RA/AT SYSTEM

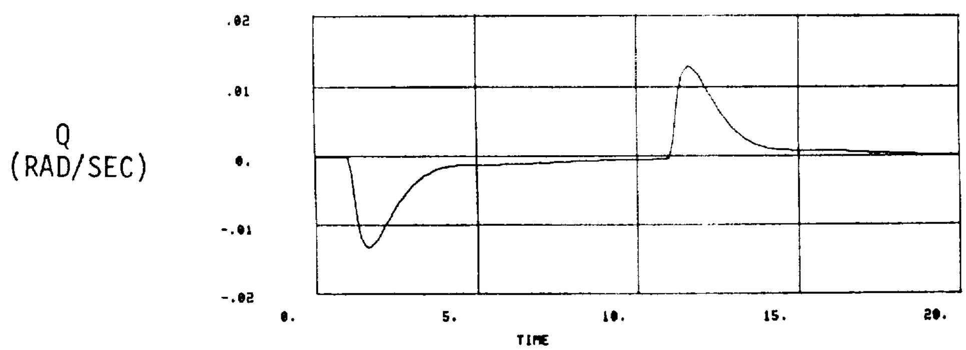


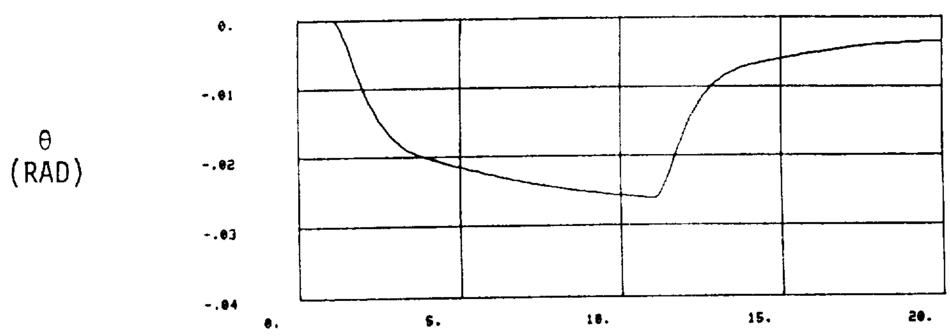
LONGITUDINAL AXIS - AT/AT SYSTEM

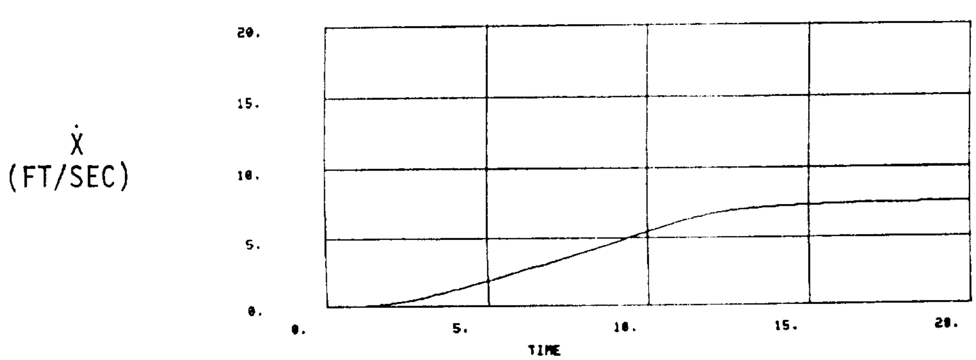


LONGITUDINAL AXIS - AT/LV SYSTEM

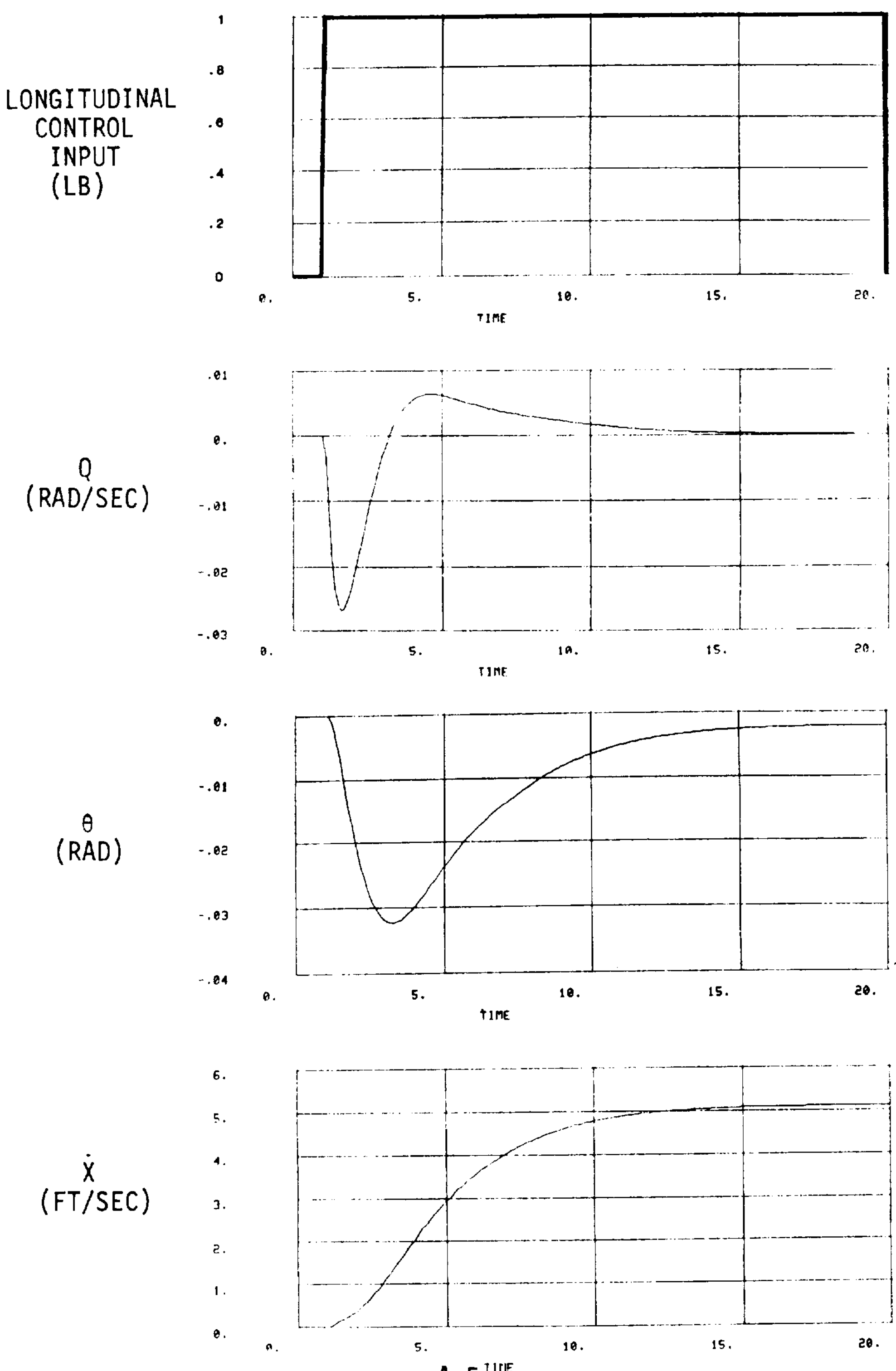




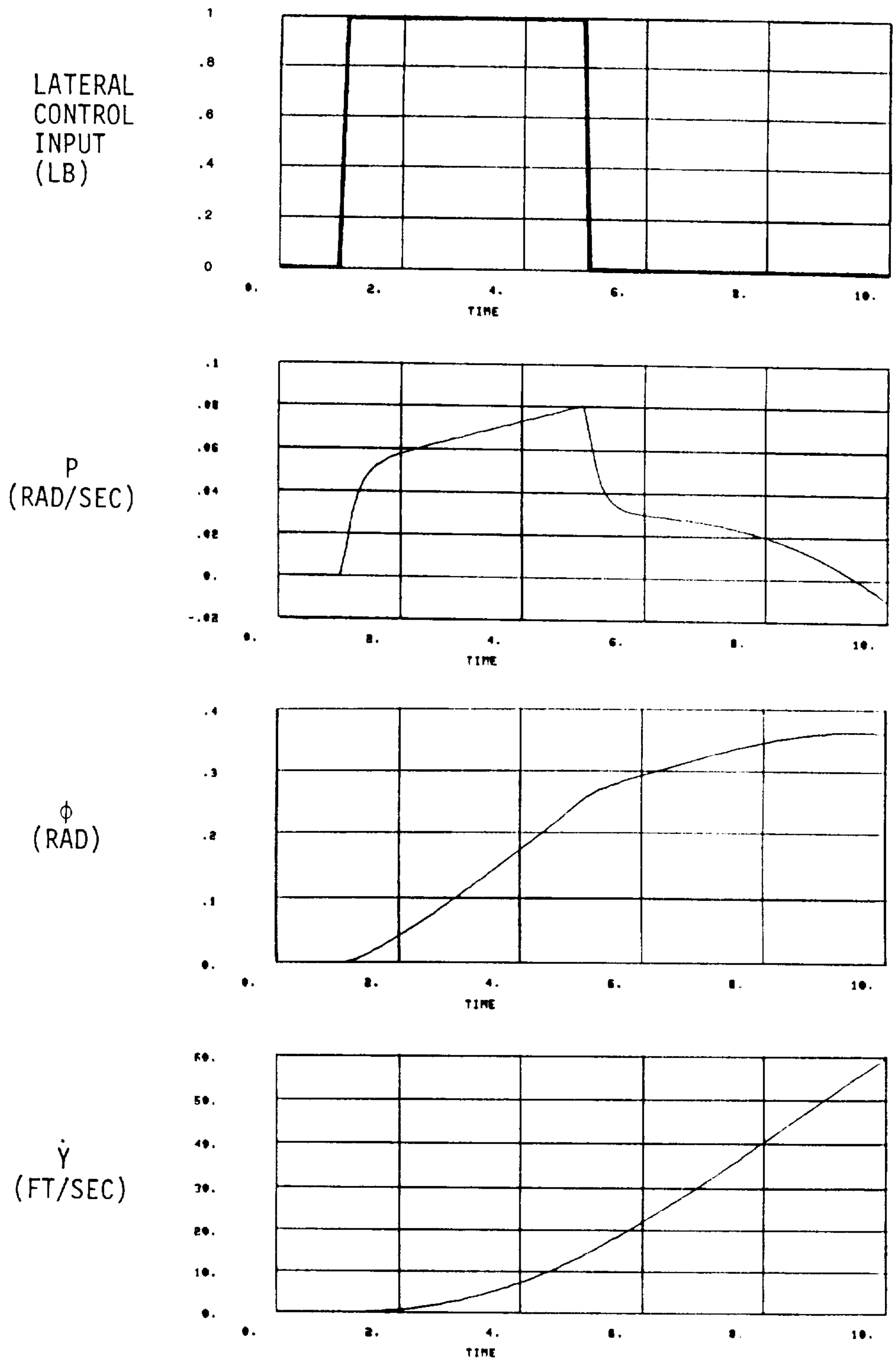




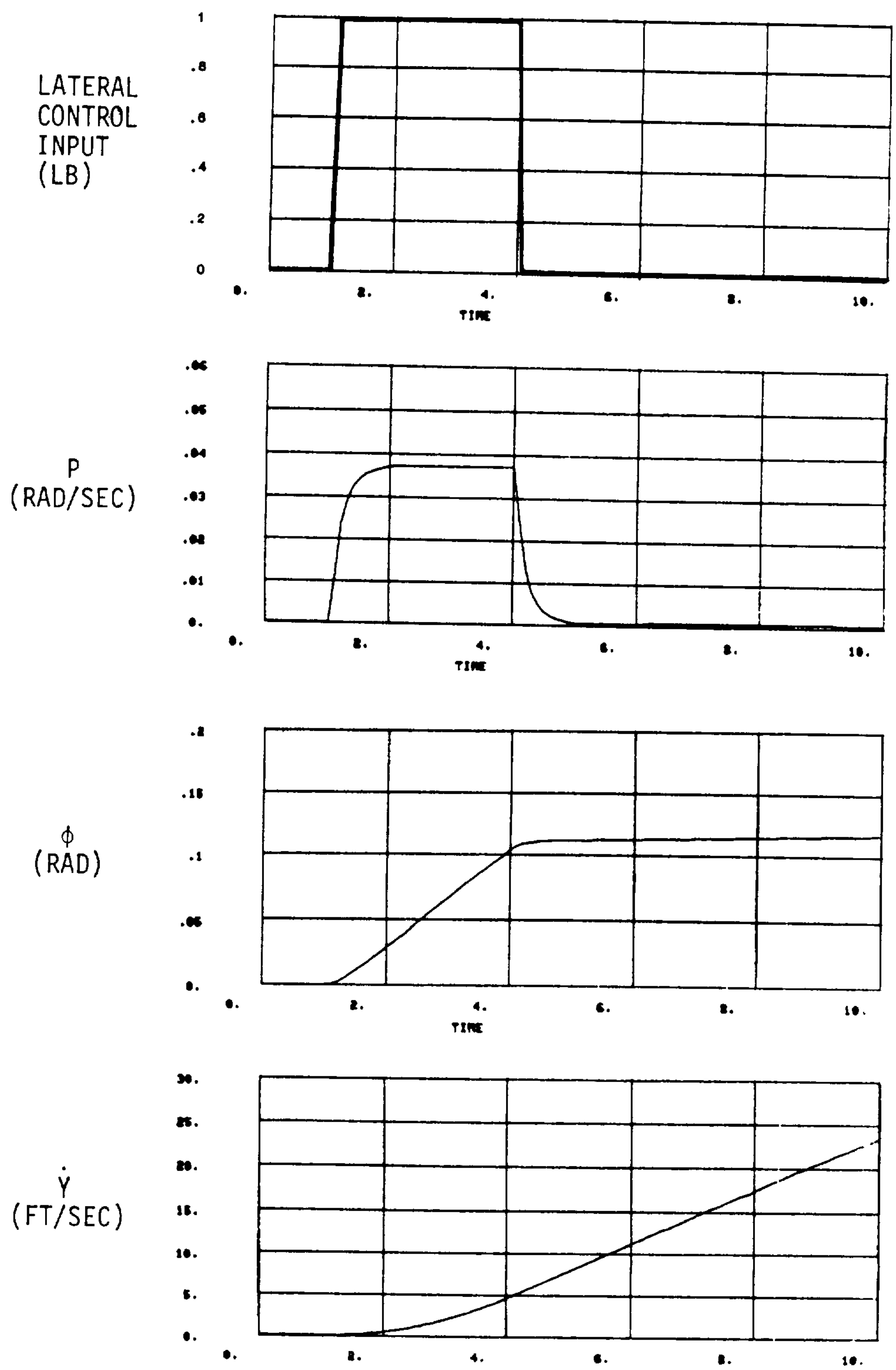
LONGITUDINAL AXIS - LV/LV SYSTEM



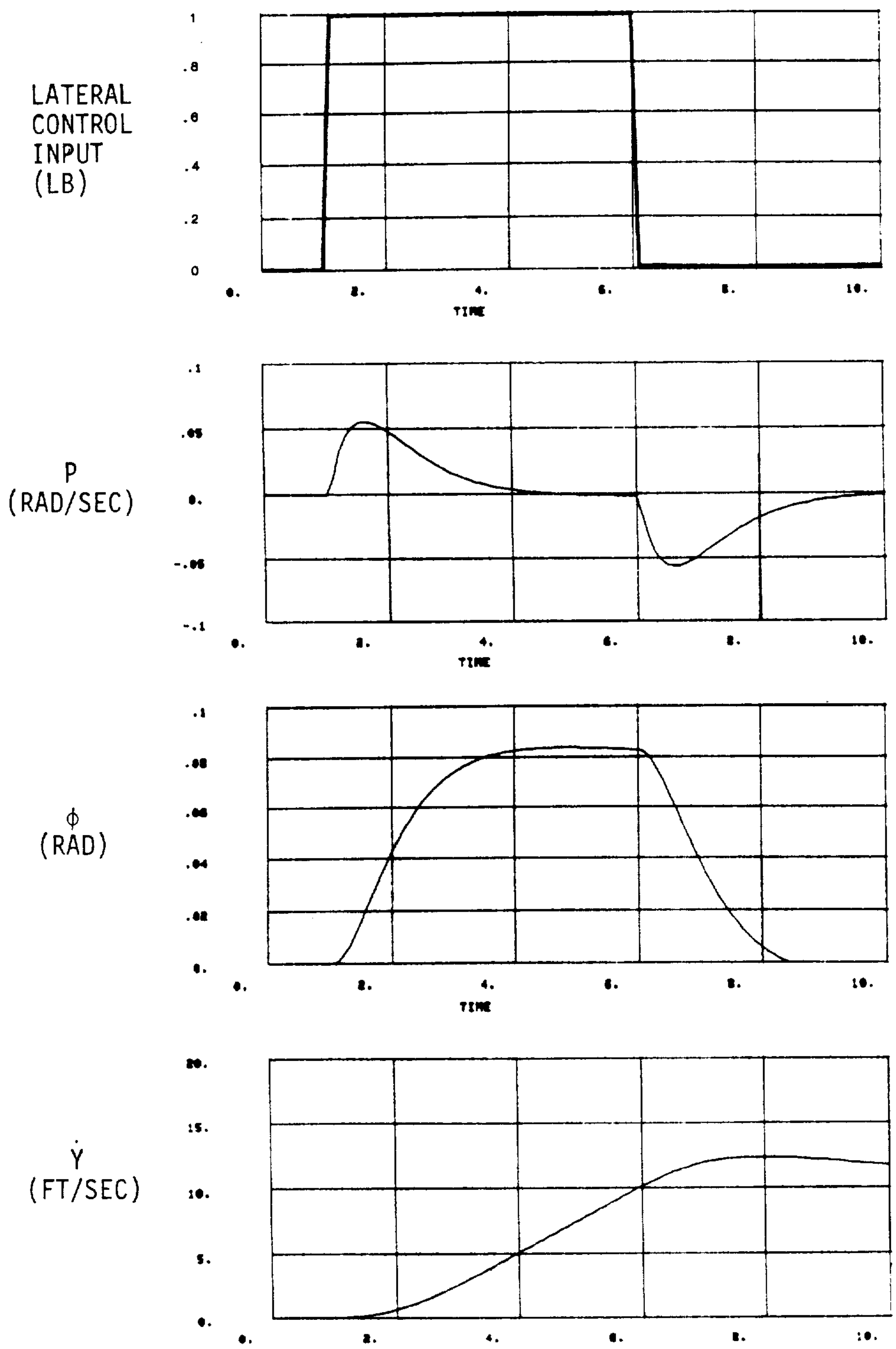
LATERAL AXIS - AC/RA SYSTEM



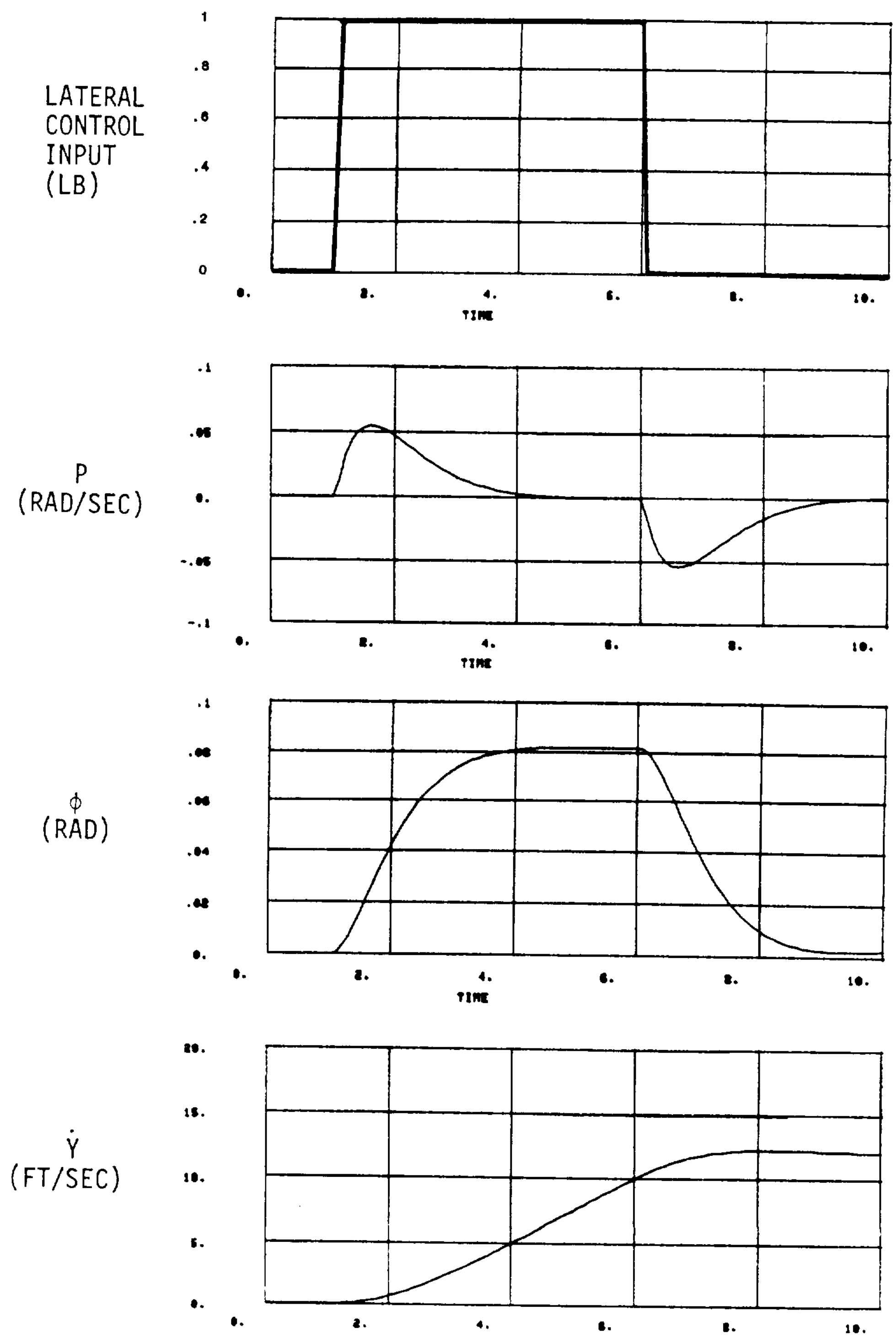
LATERAL AXIS - RA/AT SYSTEM



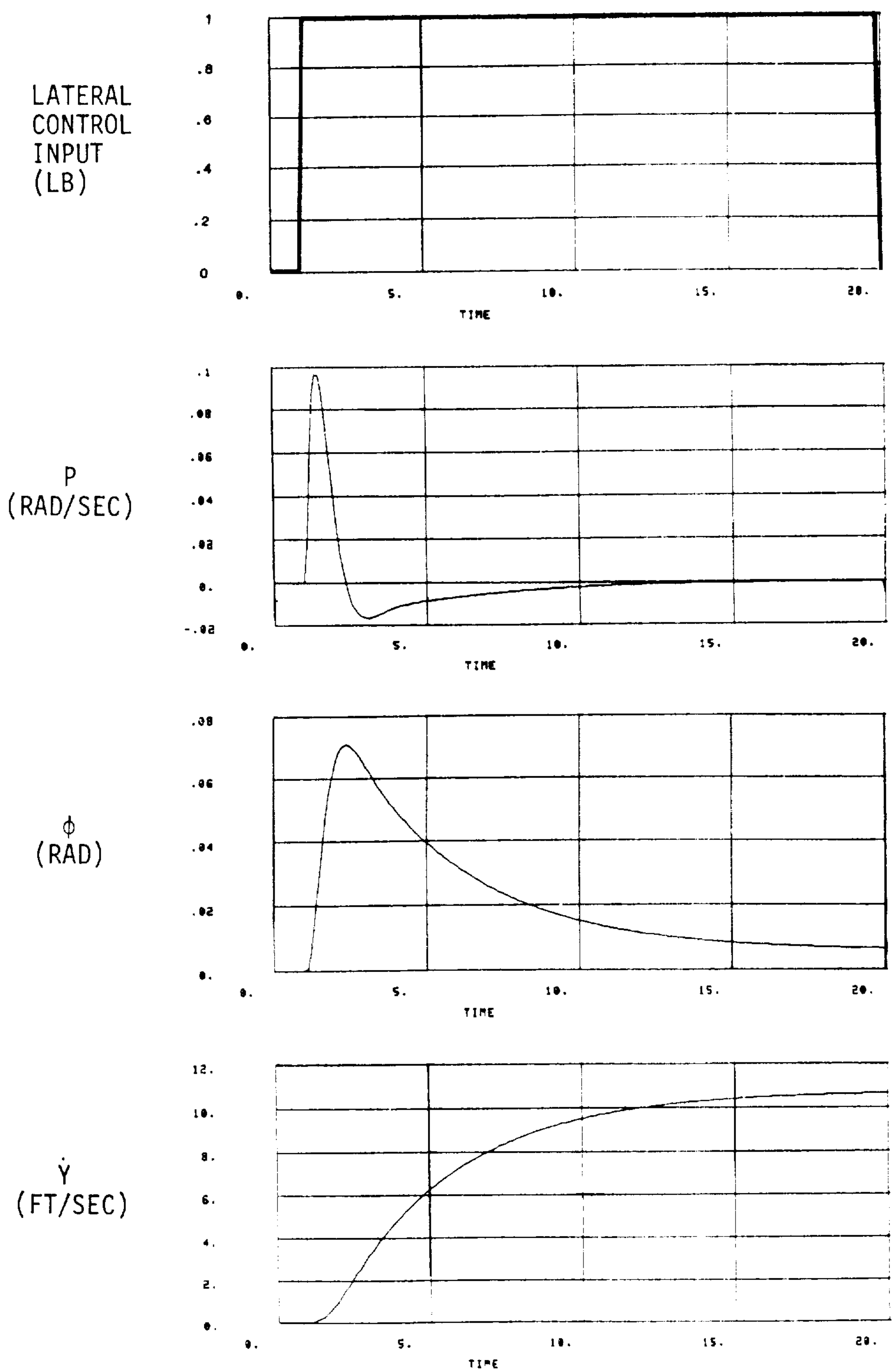
LATERAL AXIS - AT/AT SYSTEM



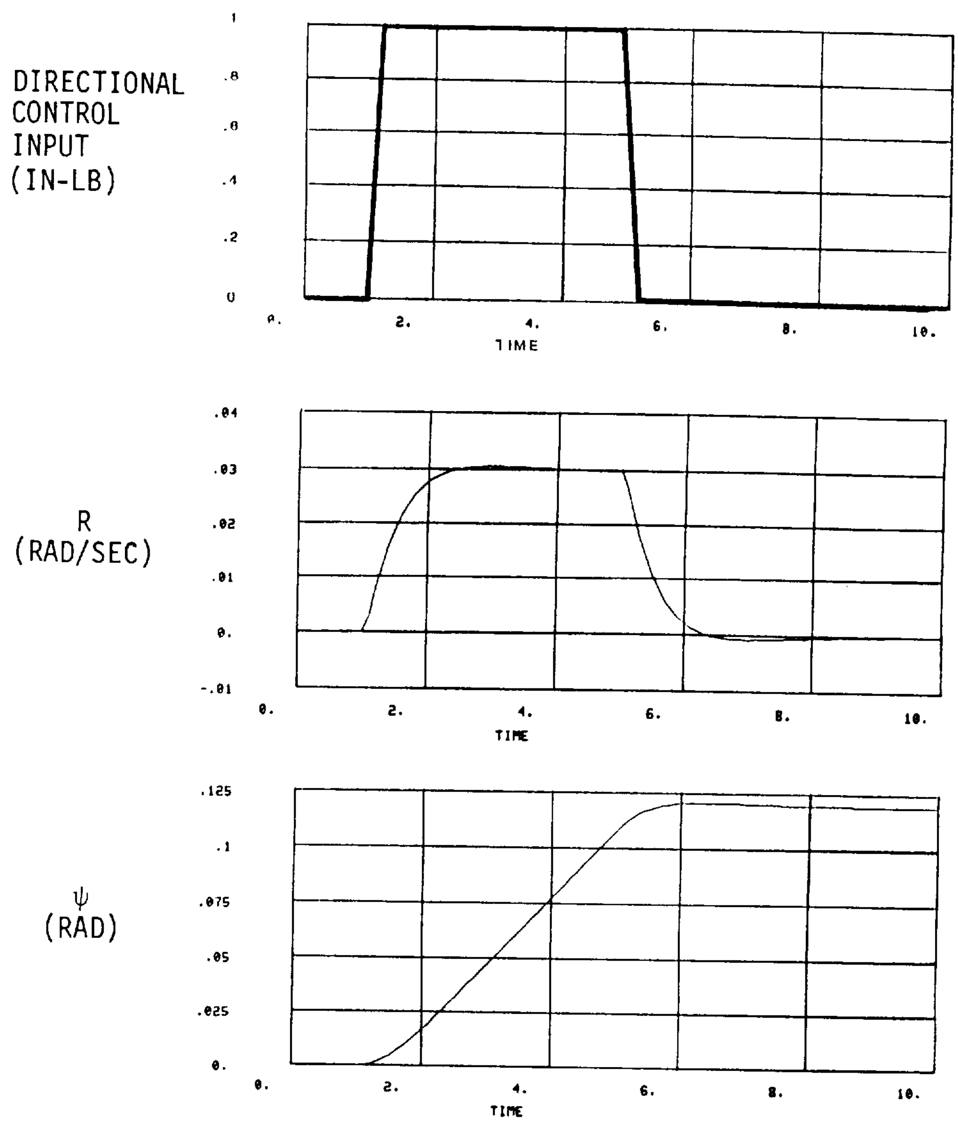
LATERAL AXIS - AT/LV SYSTEM



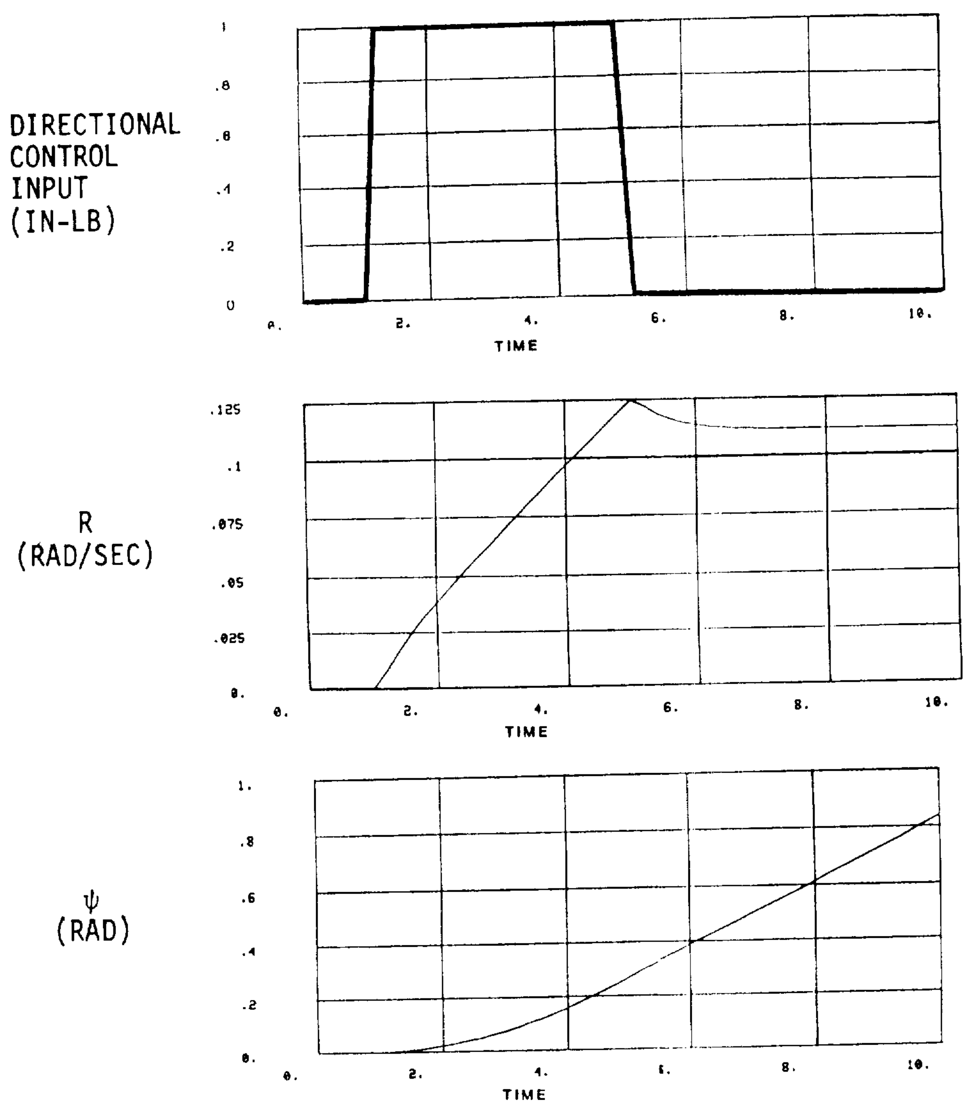
LATERAL AXIS - LV/LV SYSTEM



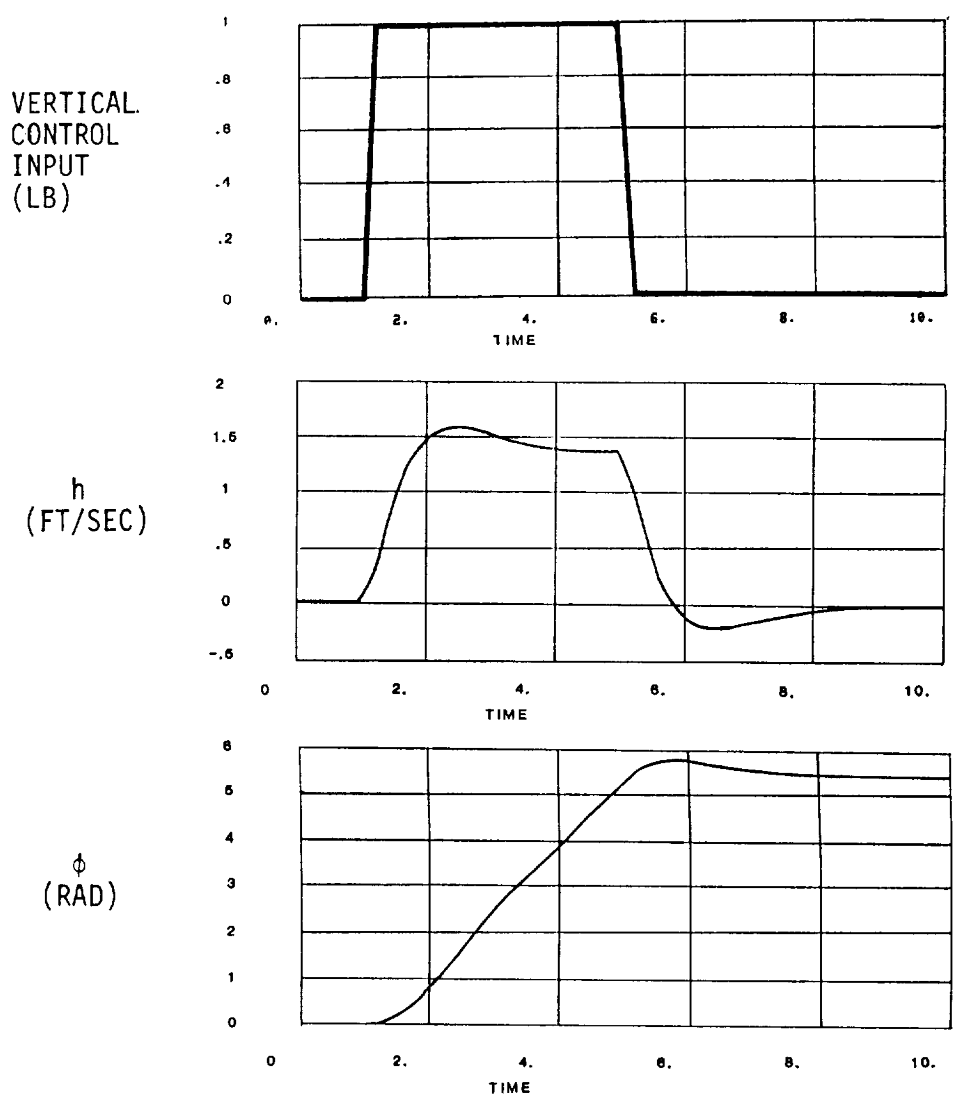
DIRECTIONAL AXIS - $\dot{\psi}/\psi_H$ SYSTEM



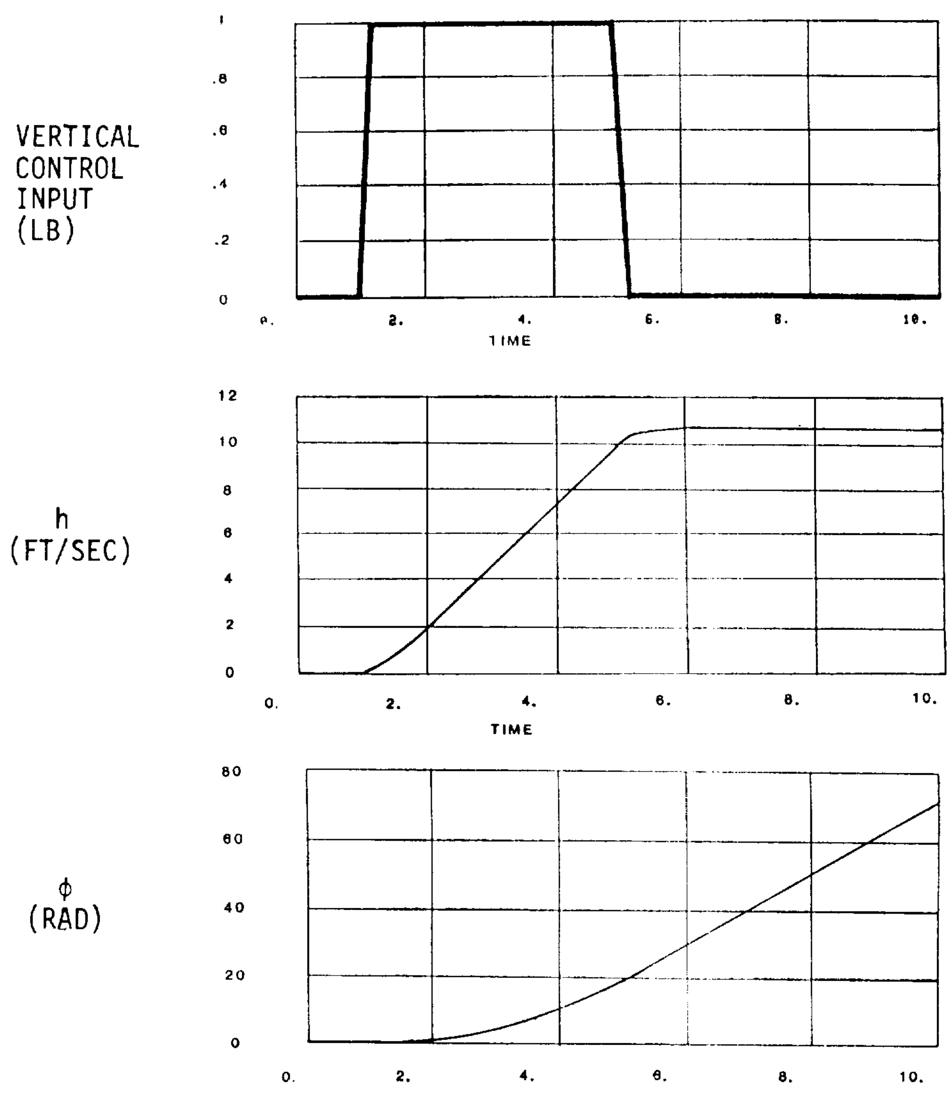
DIRECTIONAL AXIS - $\ddot{\psi}/\dot{\psi}$ SYSTEM



VERTICAL AXIS - $\dot{h}/h_H$ SYSTEM



VERTICAL AXIS - $\ddot{h}/\dot{h}$ SYSTEM



1. Report No. NASA CR- 177339 and USAAVSCOM TR 84-A-7

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Development of ADOCS Controllers and Control Laws
Volume 2 - Literature Review and Preliminary Analysis

5. Report Date
March 1985

6. Performing Organization Code

7. Author(s)
K. H. Landis, S. I. Glusman

8. Performing Organization Report No.
D210-12323-2

9. Performing Organization Name and Address
Boeing Vertol Company
P. O. Box 16858
Philadelphia, PA 19142

10. Work Unit No.
1L263211D315

11. Contract or Grant No.
NAS2-10880

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, DC 20546 & U.S. Army Aviation Systems Command, St. Louis, MO 63166

13. Type of Report and Period Covered
Final Report 1/81 - 6/84

14. Sponsoring Agency Code
505-42-11

15. Supplementary Notes
Point of Contact: Technical Monitor, Edwin W. Aiken, Ames Research Center, Moffett Field, CA 94035. Phone: (415) 694-5362; FTS: 464-5362, AUV: 359-5362

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.

17. Key Words (Suggested by Author(s))
Flying Qualities
Flight Simulation
Flight Control Systems
Side-Stick Controllers
Cockpit Displays
Helicopter
Rotorcraft

18. Distribution Statement
Unclassified - [redacted]
Subject Category 08

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
162

22. Price*

[redacted]