12-1999

V/STOL flight control functionality research to improve handling qualities in the jetborne and semi-jetborne flight regimes

Jeffrey A. Karnes

Recommended Citation

Karnes, Jeffrey A., "V/STOL flight control functionality research to improve handling qualities in the jetborne and semi-jetborne flight regimes. " Master's Thesis, University of Tennessee, 1999.
https://trace.tennessee.edu/utk_gradthes/9872

To the Graduate Council:

I am submitting herewith a thesis written by Jeffrey A. Karnes entitled "V/STOL flight control functionality research to improve handling qualities in the jetborne and semi-jetborne flight regimes." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

W. D. Lewis, Major Professor

We have read this thesis and recommend its acceptance:

U. P. Solies, Fred Stellar

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

I am submitting herewith a thesis written by Jeffrey A. Karnes entitled "V/STOL Flight Control Functionality Research to Improve Handling Qualities in the Jetborne and Semi-jetborne Flight Regimes." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Masters of Science, with a major in Aviation Systems.

Dr. W. D. Lewis, Major Professor

We have read this thesis and
recommend its acceptance:

UPSolies

Dr. U.P. Solies

Fred Stellar

Professor F. Stellar

Accepted for the Council:

Cwminkel

Associate Vice Chancellor
and Dean of The Graduate School

V/STOL FLIGHT CONTROL FUNCTIONALITY RESEARCH TO IMPROVE HANDLING QUALITIES IN THE JETBORNE AND SEMI-JETBORNE FLIGHT REGIMES

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Jeffrey A. Karnes

December 1999

DISCLAIMER

The flight test results contained within this thesis were obtained during a United Kingdom Ministry of Defense sponsored Defense Evaluation and Research Agency project conducted at DERA Boscombe Down Flight Test Center, Amesbury, Wiltshire, U.K. The discussion of the data, conclusions, and recommendations presented are the opinion of the author and should not be construed as an official position of the United States Department of Defense, the United Kingdom Ministry of Defense, or the Defense Evaluation and Research Agency.

DEDICATION

This thesis is dedicated to my outstanding family: To my wife Jacqueline, who has given me unlimited time outside of work to complete the course requirements and produce this thesis after spending much time away from home supporting the needs of the U.S. Marine Corps. To my sons Glenn and Blake, for all their understanding and support during my busy schedule.

ACKNOWLEDGMENTS

Sincere appreciation is extended to Mr. Gerry Shanks, Squadron Leader Justin Paines, Lieutenant Commander Paul Stone, and all the test engineers and support personnel working for DERA on the VAAC program. It was an honor to be asked to support this ground breaking flight test program, and much insight was gained into improving V/STOL handling qualities.

ABSTRACT

Since the 1950's, several nations have attempted to build Vertical and Short Takeoff and Landing (V/STOL) jet fighter aircraft in a variety of configurations. One of the greatest challenges of each design team was in designing and implementing a flight control system that reduced pilot workload to an acceptable level during the transition from conventional flight to fully jetborne flight. Not all the ideas worked, and even the more successful aircraft were difficult and dangerous to fly. Pilot workload of the only currently operated V/STOL attack fighter design, the Harrier, was reduced by installing limited authority augmented flight controls to increase aircraft stability, but still it remains more difficult to fly than conventional aircraft. The United States Marine Corps (USMC) and the United Kingdom's Royal Air Force (RAF) and Royal Navy (RN) have decided to replace their aging Harrier fleet of aircraft with an affordable next generation Short Takeoff and Vertical Landing (STOVL) strike fighter. All three services require the new STOVL aircraft to possess vast improvements in handling qualities over the Harrier.

This thesis examines the solutions to reduce the excessive workload associated with V/STOL flight. In this thesis, specific comments on individual evaluated mode effects on handling qualities will be addressed, while deficiencies due to individual inceptor mechanical characteristics will be minimized. The analysis and solutions are based on the author's research, extensive Harrier flight time, and recent V/STOL flight test experience. The coupling of a highly augmented digital flight control system with STOVL task optimized, blended control response types controlled by an intuitive flight

control inceptor scheme would greatly improve the handling qualities of an advanced STOVL strike fighter. The preferred inceptor scheme includes a left inceptor, a right center inceptor with an attitude trim switch and a thumbwheel, and control pedals. During STOVL operations, the recommended response type blended flight control design includes: sideslip command blended into yaw rate command on the control pedals, flightpath command blended into height rate command on the left inceptor, roll rate command with attitude hold blended into roll attitude command with natural ground referenced lateral acceleration coupling on the right inceptor lateral axis with crosswind compensation, flightpath command blended into pitch attitude command with augmented natural ground referenced longitudinal acceleration coupling on the right inceptor longitudinal axis, pitch and roll attitude right inceptor trim switch for use in the slow speed flight region, Translational Rate Command sub-mode option with the right inceptor, and flightpath referenced acceleration command blended into ground referenced acceleration command on the right inceptor located thumbwheel with speed hold detent. Implementation of the above concepts would greatly improve handling qualities in the STOVL flight regime.

It has been decided that there is an advantage for the next generation of strike fighter to have a STOVL flight capability, but without increased operational cost or risk. To insure these requirements are satisfied, the aircraft contractors and military must use the existing technologies available to vastly reduce the pilot workload over past and current V/STOL aircraft designs.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	Acceleration Command
ACT	Active Control Technology
AFS	Advanced Flight Simulator
AGL	Above Ground Level
AOA	Angle of Attack
CG	Center of Gravity
CMD	Command
DERA	Defense Evaluation and Research Agency
FCC	Flight Control Computer
FCS	Flight Control System
FOD	Foreign Object Debris
HGI	Hot Gas Ingestion
HOTAS	Hands on Stick and Throttle
HUD	Heads Up Display
IFPC	Integrated Flight/Propulsion Control
IGE	In Ground Effect
IM	Independent Monitor
KGS	Nautical Miles per Hour Ground Speed
KIAS	Nautical Miles per Hour Indicated Airspeed
LI	Left Inceptor
NM	Nautical Mile
OCF	Out Of Control Flight
OGE	Out of Ground Effect
PIO	Pilot Induced Oscillation
PVI	Pilot Vehicle Interface
RAF	Royal Air Force
RC	Rate Command
RCS	Reaction Control System

RI	Right Inceptor
RN	Royal Navy
SA	Situational Awareness
STO	Short Takeoff
STOVL	Short Takeoff and Vertical Landing
TAC	Translation Acceleration Command
TRC	Translational Rate Command
UK	United Kingdom
USAF	United States Air Force
USMC	United States Marine Corps
USNTPS	United States Navy Test Pilot School
VAAC	Vectored thrust Aircraft Advanced flight Control
VL	Vertical Landing
V/STOL	Vertical and Short Takeoff and Landing
VTO	Vertical Takeoff

INTRODUCTION

Only two Vertical and Short Takeoff and Landing (V/STOL) jet aircraft designs (the British Harrier and the Soviet Forger) have made it into operational service as fighter/ attack aircraft. Both designs were innovative in bringing a V/STOL capability to fixed wing, jet aviation, but both are difficult to fly in the semi-jetborne and jetborne flight regimes. Their unique design compromises have resulted in handling quality deficiencies, which created a dramatically higher than average accident rate compared to conventional aircraft. During fiscal years 1991 through 1998, the Class A mishap rate of the Harrier (mishap with fatal injuries or total loss of aircraft) was 3.8 times the rate of the other fighter/attack aircraft types in the United States Marine Corps (USMC) inventory.[1] When compared to the United States Air Force's (USAF) similar conventional single engine, single seat fighter attack aircraft, the F-16, the Harrier's Class A mishap rate was 3.2 times higher.[2] Due to its inherent high pilot workload and high accident rate, the USMC only assigns new replacement pilots with a minimum flight school composite score of 178 out of 260 to the Harrier community. During USMC Harrier transition training, an expensive and time consuming 26 sortie simulator and flight V/STOL familiarity phase is required to teach the difficult art of V/STOL flight prior to advancing to more important mission related tactics training.[3] Once initial V/STOL training is complete, an inordinate amount of flight time is spent during each sortie in the landing pattern to maintain proficiency in the high workload V/STOL flight regime. Adversely impacting high tempo ship operations, the USMC Harrier's handling deficiencies during V/STOL transition require excessive precision approach weather minimums of 300 ft ceilings with 1 nautical mile (NM) visibility during the day and 400 ft with 1 NM at night, which is considerably higher than conventional carrier aircraft minimums of 200 ft with 1/2 NM.[4] To help reduce the government cost of destroyed aircraft, lost lives, and extra aircrew training, a solution to reduce pilot workload must be found during development of the next generation of STOVL strike fighter. The coupling of a highly augmented digital flight control system with a task optimized, blended control response type configuration controlled by an optimized flight control inceptor scheme would make great strides in achieving this goal.

This thesis begins by discussing the basic requirements, options, and difficulties in achieving controlled flight in the jet powered V/STOL flight regime, and then describes the flight control systems and inceptor strategy of a legacy V/STOL aircraft design, the Harrier, to show past solutions and compromises. It then discusses a current research program working on solutions to reduce pilot workload and improve flight task performance. Finally, it analyzes the research and gives the best solution for improving handling qualities in the semi-jetborne and jetborne flight regime for the next generation of STOVL strike fighter.

CHAPTER 1

CONTROLLED FLIGHT IN THE V/STOL FLIGHT REGIME

INTRODUCTION

This chapter will describe the requirements for controlled flight in the conventional and V/STOL flight regimes. With an understanding of this, V/STOL handling quality deficiencies and solutions can be better analyzed. Primary flight controls, flight control inceptor schemes, flight control response types, aircraft stability in the V/STOL the flight regime, and handling qualities will be discussed. Throughout this thesis, the phrase V/STOL or STOVL flight regime will be considered synonymous with the phrase semi-jetborne and jetborne flight regime, since they are both widely accepted as describing the same characteristics.

AIRCRAFT CONTROL

To achieve controlled, powered flight, an airplane should be inherently stable and the pilot must be able to control attitude and flightpath magnitude and direction. Aircraft static stability is defined as the tendency of an airplane to return to its original attitude after being perturbed by some outside force. Its static stability is described as positive, neutral, or negative based upon the aircraft tendency to return to its original attitude, remain at its new attitude, or diverge from it, when it is perturbed. This static stability is a function of aircraft design, and in conventional airplanes includes parameters such as center of gravity (CG) location, wing design, vertical/horizontal tail size, fuselage design, and other design features. Aircraft dynamic stability is defined as the motion that results overtime after the aircraft is perturbed from equilibrium by some outside force. It is also described as positive, neutral, or negative based on its tendency to damp, remain constant, or diverge in amplitude. In modern airplanes, Active Control Technology (ACT) or "fly by wire" digital flight control systems (FCS) allow an aircraft to maintain positive stability even when possessing an unstable airplane design or when flying in an unstable flight regime.[5] For flightpath magnitude control, a pilot must be able to change engine propulsive output by a throttle mechanism and aircraft attitude in relation to the gravity vector. To achieve flightpath directional control, a pilot must be able to change and/or maintain aircraft attitude, which is required to manipulate the orientation of the lift and fixed thrust vectors. When the airplane is defined in a three axes coordinate system, there are three basic airplane motions for attitude control: pitch, roll, and yaw, shown in Figure A-1.[1] In a conventional airplane FCS, primary flight controls are used to control the above listed motions, and these primary flight controls consist of cockpit control inceptors linked mechanically or electronically to aerodynamic, moveable surfaces located on the airplane. These FCS can be of the unaugmented, limited authority augmented, or full authority augmented type. Unaugmented describes a basic conventional mechanical control system, which requires pilot input to stop divergent perturbations or oscillations not suppressed by the basic aircraft structural design.

---

[1] All Figures located in Appendix A

Limited authority augmentation describes a FCS with some auto-stabilization features such as rate dampers to increase stability, but do not have full control surface deflection authority. Full authority augmentation describes a digital FCS with feedback loops to maintain stability and precise aircraft control, which feeds back deviations to commanded inputs for the FCS to correct. In typical conventional airplanes, the primary moveable aerodynamic surfaces include ailerons/flaperons, elevators/stabilators, and a rudder, which all use airflow over the control surfaces to produce aerodynamic lift. However in jet powered V/STOL aircraft, the use of aerodynamically derived control is not enough for operation in the slow speed V/STOL flight regime where dynamic pressure is too low.

V/STOL FLIGHT CONTROL SYSTEMS

Pitch, Roll, and Yaw Control

A more complex FCS is required to control flightpath in jet powered V/STOL aircraft as it operates in conventional aerodynamic, semi-jetborne, and pure jetborne flight regimes. As an aircraft's forward airspeed decreases to zero, aerodynamic control surfaces become less effective for controlling the aircraft, which requires an additional FCS to enhance then take full authority over the conventional aerodynamic control system. Furthermore, the additional FCS must overcome severe stability deficiencies found in the V/STOL flight regime, which will be discussed later. Past jet powered V/STOL FCS solutions included thrust vectoring, differential thrust modulation and/or reaction control systems (RCS).[6] The thrust vectoring solutions manipulate propulsive nozzle direction to produce desired rotations about the control axes. The differential thrust modulation system uses separate engines or nozzle exit area flow control to alter thrust levels, and RCS works by directing engine bleed air out of small directional nozzles located at various locations on the aircraft to control pitch, roll, and yaw, shown in Figure A-2 and A-3 respectively. These V/STOL FCS must be well designed to insure that enough control power exists throughout the conventional to jetborne transition, and it must be added and subtracted incrementally to prevent any degradation in handling qualities. Stated simply, control power is the effectiveness of the control surfaces in applying forces or moments to an aircraft, and is measured in units of angular acceleration.[7] Control power is a function of flight control surface and/or nozzle size, shape, location, dynamic pressure, and position.

Thrust Control

Due to its unique design, jet powered V/STOL aircraft have the capability to expeditiously change engine thrust vector angle without altering aircraft attitude. A V/STOL jet fighter can fly at speeds less than conventional fighters, because it can vector thrust to balance some or all of its own weight in 1 g flight. With the thrust vector fully or partially supporting aircraft weight, changes in thrust magnitude and direction will instantaneously change the aircraft's flightpath, which makes the engine of a V/STOL airplane an integral part of its primary FCS. In some new STOVL designs, the entire FCS is called an Integrated Flight/Propulsion Control (IFPC) system due to the importance of engine control to overall airplane flight control. These IFPC Systems produce stabilizing or pilot commanded moments via all the remotely located control effectors, which include ailerons, stabilators, RCS nozzles, and engine thrust nozzles. Engine characteristics such as response time, thrust control fidelity, and degradation are all-important factors in V/STOL aircraft operation.

FLIGHT CONTROL INCEPTOR SCHEMES

Cockpit flight controls or control inceptors allow the pilot to interface with the flight control system. The primary flight control inceptor scheme used on most conventional fighter type aircraft includes the centerstick, throttle, and rudder pedals. In this configuration, longitudinal and lateral stick inputs control pitch and roll respectively, and rudder pedal inputs control yaw, as shown in Figure A-4. Once again, V/STOL airplanes require a more complicated flight control inceptor scheme, since there are more parameters to directly manipulate. As previously mentioned precise altitude control is imperative in V/STOL aircraft. The throttle is considered part of the primary flight control inceptor scheme. Thrust vector control is also required during V/STOL flight, which typically requires at least one additional inceptor in the cockpit. A previously implemented flight control inceptor scheme used by the Harrier will be discussed in detail later as an example.

FLIGHT CONTROL RESPONSE TYPES

If a single axis inceptor control step input is made in the cockpit, then that input is transmitted to its corresponding moving control surfaces via digital or mechanical linkage. The control surfaces will deflect in magnitude proportional to the input, and the aircraft responds in a somewhat predictable manner. The manner in which the airplane responds to the control input is called its response type, and has a major impact on how an airplane feels to the pilot. The three basic response types of control systems are proportional or attitude, rate, and acceleration.[8] These three basic types describe short-term aircraft responses, and may be affected by input size and duration. In response to a control step input on an attitude control system, a steady state attitude is attained after some transient motion. The new attitude is proportional to the control inceptor deflection, and it remains constant until the control input is removed, shown in Figure A-5. The aircraft will return to its original attitude, when the control input is released. An attitude response type describes the pitch and yaw axis of most unaugmented airplanes in conventional flight. With a rate control system, the airplane response to a control step input is to accelerate to a proportional steady state rotation rate about the axis, as seen in Figure A-5. The rotation rate will cease when the step input is removed. A rate response type normally describes the roll control system of a conventional airplane, and is the result of aerodynamic damping in an unaugmented flight control system.[8] With an acceleration control system, the airplane response to a control inceptor step input is an angular acceleration produced by the proportional moment generated, as seen in Figure A-5. The angular rate generated will remain constant when the initial inceptor step input is removed, and requires an opposite step input of equal size and duration to stop. The F-104's lightly damped roll axis is an example of an acceleration control system.[9] In the past, the inceptor control input was transmitted via mechanical linkage, which when coupled with the aircraft structural design dictated the response types found in all three axes. The characteristic response types are similar in most older unaugmented conventional aircraft, and included attitude type in the pitch and yaw axes, and rate type in the roll axis. In limited authority augmented jet powered V/STOL airplanes like the Harrier, control system response types change entering the slow speed V/STOL flight regime, as seen by the roll axis control system changing from rate to acceleration response type due to reduced aerodynamic forces and damping and its RCS. This further complicates the flight control design as separate response type control regions must be optimized with individual control power and sensitivity characteristics to produce acceptable flying qualities. It also adversely affects pilot workload, as totally different control inceptor input strategies are required to fly the aircraft based on airspeed region. With the advent of digital flight controls and ACT, any of the three basic response types can be implemented and even modified to specification in any control axis. This allows the FCS to be designed to incorporate a selected optimum single or several blended response type/s for each axis, and may by be entirely changed during mode switches in conventional or V/STOL flight regimes. Response type selection is very important in optimizing the flight controls and handling qualities of the next generation STOVL strike fighter design.

AIRCRAFT STABILITY IN THE V/STOL FLIGHT REGIME

Pitch, Roll, and Yaw Static Stability

As mentioned previously, positive aircraft stability is an important part of aircraft flight control, and this stability is more difficult to design and maintain for V/STOL jet fighters. As an airplane slows in the semi-jetborne flight regime, its inherent stability decreases, and even passes through regions of neutral to negative stability as it approaches stable fully jetborne flight. This phenomenon is due to the reduced airflow over the aerodynamic stabilizing surfaces like the tail section, and the increased dominance of destabilizing propulsion effects.[10] To augment the lost aerodynamic stability forces, V/STOL jet aircraft must rely on added RCS or differential thrust FCS to produce the stabilizing control forces in all three axes. Prior to flight augmentation and ACT systems, the V/STOL pilot had to make timely and well shaped control inputs to actuate the FCS, and prevent departure from controlled flight due to outside perturbations and pilot induced oscillations (PIO). This made jet powered flight in the V/STOL flight regime difficult, tiring, and dangerous.

Propulsive Effects on Stability

As airspeed decreases, propulsive effects due to increased thrust levels and thrust vector modulation begin to dominate the aerodynamic effects of the V/STOL aircraft, which has a great influence on the overall aircraft stability. These normally destabilizing propulsive forces affect static and dynamic stability in the pitch, roll, and yaw axes. In addition to the conventional stability requirements in the pitch, roll, and yaw axes, jet powered V/STOL aircraft require tight thrust control to insure adequate flightpath and altitude control, as the propulsion system becomes the dominant flightpath manipulator in the semi-jetborne and jetborne flight regimes. This will be called propulsive vertical flightpath stability, and by definition is characterized as neutral or negative. Some known destabilizing propulsive system effects on stability include nonlinear jet induced aerodynamic effects, suckdown and fountain effects, and hot gas ingestion (HGI), which all have different characteristics based on whether in ground effect (IGE) and out of ground effect (OGE).[11] IGE is defined as the ground influences on propulsive jet effects magnitude or characteristic. Other destabilizing propulsive effects include aircraft attitude and height coupling and gyroscopic moments due to engine core rotation.[10] Even today with exhaustive research and super computers, propulsive effects are not fully understood, especially when analyzing the wide variety of potential STOVL strike fighter configurations being developed.

Jet Induced Aerodynamic Effects

As airspeed induced aerodynamic forces decrease at reduced airspeeds, propulsion induced aerodynamic forces increase proportionally. These propulsion-induced effects are usually destabilizing, and are a function of aircraft design. A good example of this is called intake momentum drag, which affects the Harrier. In the 90 to 30 kts airspeed region, the stabilizing vertical tail aerodynamic sideslip restoring force may not be adequate to overcome the destabilizing intake momentum drag yaw force. This intake momentum drag is produced when the relative wind must turn to align with the engine's longitudinal axis in the intake due to a sideslip condition.[12] As with some conventional airplane designs, forward flight with sideslip, defined as angle between aircraft heading and actual flightpath, may induce a destabilizing rolling moment called lateral and directional coupling or dihedral effect, as shown in Figure A-6.[10] At slow airspeeds, this rolling moment may not be controllable even with full aerodynamic aileron and lateral RCS control moments, resulting in a disastrous out of control flight (OCF) condition. Other jet induced aerodynamic effects are created by entrained airflow downwash, and can aid or destabilize flight in the slow speed flight regime. With lift nozzles located near the front of the wings, high velocity jet exhaust creates a downward airflow entrainment along the wing leading edge, which will effectively reduce the effective wing angle of attack and associated wing lift at that pitch attitude, as shown in Figure A-7. With lift nozzles located near the aft portion of the wings, high velocity jet exhaust creates a downward airflow entrainment along the wing trailing edge, which increases wing lift at slower airspeed. However, the same downward airflow may act on the horizontal tailplane reducing its effective angle of attack, and create a destabilizing airplane pitch up, as shown in Figure A-7.

Suckdown and Fountain Effects

Flightpath stability is an important component of the overall V/STOL fighter stability. The same high velocity jet exhaust discussed above entrains the surrounding air, which creates an area of low pressure underneath the airplane, as shown in Figure A-8. This is called free air suckdown, and may account for up to 30% effective lift loss of the airplane.[10] This air entrainment effect is amplified near the ground as the jet exhaust flow hits the ground and radially spreads out, creating a large wall jet with an even greater air entrainment area.[11] This lift loss is a function of aircraft design and distance to the ground, and is destabilizing during both takeoff and landing. Large wings and tightly condensed lift nozzle locations intensify this IGE phenomena, requiring excess thrust and quick engine response to overcome these vertical flightpath instabilities. Variations in the low-pressure field underneath the aircraft due to aircraft design cause asymmetric lift conditions, which create destabilizing pitch and rolling moments. In some V/STOL aircraft configurations, increased thrust from one roll control nozzle to create a commanded rolling moment may actually cause an opposite rolling moment due to the increased suckdown on that side of the aircraft. Another destabilizing effect is called fountain effect. Depending on wind direction, aircraft attitude and configuration, thrust vector angle, and number of lift nozzles or engines, multiple high-energy jet exhausts hit the ground, collide, and reflects back into the air in the form of an intense fountain.[12] This high energy fountain will impinge on the bottom of the airplane at changing locations as a function of height above the ground, wind, and forward velocity, and may cause uncommanded rolling or pitching moments, as shown in Figure A-9. This fountain can also be beneficial, as it can impart a high-pressure upward lifting force on the bottom of the aircraft fuselage near the ground. This force can offset the adverse suckdown effect, but remains destabilizing to vertical flightpath control as its magnitude and beneficial influence change with aircraft attitude, height above the ground, and wind conditions. In unaugmented aircraft, the V/STOL FCS, engine, and pilot must be able to quickly respond to these rapidly changing destabilizing forces to maintain adequate aircraft control.

Hot Gas Ingestion

Since the propulsion system of a V/STOL jet fighter is a major contributor to flightpath stability, degradation of engine performance adversely affects this stability. Jet engine propulsive performance is directly related to intake air temperature, and small amounts of increased inlet temperature equate to a significant reduction in available thrust. This thrust loss requires immediate throttle input in the V/STOL environment to prevent aircraft settling, which may not be offset with increased throttle due to the turbine temperature or engine mechanical limits. The hot gas can be directed straight into the intake by the near-field or fountain effect in the hover, or indirectly through the far-field by recirculation, wind effects on the jet exhaust flow wall or with forward motion of the aircraft, as shown in Figure A-10.[12] This reingestion of hot gas can also cause inlet distortion and subsequent surging or stalling of the engine compressor blades, which may result in an unrecoverable, catastrophic loss of thrust.

Attitude and Height Coupling and Gyroscopic Effects

Attitude and aircraft height coupling has a destabilizing effect on inherent aircraft stability, while gyroscopic engine core rotation effects can be easily minimized by smart engine design. In an unaugmented V/STOL FCS, aircraft pitch or roll attitude changes without equivalent pilot commanded lift nozzle angle changes result in a thrust vector orientation change. A force imbalance will result as the thrust vector no longer aligns with its required component of aircraft weight, and the aircraft will settle without additional engine thrust. This is called a cosine loss, and it must be managed continually by the pilot or FCS to maintain precise altitude or flightpath control. By designing the jet engine core with counter rotating stage spools, the gyroscopic engine core effect on aircraft stability can be minimized.[10]

HANDLING QUALITIES

The term handling qualities and its use in evaluating different flight control configuration flying characteristics is used several times in this thesis, and warrants definition. Since the Wright Brother's first flight at Kitty Hawk, pilots have had qualitative impressions on how well different airplanes fly. With the advent of the professional test pilot, aeronautical engineers have tried to elicit comments from them to improve the product, and yet have had difficulty in reducing the variability among pilot's comments to produce concise usable data. The pilot's comments are important because an aircraft may attain great performance (e.g. precise bank angle control, precise landing spot control), but at an excessive price in pilot workload. To fully evaluate an aircraft, pilot rating scales were developed and revised to impose a repeatable, analytical process. George E. Cooper and Robert B. Harper developed the most widely accepted process, and their scale is called the Handling Qualities Rating Scale, as shown in Figure A-11. By their process, before you can understand the ratings and their meanings you must know the supporting definitions. Handling qualities are defined as "those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role".[13] With role being "the function which defines the intended use of the aircraft".[13] These qualities or characteristics include Pilot Vehicle Interface (PVI) (e.g. controls and displays), aircraft environment (e.g. weather conditions, turbulence), and pilot stress, and are not just limited to stability and control characteristics.[13] Task, as it relates to handling qualities, is defined as "the actual work assigned a pilot to be performed in completion of, or as representative of, a designated flight segment."[13] In other words, task is workload involved with controlling an aircraft and non-directly associated functions such as navigation and communication. The term pilot compensation is used to indicate that the pilot must increase workload to improve aircraft performance of the assigned task. The developed Handling Qualities Rating (HQR) scale is divided into four categories, which delineate task performance and associated pilot workload. The first category is "satisfactory", which means performance and workload are good enough without aircraft improvement. The next category is "unsatisfactory but acceptable", which implies that performance and workload are just good enough but improvement desirable.[13] The third category is "unsatisfactory", which implies task performance and workload are not within acceptable limits but the aircraft is controllable. The last category is "uncontrollable", which implies that the pilot cannot maintain control of the aircraft by any means possible. The four categories are further divided into sub-categories to describe task performance and pilot workload in more detail. For the evaluation, a task is chosen with a desired and an adequate performance tolerance band, which the pilot will try to attain during the flight or simulation. After performing the task, the pilot will ascertain aircraft task performance and his workload in achieving this performance level. For example, it is desired to capture a 50 ft AGL hover altitude during a Vertical Takeoff (VTO) within 5 feet, but considered adequate to capture it within 10 feet. Right after performing the task the pilot enters the HQR scale, answers the questions, and chooses a workload sub-category. This produces a numerical 1-10 HQR, which can be used to analyze, optimize, or chose a preferred flight control concept for every task of any aircraft. [14]

CHAPTER 2

LEGACY JET POWERED V/STOL ATTACK FIGHTER

INTRODUCTION

The British designed and British/American improved Harrier represents the only remaining "Fleet" operational jet powered V/STOL aircraft. Although not easy to fly and slightly less capable in conventional flight performance than other modern jet fighter designs, it demonstrated a unique, highly desirable operational basing capability. Analysis of the Harrier's flight control inceptor scheme, aircraft stability effect on pilot workload, and flight control response type configuration is necessary for understanding design compromises leading to high pilot workload.

HARRIER

Designed in the late 1950's as a supersonic V/STOL strike/reconnaissance aircraft using the Bristol Aero Engines Ltd. BE.35 and later developed as a V/STOL close air support/reconnaissance aircraft for NATO, the prototype P.1127 first flew in 1960.[15] After 8 years of development and optimization, the GR Mk.1 Harrier joined the Royal Air Force (RAF) in 1969 as the first operational V/STOL jet aircraft, shown in Figure A-12.[15] Since then, the Harrier has further evolved into the improved AV-8B/GR Mk.7 and the Royal Navy's (RN) FRS 2 Sea Harrier, and is currently operated by the RAF, RN, USMC, Spanish Navy, Italian Navy, Thai Navy, and Indian Navy. Its special V/STOL design characteristics include a single Pegasus turbofan engine with four rotating nozzles and a RCS, which augments the conventional FCS in the V/STOL flight regime.

FLIGHT CONTROL INCEPTOR SCHEME

The Harrier's flight control inceptor scheme includes the usual centerstick for lateral and longitudinal control inputs and rudder pedals for directional control inputs, which control both the conventional and RCS FCS. Being a V/STOL design, the Harrier throttle is an integral part of the primary FCS, and the Harrier also incorporates a separate nozzle control lever next to the throttle to control nozzle angle (thrust vector angle), as shown in Figure A-13. Considering that both the aerodynamic control surfaces and the RCS nozzles of the FCS are mechanically linked to the cockpit control inceptors, the Harrier possesses an elegantly simple, yet functional compromise for a flight control inceptor scheme. In the conventional and V/STOL flight regimes, basic lateral, longitudinal, and directional control inputs are intuitive, but extensive pilot training is required to learn the correct input magnitude and timing. The nozzle control lever makes the Harrier flight control inceptor scheme different from conventional jet aircraft, and this additional inceptor controls the thrust vector through a 100° of travel. The nozzle control lever has several tactilely significant mechanical reference points along its range of motion called the hover-stop, braking-stop, and 5° increment adjustable Short Takeoff (STO) stop positions, which allow expeditious, accurate thrust vector angle selection, as shown in Figure A-13. Its location and basic mechanization are simple, but its manipulation increases pilot workload during V/STOL flight. The nozzle lever's location requires the pilot's left hand to control both throttle and nozzle lever input through a timeshare control input strategy. At slower semi-jetborne speeds, flightpath and airspeed control are difficult, as nozzle angle changes require immediate throttle adjustments to prevent uncommanded flightpath deviation. Increased possibility of cognitive failures in selecting the wrong inceptor for input makes this inceptor scheme susceptible to control misapplication resulting in disastrous consequences. Many of these cognitive failure events such as pulling the throttle to idle vice selecting hover-stop on the nozzle lever during shipboard launch have been repeatedly documented. To alleviate some of the workload associated with the final approach to the ship, the RN's Sea Harrier incorporates a beeper switch, which allows hover-stop ±10° of nozzle angle control by an easily accessible three position Hands on Stick and Throttle (HOTAS) switch on the throttle. Because of this high workload and objectionable characteristic of multiple left inceptors, excessive funding has been wasted in crashed or damaged aircraft and extra V/STOL proficiency training.

AIRCRAFT STABILITY AND PILOT WORKLOAD

In unaugmented or partially augmented FCS, reduced stability results in increased pilot workload, as uncommanded force perturbations and undesirable oscillations with light or no damping require timely pilot input to control. As mentioned previously, aircraft stability decreases with decreasing airspeed, and the Harrier is no exception to this rule. Since early development, many strides have been made in improving the stability of the Harrier, but it still posses reduced stability characteristics that adversely affect handling qualities. These fixes included dropping the speedbrake to half during approach to prevent a directional oscillation in the AV-8A, but all problems and solutions will not be discussed further due to their current reduced relevance. Due to stability characteristics and associated forces, V/STOL flight is usually separated into two flight regimes, semi-jetborne and jetborne, but a third group of combined semi-jetborne and jetborne IGE will also be discussed.

Semi-Jetborne Flight Regime

For the Harrier, the interesting portion of the semi-jetborne flight regime is defined as a range of 150 to 30 kts, and is characterized by increasing propulsive force dominance over aerodynamic forces. A limited authority, three axes, auto-stabilization FCS using angular rate dampers has been added and improved on the Harrier, which limits pitch, roll, and yaw rates to a controllable level. It has been shown that a pilot can control divergent perturbations and oscillations, if their divergence rate is slow.[15] A good example of this is found with the previously discussed intake momentum drag, which is a large contributor to the high workload in a Harrier. Even with its limited authority auto-stabilized FCS, divergent yaw and roll rates can build up due to this phenomena, and result in an unrecoverable departure. To prevent this, every effort must be made to minimize sideslip during transition through the airspeed range of 30 to 90 kts, as the Harrier's yaw axis has neutral static stability between 50 and 60 kts and negative static stability below 50 kts.[12] A windvane has been installed on the fuselage in front of the pilot to alert the him of excessive sideslip buildup. This externally mounted windvane complicates the pilot's instrument scan. The Harrier has a greatly reduced longitudinal static stability in the V/STOL flight regime, which is adversely influenced by aft CG positions, forward extending external store aerodynamic effects, and propulsive effects.[16] The Harrier's longitudinal static stability becomes unstable at or above 15° AOA as longitudinal perturbations cause AOA divergence with disastrous results. The previously mentioned propulsive effects further reduce longitudinal static stability on the Harrier by downward entrainment of the stabilator leading edge airflow, resulting in reduced effective stabilator AOA and stabilizing lift. This stabilator lift reduction causes a nose up pitching moment, requiring pilot input to control. In cases of high thrust settings, large nozzle angles, and aft CG locations, the entrainment can be so great that full forward stick input is insufficient to reduce aircraft pitch attitude, requiring an unintuitive, instantaneous 20° nozzle aft input or idle throttle transient to break the entrainment and regain pitch attitude control.[12] This condition can be entered by over-controlling the pitch attitude during high performance STO or allowing the AOA to increase above 15°, resulting in a possible OCF situation. To prevent this, absolute pitch attitude and AOA control vigilance is required during maneuver in the 30 to 120 kts airspeed region, which greatly increases pilot workload during an already high workload flight phase. In the semi-jetborne OGE flight regime, the Harrier propulsive vertical flightpath static stability is characterized as neutral, which requires throttle input to correct deviations due to external forces such as wind gusts. Although offering increased landing spot precision and reduced landing surface area than conventional aircraft, the adverse characteristics of the Harrier within the semi-jetborne flight regime make it a high workload, dangerous part of flight envelope.

Jetborne Flight Regime

For the Harrier, the jetborne flight regime is defined as airspeeds at or below 30 kts. In an OGE hover, the Harrier posses neutral static stability in the roll and pitch axes and negative static stability in the yaw axis, resulting in aircraft neutral dynamic stability in all three axes. In propulsive vertical flightpath stability, the Harrier also possesses neutral static stability. Neutral static stability requires increased pilot workload to correct for external force perturbations, while negative yaw axis static stability requires immediate pilot attention to stop divergence due to external force perturbations. Height deviation due to the attitude change coupling has the greatest effect on propulsive vertical flightpath stability in the jetborne flight regime, where all of the aircraft lift is provided by engine thrust. This effect requires a workload intensive, multi-inceptor control input strategy during any attitude change in the hover.

Stability in Ground Effect

Since the IGE propulsive effect mechanisms are basically the same whether in semi-jetborne or jetborne flight, the effects on Harrier stability and pilot workload will be discussed together. Again, Harrier thrust control is unaugmented, so any external perturbation must be corrected by precise, timely pilot throttle input and quick, accurate thrust response. IGE occurs near the ground, so this section describes propulsive effects during STO, vertical takeoffs (VTO), slow landings, and VL. Previously described in detail, suckdown will not be discussed further, except to state that it adversely affects propulsive vertical stability by increasing in magnitude closer to the ground. This lift reduction requires precise, rapid thrust addition near the ground to prevent hard landings. The thrust fountain can adversely affect the pitch, roll, and propulsive vertical flightpath stability of the Harrier, and influences the aircraft much higher above the ground than IGE suckdown. High wind conditions, aircraft forward velocity, and thrust vector angle can cause the reflected fountain to impinge on a wing, stabilator, or fuselage, resulting in an uncommanded, destabilizing pitch or rolling moment. The fountain magnitude and impingement point change as a function of height above ground, which make it highly unpredictable. The fountain is also an unpredictable HGI vehicle, which adversely affects the propulsive vertical flightpath stability. Driven by the same wind conditions, aircraft forward velocity, and thrust vector angle, far field HGI effects can have the same adverse affect on vertical flightpath stability. Aircraft control to prevent hard landings and insure successful takeoffs requires complex real time thrust margin prediction and monitoring, extra engine stall margin, and rapid thrust response to precise pilot throttle inputs.

FLIGHT CONTROL RESPONSE TYPES

Having a mechanically linked, limited authority auto-stabilization FCS, the Harrier has unaugmented conventional airplane-like response types in all three control axes during conventional and high speed semi-jetborne flight as aerodynamic forces and moments dominate. These include the pitch and yaw control systems being attitude types, and the roll control system being a rate type. Again, these response types describe short-term aircraft responses to control step inputs. All three axis control systems change response type characteristics between 30 and 120 kts. In the pitch axis, the first response change to a rate type occurs at 100 to 110 kts, as the aircraft passes through a neutral stability region.[16] In the roll and yaw axes, the response change to an acceleration type occurs at 50 to 60 kts, as the aircraft enters the neutral stability and negative stability regions respective.[12] Once in the OGE jetborne flight regime with small aerodynamic forces and damping, all three axis control systems can be described as acceleration response types due to the aircraft's RCS, limited authority auto-stabilization FCS, and neutral to unstable static stability.[15] From a static OGE hover, any control input results in short term accelerated motion, requiring equal and opposite control inputs to stop. As mentioned before the throttle is an integral part of the V/STOL jet aircraft FCS, and its response type must be discussed. In the Harrier, the unaugmented throttle directly controls thrust, so it is considered an acceleration response type controller. This requires a highly responsive engine and multiple timely, precise control inputs to capture and maintain a desired altitude. In the days of unaugmented or partially augmented mechanical flight controls, this assortment of changing response types was the only way to successfully accomplish the flight control requirements for V/STOL flight.

CHAPTER 3

V/STOL FLIGHT CONTROLS FUNCTIONALITY RESEARCH

INTRODUCTION

Both the United States and the United Kingdom (UK) have been working individually and collectively to develop and demonstrate flight control systems to improve handling qualities for incorporation into the next generation STOVL jet strike fighter. Much of this work has been accomplished at the NASA Ames Research Facility and by the UK's Defense Evaluation and Research Agency (DERA). With the advent of ACT, vast increases in flight control configurations with different optimized response type combinations are available to help accomplish specific flight tasks. DERA's Vectored thrust Aircraft Active flight Control (VAAC) Flight Test Program has been the cornerstone of much of the groundbreaking research in this area, and continues to offer the only in-flight V/STOL flight control testbed available today.

VAAC FLIGHT TEST PROGRAM

The UK's DERA has developed the VAAC research program using a modified Harrier TMk4 and the three axes motion based Advanced Flight Simulator (AFS). They cited four reasons for initiating the research to improve the performance and handling qualities of jet powered V/STOL aircraft.[17] The first was to reduce from three the number of flight control inceptors required to fly the next generation jet aircraft in the V/STOL flight regime, which currently requires excessive initial training and continual proficiency flights to precisely operate safely. The next reason for the research was to reduce the peak pilot workload associated with bad weather or night final V/STOL approaches to confined sites like the ship, which currently requires excessively high weather ceiling minimums and has resulted in regular flight mishaps. Additionally, the research investigated how to control the next generation STOVL jet fighter' s potentially unstable jetborne and semi-jetborne propulsive configuration, which will include non-Harrier like engine thrust nozzles located far from the aircraft CG. Finally, the research attempted to find an optimum flight control law to interface with the new complicated, advanced IFPC designs, which will have too many effectors for the pilot to manually control. As the VAAC flight research program has progressed, an additional tested concept has evolved to be called control strategy, which involves optimum number of control inceptors and right or left handed manipulation of them.[18] The engineers developed V/STOL optimized flight control laws with blended response types in all axes using ACT and radically new flight control inceptor schemes, which were fine-tuned in the AFS before being evaluated in the VAAC Harrier.

VAAC AIRCRAFT DESCRIPTION

The VAAC Harrier is a two seat Harrier TMk4 trainer modified for V/STOL flight control research, as shown in Figure A-14. The mechanical linkage from the rear cockpit flight control inceptors was replaced with a digital link through a full authority flight control computer (FCC), which could be used to alter the response type generated by any of the Harrier like centerstick, nozzle lever, and throttle still located in the aft cockpit, as shown in Figure A-15. Since the aircraft responses generated by centerstick and throttle were no longer standard in the VAAC, their names were changed to right and left inceptor, respectively. Located on these inceptors, several selectable control features were installed for flight control inceptor scheme research. A thumbwheel was added to the left inceptor (LI), and the standard Harrier designation slew control was converted into a Translational Rate Command (TRC) slew, as shown in Figure A-13. On the right inceptor (RI), the sensor select switch was converted into another selectable TRC slew, and the conventional trigger was converted into a selectable height hold switch, as shown in Figure A-16. For safety, the program used a safety pilot in the front cockpit with access to all of the standard Harrier mechanical flight controls and an Independent Monitor (IM) to maintain the aircraft within its limited safe operational envelope. The IM compared the aircraft's response from rear cockpit inceptor input to the safe flight envelope of the TMk4, and would disconnect the digital flight controls before any limit was reached. Beyond the FCC, IM, and aft cockpit arrangement, the VAAC retains all of its standard flight control surfaces and Pegasus Mk103 engine.[19]

FLIGHT EVALUATION METHODOLGY

Preceded by familiarization sorties in the UK's AFS at the Advanced Flight Simulation Complex at DERA Bedford, the author acted as the evaluating test pilot during seven flights in December of 1998 with each sortie lasting an average of 0.7 hours duration, and evaluated all the previously described control modes and sub-modes.[20] Due to the limited flight clearance envelope of the VAAC at the time, evaluations were limited to approaches, VL, and waveoffs, since no takeoffs or rolling landings were allowed from the aft cockpit. The evaluation pilot located in the rear cockpit took command of the VAAC for the evaluation after the safety pilot controlled the takeoff sequence. Each evaluation flight consisted of multiple low approaches down the runways at DERA Boscombe Down until fuel weight was within VAAC VL performance. Once within limits, full decelerating approaches were flown to a hover acquisition point over the runway, then 45° descending translations to VL were flown to the V/STOL pad located on a taxiway adjacent to runway 05/23. HQR's were assigned to control modes and sub-modes based on workload and performance while accomplishing three tasks: approach and gross hover acquisition, descending 45° translation over the pad, and VL. The approach and gross hover acquisition task consisted of an initial nominal 3° glideslope approach from a visual landing pattern to a 150 ft AGL hover over the runway adjacent to the V/STOL pad, as shown in Figure A-17. From the runway, a 45° descending translation along the taxiway was performed to a 100 ft AGL hover over the V/STOL pad, as shown in Figure A-18. From a stabilized hover, a desired 300 fpm rate of descent was attempted, which ended in a VL at the pad, as shown in Figure A-19. During several stabilized hovers, several surprise waveoffs were initiated after safety pilot call. Modes were evaluated by speed to wingborne flight and intuitiveness of required control input strategy. The performance parameters that the control modes and sub-modes were judged against for desired and adequate performance during the listed tasks are listed in Figures 17 to 19. The control modes and sub-modes were also compared by timeliness of task completion and occurrences of pilot cognitive failures and control misapplications. The evaluations occurred in weather conditions including calm and high, gusty crosswinds, cloudless skies, low ceiling rainy skies, and even low visibility dusk conditions.[20] In this thesis, specific comments on individual mode effects on handling qualities will be addressed, while deficiencies due to individual inceptor mechanical characteristics will be minimized. By greatly reducing workload, the VAAC's highly augmented digital FCS alone greatly improved handling qualities compared to the limited authority auto-stabilized Harrier FCS. By closing a feedback control loop around different parameters controlled by the FCS, all deviations due to IGE, OGE, or wind gust perturbations were automatically eliminated by the FCS. Due to IM kickoffs, insufficient fuel, or other problems not all of the modes and sub-modes received HQR rates, however some qualitative analysis was completed on all of them.

FLIGHT CONTROL MODE DESCRIPTION AND EVALUATION

During Phase 2 of the VAAC flight test program at DERA Boscombe Down, previously tested, promising flight control solutions were further refined in an attempt to find the optimum design for future STOVL jet aircraft. Three approach control modes and four hover control sub-modes were evaluated. The evaluated control modes included Unified, Mode Change, and Fusion modes, while the evaluated sub-modes included Augmented Translation Acceleration Command (TAC), RI slew stick TRC, RI slew button TRC, and LI slew button TRC.[19] Laterally, the RI in all three approach control modes was a roll rate with attitude hold CMD control at higher speeds before being blended between 130 and 100 Nautical Miles per Hour Indicated Airspeed (KIAS) into a bank angle CMD control. This naturally coupled into lateral acceleration, as shown in Figure A-20.[20] In all three approach control modes, control pedals commanded sideslip with active FCS sideslip suppression at higher speeds before being blended into a yaw rate CMD control between 30 and 20 Nautical Miles per Hour Ground Speed (KGS), as shown in Figure A-20.[20]

Unified Control Mode

Control Mode Description

The Unified mode incorporated a "frontside" control input strategy design philosophy, which is associated with all jet aircraft in up and away conventional flight and all conventional aircraft landings. The term "frontside" is derived from the flight conditions on the front portion of the power required curve, where throttle inputs easily change airspeed by thrust and longitudinal stick inputs easily change flightpath by pitch attitude. With this in mind, the mode was developed for the right inceptor (RI) to control flightpath and the left inceptor (LI) to control longitudinal acceleration throughout an aircraft's V/STOL flight envelope. Longitudinally for this control law configuration, the RI was a flightpath rate CMD control at higher speeds before being blended between 35 and 25 KGS into a height rate CMD control or a height acceleration CMD control with a trigger hold switch, as shown in Figure A-16 and A-21.[20] Once in the 130 to 65 KIAS blend region, pitch attitude automatically rotated from the commanded position to the optimum 6 1/2° landing attitude, but it was still trimmable using the RI top trim button. The LI was a ground referenced acceleration CMD control with a velocity hold center detent at higher speeds before being blended between 35 and 25 KGS into a groundspeed CMD control with a zero groundspeed hold aft second detent, as shown in Figure A-21.[20] The zero groundspeed hold second detent function was selectable for evaluation purposes.

Unified Control Mode with Height Acceleration CMD Evaluation

Unified control mode with height acceleration CMD configuration was evaluated during the first familiarization sortie. HQR's were assigned during any of the task phases. Qualitative evaluation of this mode configuration did, however, give an impression of its usefulness at improving handling qualities.

Approach and Gross Hover Acquisition

In the visual landing pattern, airspeed control was easy using the acceleration CMD with velocity hold detent on the LI, resulting in deviations and overshoots of only ±1 KIAS. During deceleration to 100 KIAS, desired glideslope maintenance required repeated forward stick inputs to prevent level off due to control mode blending into height accelertion CMD.

Hover Translation to the Pad

During translation to the pad from the R/W, initial single lateral axis input attempts resulted in an inadvertent forward longitudinal stick input, causing an undesirable aircraft descent. Difficult 45° translation and VL tasks required a complicated, multi-inceptor input strategy to control groundtrack and position, resulting in excessive deviations. Less than intuitive control law and flight control inceptor scheme during translation and hover tasks required excessive thought to insure correct control input, resulting in control misapplication and undesirable deviations during high workload maneuver. This cognitive overload resulted in low Situational Awareness (SA) of other flight associated sub-tasks like engine monitoring and obstacle avoidance. With the height acceleration CMD mode configuration, altitude control during translation and hover was difficult using longitudinal stick input, resulting in continual small altitude overshoots. Use of the trigger to capture desired altitude required separate, obscure button input, resulting in little use during the high workload portion of the task. Upon trigger initiation, control law effectively maintained altitude within ±10 ft.

Vertical Landing

High longitudinal stick force gradient and low longitudinal stick response gradient resulted in difficulty in achieving desired descent rate. Excessive longitudinal acceleration response to small LI input out of the second detent resulted in a jerky translation and hover, which adversely affected helpful inner ear acceleration cues. Final VL position error was 3 ft forward on the left markers and 2 ft forward on the right.

Configuration Summary

Implementation of objectionable height acceleration CMD on the RI with altitude capture trigger adversely affected both workload and precision during altitude capture and maintenance sub-tasks and during precise descent rate control. In high workload situations, a pilot will continue to struggle with an inefficient control input strategy, because he does not have the excess cognitive processing time to remember to locate and engage the obscure trigger controller. Additional excessive control input manipulation requirements to attain desired performance should be avoided, especially during high workload maneuver. These objectionable configuration characteristics also adversely impacted task timeliness and precision during gross hover acquisition and translation. Height acceleration CMD should not be used in the Unified Mode.

Unified Control Mode with Height Rate CMD Evaluation

Approach and Gross Hover Acquisition

Flightpath maintenance during deceleration was not an open loop task, requiring slight forward stick input to maintain flightpath within ±1°. Without deceleration initiation cueing in the HUD and no tactilely significant nominal rate associated hover-stop cueing on the LI, difficult deceleration control required multiple LI inputs to correct for improperly timed and sized initial input, resulting in excessively slow or overshooting approaches. High workload deceleration task and severely sloped runway elevation made altitude capture difficult, resulting in a final deviation of 13 ft low. During approach with crosswind, deviations from centerline during deceleration were caused by inadequate task maintenance time due to flightpath and deceleration control difficulty, which further increased workload to correct centerline deviations. Difficult centerline maintenance during approach due to crosswinds required increased crab angle during deceleration, resulting in a final position deviation of 20 ft right and 20 ft forward (HQR-4). Performance within desired tolerances were achieved for all sub-tasks during deceleration, but required a higher workload.

Hover Translation to the Pad

Awkward initial 45° translation required separate single inceptor inputs to reduce confusion and improve performance, resulting in an objectionable stair step groundtrack. Inceptor input strategy of only lateral RI step input followed by precise LI longitudinal inputs to finesse the desired groundtrack resulted in a jerky, vertigo inducing longitudinal swaying motion due to excessive aircraft response to small longitudinal LI inputs. Aft aircraft response to LI input was larger and jerkier than forward. Inceptor input strategy of only LI longitudinal step input followed by precise lateral RI inputs to achieve the desired groundtrack resulted in a more comfortable and precise translation. Once desired groundtrack was achieved, total workload was temporarily reduced. Workload dramatically increased again during final hover spot acquisition over the pad. Precise translation control at the end required small inputs with both inceptors, resulting in the same disturbing, jerky longitudinal aircraft response. Desired position acquisition tolerances were achievable, but the characteristics of this mode during 45° translations made this task more time consuming and less precise than a Harrier. High workload translation task and difficult to maintain forward RI force input (height rate) resulted in a stair step approach to the desired hover altitude, creating altitude control precision within ±1 ft (HQR-4.5). Although within desired tolerances, high workload and increased time requirement (36 and 42 sec) complicated this simple task. Absence of visual cues to aid groundtrack control and increased acceleration vertigo effects would adversely affect night operations in this mode. However, the height rate CMD control scheme made altitude capture much easier than the previously evaluated height acceleration CMD control scheme, which required the awkward trigger use to adequately capture altitude.

Vertical Landing

Maintaining constant forward RI (height rate CMD) input against the centering spring to maintain desired descent rate required excessive attention, resulting in descent rate fluctuations and reduced position control precision. Unintuitive flight control inceptor scheme resulted in control misapplications and increased hover position deviations during descent. IM disengagement's due to nozzle limiting at 20 ft AGL prevented touchdown evaluation. If continued, VL position control within desired tolerances may have been barely achievable. High workload and unintuitive control scheme made task difficult and time consuming (HQR-4.5). No time data to complete the task was taken due to multiple IM disengagements, but excessive time was required to perform the task.

Configuration Summary

Although offering the same control input strategy throughout the approach, translation, and VL, the Unified Mode may not be the optimum V/STOL solution. Using a "frontside" inceptor input strategy, decelerating approach to hover was not objectionable, but translating and VL tasks were objectionable. Using the LI acceleration CMD, airspeed control was relatively easy during the approach, and groundspeed CMD with the groundspeed hold second detent was well suited for the hover acquisition. Inclusion of height rate CMD instead of the previously evaluated height acceleration CMD was a marked improvement, and should be the preferable configuration in a Unified mode. Although control input strategy during translation and VL in Unified mode is similar to a frontside formation flight task, it is not well suited to timely and precise translation control required during current timely, precise V/STOL operations. Using two separate inceptors to control a multi-axis single plane task (X-Y plane) is awkward and imprecise, and using a "frontside" inceptor strategy in the hover with RI input is unintuitive and time consuming. Flight control inceptor scheme caused control misapplication during high gain maneuvers, which may endanger both pilot and a/c during normal V/STOL operations. Unintuitive flight control inceptor scheme during hover and VL may require excessive transition training for both new non-STOVL trained pilots and old Harrier pilots, and may still create hazardous situations due to control misapplication during high workload tasks.

Mode Change Control Mode

Control Mode Description

The Mode Change mode incorporated a "frontside" control input strategy design that was switched during the deceleration to a "backside" design. Associated with naval and USMC V/STOL aircraft with their slow approach speed requirements, the "backside" control input strategy uses the RI to maintain airspeed by attitude and the LI to control flightpath with thrust because of the flight conditions on the backside of the power required curve. The Mode Change mode incorporated a "frontside" control design philosophy with the Unified mode configuration until a discrete mode switch to a "backside" control design philosophy with the Translation Acceleration Command (TAC) sub-mode was initiated by pulling the nozzle control lever aft to the hover-stop position. During this evaluation, unified was modified to exclude the groundspeed CMD region and associated groundspeed hold second detent function of the LI. With Augmented TAC initialization at ≤30 KGS, the RI was a pitch attitude CMD control. This pitch attitude CMD naturally coupled into ground referenced acceleration, which was increased by 1.27 times with thrust vector augmentation. The attitude based acceleration was augmented by longitudinal thrust component of the thrust vector angle, as shown in Figure A-22.[20] In this mode, the spring centered inceptor position held achieved groundspeed. A selectable groundspeed sump option captured and maintained aircraft position over the ground as translation groundspeed was manually reduced to one KGS. In Augmented TAC sub-mode, pitch attitude was trimmable, but there was no ground referenced acceleration coupling associated with the attitude change. The LI was a height rate CMD control with an altitude hold detent, as shown in Figure A-22.[20]

Mode Change Control Mode Evaluation

The Mode Change control mode was evaluated during operation with the Unified control mode portion with RI height rate CMD and without the LI second detent zero groundspeed hold function and the Augmented TAC sub-mode portion. The TAC sub-mode was evaluated with groundspeed sump function active and off. An additional evaluation of the Augmented TAC sub-mode was accomplished during a waveoff maneuver initiated from a stabilized hover.

Approach and Gross Hover Acquisition

Prior to the mode switch, the Unified control mode portion exhibited the same handling quality characteristics as previously listed with the following exceptions. In Unified mode with LI acceleration CMD, difficult hover acquisition control required multiple, timely LI inputs to capture and maintain the desired hover spot. In addition, confusion and incorrect selection of the inactivated zero groundspeed second detent resulted in the aircraft translating aft at 7 KGS. High workload during gross hover acquisition coupled with the change in inceptor input strategy at the mode switch resulted in control misapplication and confusion, when the RI was mistakenly pushed forward to initiate a descent. Corrections for altitude/hover position overshoots and difficult flightpath/deceleration control increased workload, although desired tolerances at 25 ft right were achieved (HQR-4). Switching modes to the Augmented Translation Acceleration Command sub-mode in a stabilized hover did, however, change the RI to a x-y plane acceleration controller, which had a more intuitive inceptor input strategy.

Hover Translation to the Pad

Using the RI in Augmented TAC mode, translation and hover position control within the x-y plane was more precise and expeditious. Easy altitude control using height rate CMD on the LI resulted in precise altitude maintenance during translations. During several practice runs, less than optimum RI mechanical characteristic adversely affected translation and altitude capture precision, but pilot compensation reduced the effect over time. Control inceptor mechanical characteristics included stick force gradients, breakout and friction, stick centering, and aircraft response gradients. Final evaluation pass resulted in a lower workload, more precise translation, and required 35 sec to complete. Hover position acquisition and altitude capture of 3 ft low were within desired tolerances (HQR-3). With Augmented Translation Acceleration Command, RI x-y axes control scheme was intuitive, and no control misapplications occurred during this phase.

Vertical Landing

Without groundspeed sump function engaged, drift in the hover and during VL was minimized by the groundspeed control of the Augmented Translation Acceleration Command mode, and VL positioning was precise at only 1/2 ft forward of the target spot. Further evaluations were accomplished with the groundspeed sump function engaged.

Descent rate control was easy during VL task using the LI height rate CMD in conjunction with the predicted and actual climb-dive marker HUD symbology, requiring only a single control input to achieve desired results. Less than optimum RI mechanical characteristics coupled with the high gain nature of the precision VL task adversely affected VL handling qualities, requiring reduced gains with either reduced descent rates or reduced landing spot precision to prevent an objectionable oscillatory longitudinal aircraft swinging motion during the descent. Constant 300 fpm descent rates and lower gain compensation to reduce sensitivity resulted in landing deviations of left-3 ft forward and right -4 ft forward (HQR-4). Final VL task took a total of 20 sec from stabilized hover to touchdown. No cognitive failures of control input strategy occurred during this portion of the evaluation. The presence of pitch changes with longitudinal stick input in Translation Acceleration Command was not objectionable for medium to small inputs.

Waveoff Evaluation

Upon safety pilot waveoff call in a stabilized hover in the Translation Acceleration Command sub-mode, initial forward LI input to climb and forward RI to accelerate resulted in a 500 fpm climb and negligible forward motion. With the RI centered and the LI reduced to 75% forward, a mode switch to Unified mode was accomplished to continue the maneuver. Upon mode switch, nozzles sharply rotated aft 15°, and flightpath abruptly dropped 2°. This resulted in an IM disengaged due to nozzle angle limits, and the task was abandoned. Inceptor position is too critical during waveoff and correct inceptor strategy did not achieve desired aircraft response.

Control Mode Summary

Less than optimum flight control law tuning and inceptor mechanical characteristics aside, the Mode Change mode may not be the optimum V/STOL solution due to Control Mode Harmony blending issues. The mechanical characteristics lowered the HQR rating by adversely effecting pilot workload and task precision, but they were not the most important deficiencies of this control mode. Changing modes and inceptor input strategy during critical workload intensive gross hover acquisition resulted in cognitive lapses and control misapplications, requiring time consuming control input to correct deviations. This may endanger both aircraft and pilot during night approaches to the ship, and will at least adversely affect both task timeliness and precision. Once stabilized in hover, Augmented Translation Acceleration Command sub-mode control input strategy with its associated RI x-y axes control scheme was intuitive during translation and VL, and the LI height rate CMD reduced workload considerably during both altitude maintenance and descent rate control sub-tasks. Translation and VL were completed in a much more timely manner in Augmented Translation Acceleration Command control scheme than Unified, resulting in it being preferred for that portion of the task. Presence of pitch changes with longitudinal stick input in Augmented Translation Acceleration Command was not objectionable, and gave helpful control input size cueing. Waveoff in Translation Acceleration Command mode was totally ineffective, and mode change to Unified was awkward and time consuming. Intuitive inceptor input technique of advancing the LI to get away from the ground resulted in a dangerously abrupt nozzle aft movement, followed by a discomforting, abrupt flightpath drop. In its current form, this mode does not show promise for operation in the V/STOL environment, however the Augmented Translation Acceleration Command portion did show favorable characteristics during the translation and VL phases.

Fusion Control Mode

Control Mode Description

Fusion mode was developed to offer a "frontside" or "backside" control input strategy to accommodate all preferred pilot techniques and flight situations. Longitudinally, the RI was a flightpath CMD control at higher speeds before being blended between 130 and 65 KIAS into a pitch attitude CMD. This pitch attitude CMD naturally coupled into ground referenced acceleration, which was increased by 1.27 times with thrust vector augmentation, as shown in Figure A-23.[20] The groundspeed sump option was added to reduce pilot workload during precise hover acquisition tasks, which automatically maintained aircraft hover position over the ground as the translation rate was reduced within 1 KGS with a centered RI. Pitch attitude was trimmable below the 130 to 65 KIAS blend region, and the trim switch was a pitch attitude CMD control. The LI was an angle of attack CMD control or a flightpath rate CMD control before being blended between 35 and 25 KGS into a height rate CMD control, as shown in Figure A-23.[20] Below the blend region, the RI and LI functioned exactly like the Augmented Translation Acceleration Command sub-mode. A thumbwheel located on the LI was a flightpath-referenced acceleration CMD control with airspeed hold detent before being blended between 130 and 65 KIAS into a ground referenced acceleration CMD control with groundspeed hold detent, as shown in Figure A-23.[20] A selectable crosswind compensation function was designed to reduced groundtrack deviation by automatically banking up to 7° into the wind from 120 KIAS to 30KGS, and then by automatically increasing crab angle into the hover.

Fusion Control Mode Evaluation

Fusion control mode was evaluated in two configurations with the LI as an AOA CMD and as a flightpath rate CMD controller. Since the above configuration differences only effect operation in the blend region and at higher airspeeds, their individual evaluations will be limited to the approach portion only. An additional evaluation of the Fusion mode in the RI flightpath rate CMD configuration was accomplished during a waveoff maneuver initiated from a stabilized hover.

Approach with the AOA CMD Configuration

True "backside" control input strategy with this AOA CMD configuration could not be used as attempts to control flightpath with the LI resulted in predictable deviations off optimum AOA, which by definition defeats the purpose of a "backside" approach technique. Without deceleration initiation cueing in the Heads Up Display (HUD) and no tactilely significant nominal rate associated hover-stop like cues on the thumbwheel, closure control was extremely difficult, resulting in continuous monitoring and exhaustive thumbwheel input repositioning. Asymmetrically, excessive deceleration response rates at high speeds compared to inadequate deceleration response rates at airspeeds less than 50 KIAS increased pilot workload, and resulted in excessive targeted hover spot overshoots. During entire evaluation flight control inceptor scheme was intuitive, and no control misapplications occurred.

Approach with the Flightpath Rate CMD and Crosswind Compensation

Unnatural flightpath rate CMD on the LI required two equal sized inputs to alter flightpath, resulting in excessive control inputs and HUD monitoring to prevent gross overshoots. Designed to accept either a "frontside" or "backside" control input strategy, awkward and workload intensive flightpath rate control configuration forced conversion from the preferred "backside" control input technique to the less desirable "frontside" technique. In addition, flightpath modification using the LI resulted in pitch attitude coupling, requiring forward RI input during glideslope reductions to maintain optimum angle of attack. Less than optimum thumbwheel mechanical characteristics and absence of deceleration initiation cueing in the HUD or tactilely significant nominal rate associated hover-stop like cues on the thumbwheel made closure control extremely difficult, resulting in continuous monitoring and exhaustive thumbwheel manipulation. Location of the thumbwheel on the LI further increased workload during "backside" style approaches, as both flightpath control and acceleration control were driven with the same hand. During deceleration to the runway in a slight crosswind, an uncommanded, groundtrack maintaining 2° bank angle was visible, but not objectionable. Unfortunately, no final HQR assignment run was accomplished, so only a qualitative analysis was possible.

Gross Hover Acquisition

Approaching the hover with crosswind compensation engaged, the groundtrack maintaining bank angle turned into a crab with some added pilot control pedal augmentation. Workload intensive deceleration control adversely affected other tasks, resulting in final deviations of 16 ft low and 20 ft left of target (HQR-3). During the entire approach to hover, control input strategy was intuitive, and no control misapplications occurred.

Hover Translation and Vertical Landing at the Pad

After the decelerating approach, aircraft control during descending 45° translation and VL was smooth and precise in Augmented Translation Acceleration Command sub-mode, and no cognitive failures or control misapplications occurred. Augmented Translation Acceleration Command characteristics were previously described. Precise three dimensional flightpath control was achievable during descending translation, resulting in precise groundtrack control and altitude capture within ±2 ft (HQR-3). Intuitive control strategy also resulted in precise, timely, ±1 ft position control during VL, but pilot gain reduction to compensate for pitch sensitivity and oscillatory longitudinal aircraft swinging motion increased workload (HQR-4). VL task accomplishment time was 22 seconds.

Waveoff Evaluation

An unexpected safety pilot commanded waveoff was initiated from a stabilized 150 ft hover. Intuitive control input strategy of maximum LI input with forward thumbwheel input initiated transition to wingborne flight in a timely manner. Flightpath drifted from 3° to a slightly excessive 5° with full forward RI input half way through the transition, requiring an unnatural reduction in LI input to control.

Control Mode Summary

During STOVL operations, a "backside" approach technique is flown to maintain the optimum angle of attack for greatest wing lift to reduce the engine lift requirement, resulting in increased engine life and waveoff performance. Not designed with a true "backside" approach capability, the Fusion mode with the angle off attack (AOA) CMD LI configuration used LI control of AOA to change flightpath, which by definition prevents optimum AOA maintenance. This indicated that this Fusion mode configuration is not the optimum configuration during the decelerating approach task.

Mechanical and flightpath rate CMD characteristics aside, Fusion mode was the most intuitive inceptor control scheme evaluated, resulting in the smoothest, most precise, and timely aircraft control during transition to jetborne flight and translation to VL. The mechanical characteristics impacted the HQR of the evaluation by adversely affecting pilot workload and task precision, but the merits of this control mode overshadowed these fixable characteristics. Improving thumbwheel mechanical characteristics may reduce jerky, imprecise acceleration response, which would further increase the preference of this mode. Changing LI flightpath rate CMD to flightpath CMD may also greatly improve mode operation, and allow use of the preferred "backside" control technique during precision V/STOL approaches. Placement of the thumbwheel on the RI may reduce left-hand workload during decelerating approaches using the "backside" technique. Intuitive control input strategy throughout the approach and VL resulted in a smooth transition to jetborne flight with no cognitive failures, and use of an x-y plane translation control strategy will insure safe transition training for previously trained Harrier pilots. Excessive initial response to thumbwheel input aside, waveoff in Fusion mode was very intuitive, timely, and controllable when compared to the Unified or Mode Change mode waveoffs. Further investigations of different LI command modes may improve waveoff performance and intuitiveness.

TRC Hover Control Sub-Modes

Control Sub-Mode Description

Translational Rate Command (TRC) was developed by NASA Ames researchers to reduce pilot workload during final gross hover acquisition and VL at the ship at night or in poor weather conditions. Developed as a slow speed sub-mode, its use was limited to rates less than 30 KGS. Slew controller inputs result in ground referenced, proportional translational velocities in the x-y plane, and all drift ceases with the slew controller centered.[20] An additional groundspeed hold button allows constant velocity translations to be maintained without slew control input. For this evaluation, the slew controller came in three forms: the entire RI, slew button on the top of the RI or the LI. TRC sub-mode activation occurred as a function of slew controller location, which included pressing a TRC engage button on the top of the RI or depressing the LI slew button itself. With the slew controller located on the top of the RI or LI, a TRC override feature was selectable by RI stick manipulation, which placed the FCS back into its basic control mode.

TRC Evaluation

The basic Translational Rate Command sub-mode control architecture was the same for all three evaluated configurations, so only the effects of slew controller location and Translational Rate Command functionality will be discussed further. During this evaluation, the VAAC was brought to a near hover condition in one of the three evaluated control modes before one of the TRC sub-mode configurations was engaged.

LI Top TRC Slew Controller

Evaluation consisted of sub-mode engagement during final decelerating approach to hover, and continued through subsequent translation over the pad and VL. Engagement of the sub-mode with any forward or lateral translation rate resulted in an objectionably jerky transient, as the FCS tried to stop all drift rates with bank attitude and nozzle angle changes.

Hover Translation to the Pad

Combining the engagement button with the slew controller resulted in repeated unintentional TRC disengagements during slew control input, requiring excessive time and button manipulation to complete the task. Placement of the slew controller on top of the LI (height CMD) task saturated the left hand during descending 45° translations, requiring an inefficient single plane control input strategy of removing translation control input to capture altitude or vice versa. This resulted in excessive translation times of 40 to 44 sec. Small total controller displacement and excessive initial response gradient resulted in an imprecise, jerky aircraft motion, requiring a pilot gain reduction and smaller control inputs to reduce the motion. Without direct control of attitude, abrupt jerky aircraft response to control input reduced pilot confidence, resulting in deliberately slow, less precise aircraft control. Desired performance tolerances were achieved, but task required a high workload (HQR-4.5).

Vertical Landing

Once established on altitude over the pad, use of the LI height rate CMD with the climb dive marker predictor Heads Up Display information made descent control carefree. Reduced pilot gain and small control input size to inhibit jerky longitudinal response adversely affected VL task precision, resulting in accepted VL position errors to insure safe, nominal rate landings. Near touchdown, unpredictable landing attitude control in Translational Rate Command forced a reduction in control input magnitude, which inhibited landing spot position precision. Three VL resulted in position errors of left-0 ft/right-5 ft aft, left-½ ft forward/right-2 ½ ft aft, and left-2 ft aft/right-5 ft forward respectively, although the favorable middle data was really due to precise initial positioning at altitude (HQR-4). Control input strategy was to establish and maintain a 300 fpm descent rate to the deck, forcing a higher gain, fixed time period for position error correction of 22 sec from 150 ft AGL. In close, crosswinds caused a small right wing drop, which did not require the RI TRC override feature to correct.

RI as the TRC Slew Controller

Evaluation occurred in high 15 kts of wind with 25 kt gusts and low 350 ft ceilings in light rain. Surprisingly, less than optimum wind conditions were not perceivable in the cockpit, and they had no apparent affect on task precision.

Hover Translation to the Pad

Control input strategy was very intuitive, and no control misapplications occurred during this evaluation. The high longitudinal and lateral stick force gradients were similar, but human arm muscle characteristics favor longitudinal stick inputs. This resulted in a stair step groundtrack, requiring multiple shaped RI inputs to capture the desired track. High RI stick force gradients also inhibited precise, long term control inputs, resulting in repeated input reapplication, and fatigue during translation. High RI stick force gradients adversely affected final position acquisition over the pad with similar stair step motion. This high workload also reduced time available for altitude control during translation, resulting in greater altitude deviations. Due to aft cockpit FOV and unobservable lineup cues, determination of hover position acquisition was difficult, but judged to be within desired tolerances. During one descent while translating, a single 13 ft altitude overshoot occurred, which was corrected prior to the hover. With adequate monitoring time, the LI height rate CMD made altitude capture easy, requiring only two inputs to establish the desired descent rate and capture the desired altitude within ±1 ft. Desired performance tolerances were achieved, but RI workload was high (HQR-4). Difficulty of task was due to stick mechanical characteristics, and not necessarily the mode scheme. Time to complete the task was 38 and 43 sec on consecutive translations.

Vertical Landing

Control input strategy was intuitive, and no control misapplication events occurred during VL's. Precise initial descent rate capture was easy, requiring only one low gain LI input. In an effort to prevent IM disengagements and rough aircraft movement during task, control inputs were limited in size and onset rate. This low gain compensation scheme resulted in either accepted larger position deviations on touchdown or reduced descent rates to achieve precision. High RI stick force gradients made small precise control inputs difficult to initiate and maintain, resulting in increased position errors of right-2 ft aft and left-2.5 ft fwd (HQR-4). Descent rate to achieve above performance was reduced from 300 to 150 fpm. During one VL, a wing drop at less than 10 ft required an impossible opposing lateral control input, resulting in an uncomfortable off nominal landing after an IM disengagement. From hover to VL, task required 32 and 28 sec during consecutive VL's with 200 to 250 fps descents.

RI Top TRC Slew Controller

Weather, mechanical problems, and limited time prevented the flight evaluation of the RI top TRC slew controller configuration in the VAAC. However, a good evaluation of the configuration was accomplished in the AFS, which provided acceptable insight into the configuration characteristics. Unintentional RI stick inputs during Translational Rate Command (TRC) slew control manipulation resulted in repeated TRC disengagements due to the TRC override feature on the RI. Control crosstalk occurred during single axis translation attempts, resulting in aft drift for right inputs and forward drift for left inputs. Objectionable bank angle wobble and jerky acceleration response increased pilot workload and time requirement during 45° translation and VL tasks (HQR-4). By reducing pilot gain and using a beep input technique, undesirable motion was reduced, and precision was increased during the VL (HQR-3).

Control Sub-mode Summary

Engaged in a stabilized hover, most Translational Rate Command sub-modes reduced workload in high, gusty wind conditions. However, it is desired that the flight control modes be designed to help the pilot to precisely approach and VL on the ship in a timely fashion with minimal workload. Translational Rate Command sub-mode engagement task and control input strategy change in some configurations resulted in a less fluid, time consuming translation and VL. With a properly designed "Fusion" like approach mode, currently designed Translational Rate Command sub-modes may only be engaged in the hover, and then only in strong gusty winds or low visibility weather situations. Unfavorable impressions of inceptor top Translational Rate Command slew controllers with associated small displacements and steep response gradients were very dependant on the mechanical characteristics, suggesting great care should be taken in the design. Co-locating the TRC engagement switch on the slew controller should be avoided to prevent unwanted disengagement. With the RI TRC stick slew controller, desirably large displacement and relaxed response gradient characteristics were offset by objectionable high stick force gradients and stick harmony issues. These mechanical characteristics impacted the evaluation HQR by adversely affecting pilot workload and task precision, but they can be more easily improved by design in the RI stick slew configuration. It is beneficial for the pilot to have easy access to direct aircraft attitude control to prevent unwanted perturbations such as wing drop near touchdown. LI top TRC slew controller with RI override feature was the only evaluated TRC sub-mode configuration with this capability, however placing the controller on the LI increased left hand workload during descending translations or VL. Attitude control override is desirable using the RI, but unwanted sub-mode disengagement may continue to adversely affect timely task completion. Flight control scheme and control input strategy were intuitive during the entire phase of evaluation. Having a RI x-y controller and a LI height rate controller made difficult simultaneous vertical and horizontal translations easy and precise.

CHAPTER 4

CONCLUSIONS

There is a definite tactical and strategic advantage in possessing a high performance strike fighter with STOVL capabilities to operate from austere sites close to the front lines, off small deck aircraft carriers, or from battle damaged airfields. However, the advanced strike fighter must not pay for the STOVL capability with excessive penalties in STOVL training expenses, transition handling qualities, or safety. In the past, no operational V/STOL jet has been built that gives the desired V/STOL capabilities with desired carefree handling characteristics. Currently, the most advanced, partially augmented, mechanical Flight Control System (FSC) design on the Harrier offers only a small rate reduction of destabilizing external perturbations during transition to jetborne flight and a complex control inceptor scheme, requiring a workload intensive control input strategy to maintain precise aircraft control. Current technology in flight control design allows us to overcome these limitations.

The most recent VAAC flight controls research project has answered some important questions on the direction of future jet powered STOVL flight control design and optimization. Generally, this evaluation showed the great importance of good control inceptor mechanical characteristics on effective flight control evaluation, as bad characteristics adversely affected Handling Quality Rating (HQR) and can cloud the evaluation results. By noting the mechanical characteristic adverse effects on the mode evaluation real time, the true merits and faults of each particular mode could be observed and later analyzed without difficulty. The significance of deceleration control on workload during approach in any flight control mode was also evident, which could be easily fixed by adding deceleration cueing in the Heads Up Display (HUD) and/or a tactilely significant nominal rate detent on the deceleration control inceptor. By comparing HQR, task completion timeliness, waveoff ease, and risk of cognitive failure data, Fusion mode was the clear winner in every category. As evaluated, the Fusion mode showed the advantage of having an intuitive control input strategy throughout the approach, translation, landing, and waveoff tasks, and allowed easy movement in all three axes during translations by offering Right Inceptor (RI) z-axis control during approach and RI x-y plane control near the hover. Although possessing a fused mode change when transitioning from higher semi-jetborne to hovering flight in Fusion mode, the mode change was seamless, cognitive and occurred during a reduced workload portion of the approach. When using the "backside" approach technique, Fusion mode offered the desired quality of consistency in control input strategy throughout the approach and VL process. Incorporation of a deceleration control thumbwheel and height rate CMD greatly reduced workload compared to a Harrier, but most other control input strategies and responses were similar. The crosswind compensation function also reduced workload during difficult ambient conditions. On the negative side, incorporation of angle of attack CMD Left Inceptor (LI) showed no promise during use for flightpath control, as constant, optimum angle of attack maintenance is of great importance during precise STOVL maneuver. Incorporation of the less than optimal flightpath rate CMD on the LI with blended pitch attitude CMD on the RI resulted in high workload due excessive control input requirements and pitch attitude coupling during "backside" approach technique. Increased jerkiness and absence of direct attitude control during high gain precise maneuver made Translational Rate Command a second choice as the control scheme for normal operations, however workload reduction in high winds and low visibility conditions make it a worth while sub-mode option. Evaluation results suggested no clear Translational Rate Command configuration winner, as all HQR and task completion timeliness were approximately equivalent. Due to its greater potential for mechanical characteristics and aircraft response gradient improvement, harmonious mode change control input strategy with a Translation Acceleration Command mode, and absence of accidental sub-mode deactivation problem, the RI stick slew was the best Translational Rate Command solution evaluated.

Based on operational and flight test experience, any future advanced STOVL strike fighter design should include a highly augmented digital FCS with a task optimal response control type blending design driven by an intuitive, easily assessable control inceptor scheme. The ACT FCS would maintain all flight parameter sub-tasks throughout the conventional and STOVL flight envelope, which would greatly reduce pilot workload. The FSC should be designed to incorporate a VAAC Fusion Mode like blended three-axes response design and control inceptor scheme, and should also offer a RI stick slew control TRC sub-mode for safe operation in poor weather conditions or at night. In the spring of 2001, the United States and United Kingdom will award a contract for one company to manufacture an advanced STOVL strike fighter, and they have stated that it must be effective, safe, and cheap. With this in mind, the contracting winning company and military must strive to develop an aircraft with carefree, intuitive handling qualities in the difficult STOVL flight regime.

RECOMMENDATIONS

Based on the author's operational and flight experience with current and advanced FCS, the following specific recommendations are made:

1. Optimize every inceptor, slew, and control mechanical characteristics on the VAAC Harrier prior to any further evaluation to insure conclusions are accurate and complete.

2. In any future VAAC flight control research or in any advanced STOVL strike fighter design, incorporate visual cueing in the HUD and some tactilely significant detent on the decelerating control inceptor to aid the pilot in timely, precise acceleration/deceleration control.

3. Incorporate the following: flightpath CMD into height rate CMD on the LI, a flightpath referenced to ground referenced blended acceleration CMD thumbwheel on the RI, and a RI stick slew TRC to the Fusion mode. Re-evaluated this configuration in the VAAC during approach and gross hover acquisition, translation, and VL tasks.

4. If successful at approach and VL tasks evaluate above optimized Fusion mode configuration in the VAAC during VTO, STO, rolling landings, and ship at sea operations.

5. In any future advanced STOVL strike fighter design, incorporate a further optimized Fusion like control mode and associated inceptor scheme to reduce workload during high gain STOVL tasks.

7. Research the possibility of converting a modern, larger flight envelope TAV-8B to the VAAC flight controls research configuration for more efficient, effective prototype flight control testing.

REFERENCES

REFERENCES

[1] "USMC Aircraft Flight Mishap Stats – FY 91 to 99," www.hqmc.usmc.mil/safety.nsf, Retrieved March 15, 1999.

[2] "Air Force Safety Center's Flight Safety Statistics," www-afsc.saia.af.mil/AFSC/RDBMS/Flight, Retrieved March 15, 1999.

[3] "Familiarization Phase," *AV-8B Flight and Trainer Syllabus Guide: Basics Phase*, December 1994.

[4] "LHA/LPH/LHD NATOPS Manual," NAVAIR 00-80T-106, March 1986.

[5] HoH, Rodger H., Mitchell, David G., "Handling-qualities Specification-A Functional Requirement for the Flight Control System," *Advances in Aircraft Flight Controls*, April 1993.

[6] Poole, R., "STOVL Aircraft Flight Testing," *Fundamentals of VSTOL Aircraft Design Course Class Note*, 1997.

[7] "Military Standard: Flying Qualities of Piloted Aircraft," MIL-STD-1797A, 30 January 1990.

[8] Kohlman, David L., "*Introduction to V/STOL Airplanes*," Iowa State University Press, 1981.

[9] "Introduction to Response Types," *USNTPS Flight Controls Class Notes*, January 1996.

[10] Hirschberg, Michael J., "Soviet V/STOL Aircraft: The Struggle for a Shipborne Combat Capability," American Institute of Aeronautics and Astronautics, 1997.

[11] Kuhn, Richard E., "Effect of Crossflow on the Fountain, What We Know and What Needs Investigation," *International Powered Lift Conference Proceedings*, 2 September 1998.

[12] "Flight Characteristics,"*AV-8B/TAV-8B NATOPS Flight Manual*, A1-AV8BB-NFM-000, 15 September 1990.

---

[13] Cooper, George E., Harper, Robert P. Jr., "The Use of Pilot Rating in the Evaluation of Aircraft Handing Qualities," NASA Technical Note D-5153, April 1969.

[14] Franklin, James A., "Criteria for Design of Integrated Flight/Propulsion Control Systems for STOVL Fighter Aircraft," NASA Technical Paper 3356, April 1993.

[15] Fozard, John W., "The British Aerospace Harrier, Case Study in Aircraft Design," American Institute of Aeronautics and Astronautics Professional Study Series, July 1978.

[16] "V/STOL Flight Characteristics," *The V/STOL Pilot's Book of Corporate Knowledge*, AV-8B Workbook 2W-31.

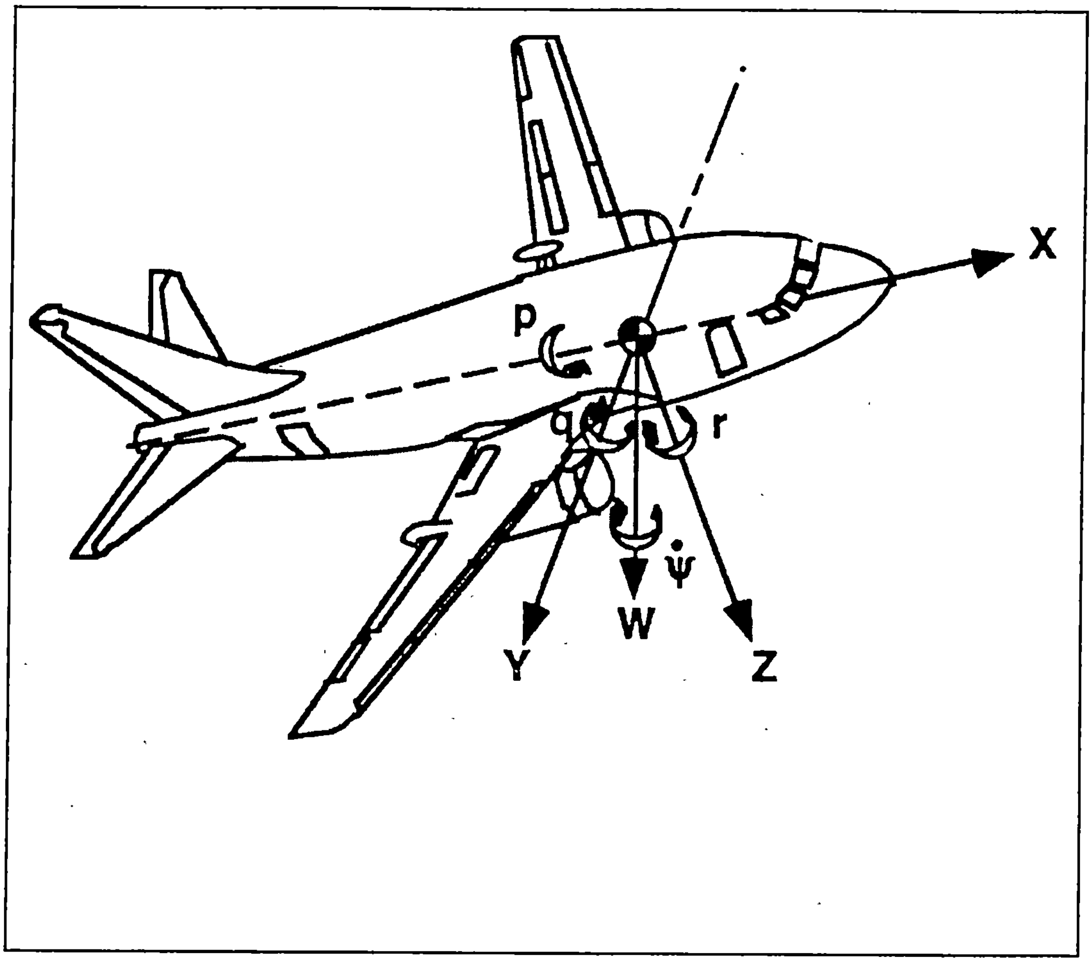
[17] Farley, John, "Thrusting Forward: VAAC Harrier Flight Test," *Flight International*, 2-8 Feruary 1994 Issue.

[18] Griffith, Daniel, "The VAAC Harrier – Phase One Summary," Experimental Flying Squadron, DERA Boscombe Down, Amesbury, Wiltshire SP4 0JF.

[19] Paines, Justin, "VAAC Pilot Briefing Notes," Experimental Flying Squadron, DERA Boscombe Down, Amesbury, Wiltshire SP4 0JF, December 1998.

[20] Karnes, Jeff, "VAAC Evaluation Daily Flight Reports," Strike Aircraft Test Squadron, NAS Patuxent River, Maryland, December 1998.

APPENDIX



p = roll

q = pitch

r = yaw

FIGURE A-1 COORDINATE SYSTEM DEFINING PITCH, ROLL, AND YAW

Source: *Static Stability & Control*, USNTPS Class Notes, July 1993.

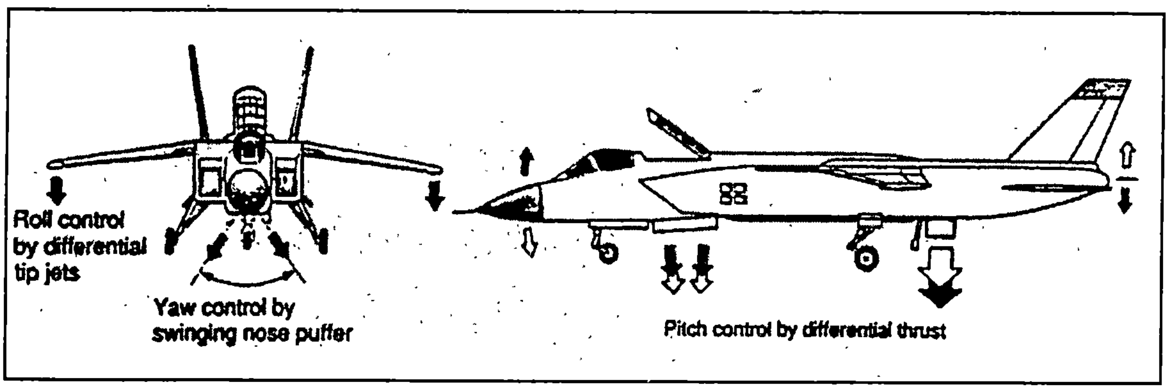


FIGURE A-2 YAK-41 ATTITUDE CONTROL SYSTEM

Source: Hirschberg, Michael J., *Soviet V/STOL Aircraft: The Struggle for a Shipborne Combat Capability*, American Institute of Aeronautics and Astronautics, 1997.

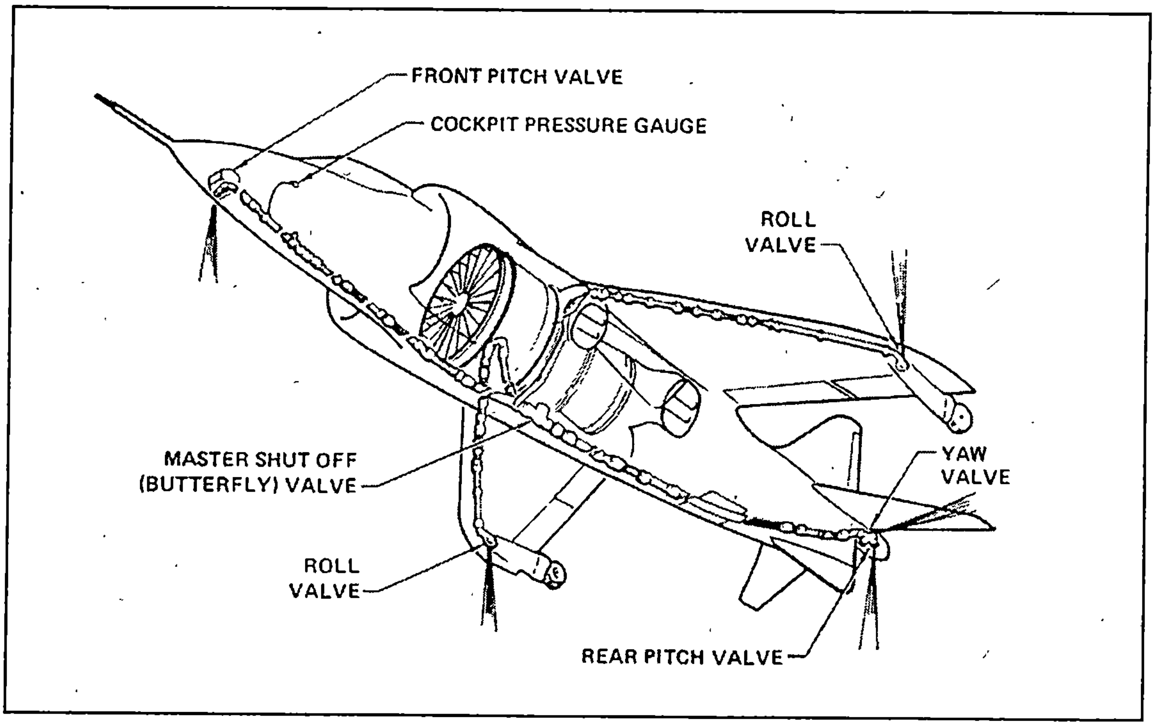


FIGURE A-3 HARRIER REACTION CONTROL BLEED SYSTEM

Source: Fozard, John W., *The British Aerospace Harrier, Case Study in Aircraft Design*, American Institute of Aeronautics and Astronautics Professional Study Series, July 1978.

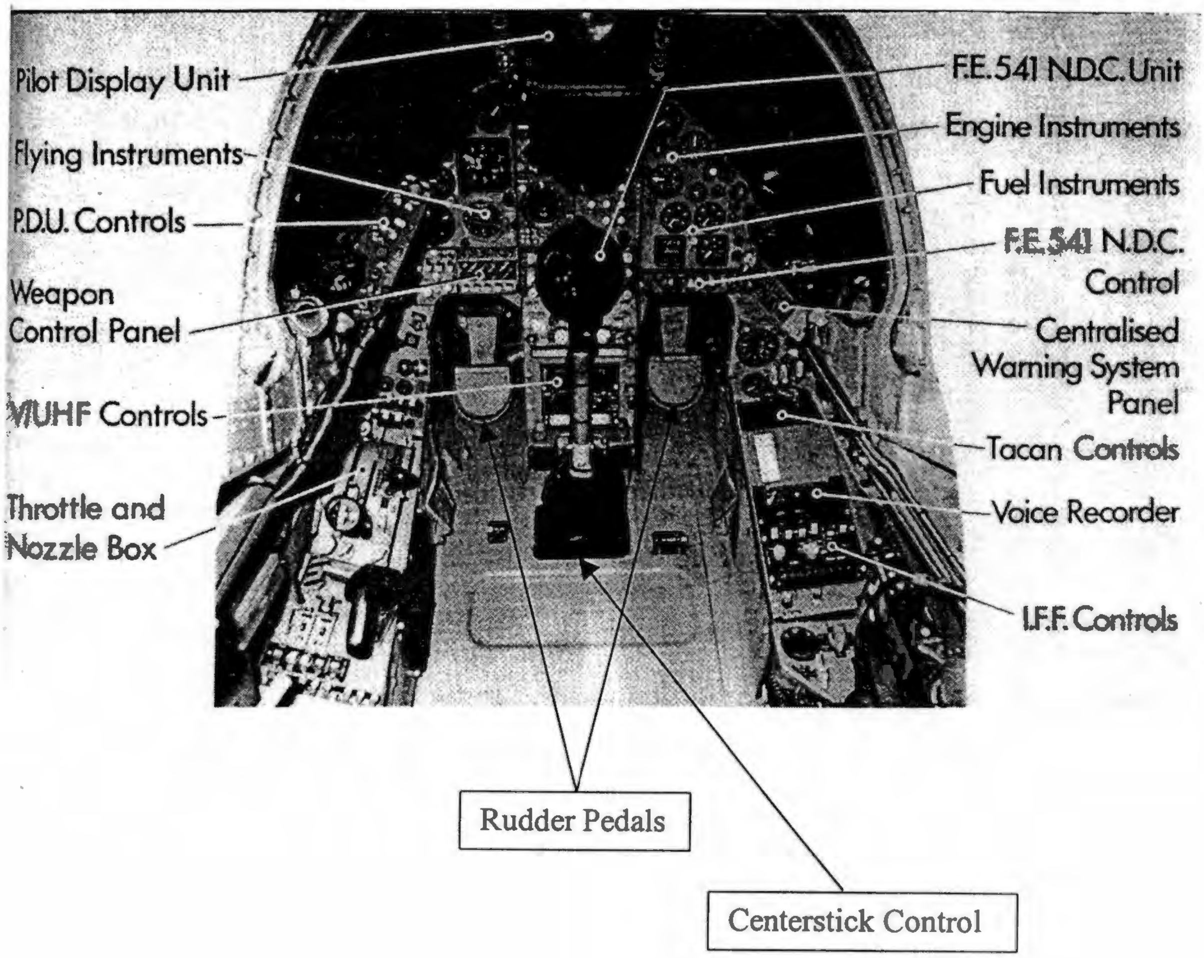


FIGURE A-4 HARRIER COCKPIT

Source: Fozard, John W., *The British Aerospace Harrier, Case Study in Aircraft Design*, American Institute of Aeronautics and Astronautics Professional Study Series, July 1978.

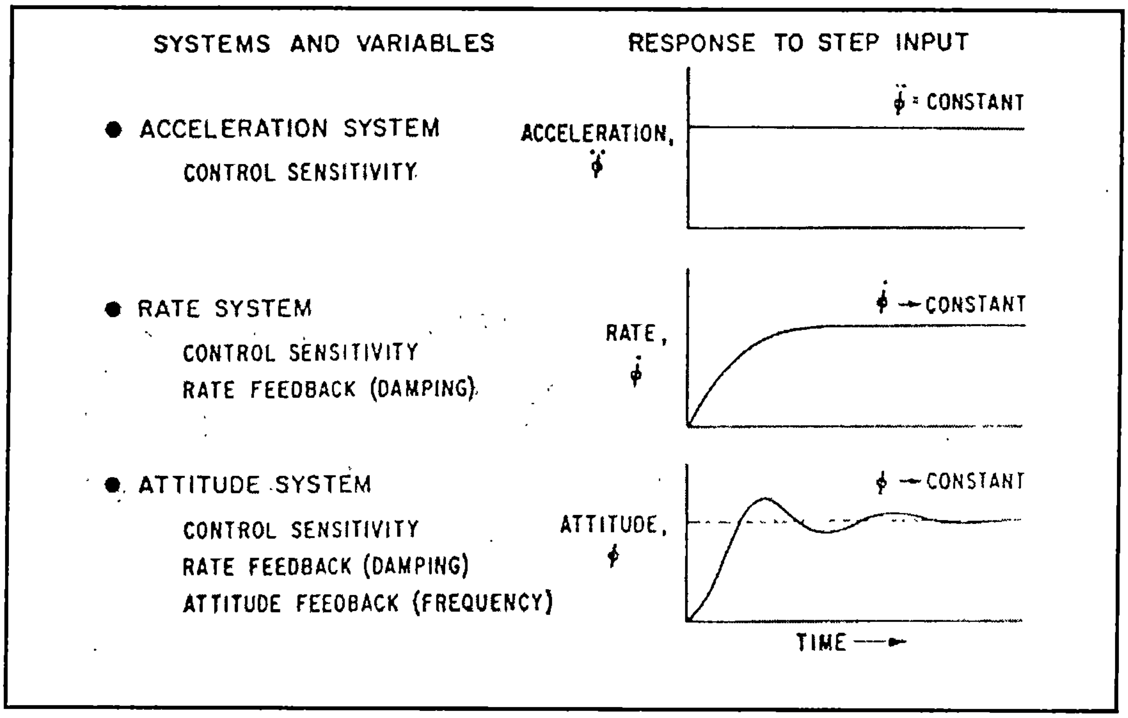


FIGURE A-5 RESPONSE TYPES

Source: Kohlman, David L., *Introduction to V/STOL Airplanes*, Iowa State University Press, 1981.

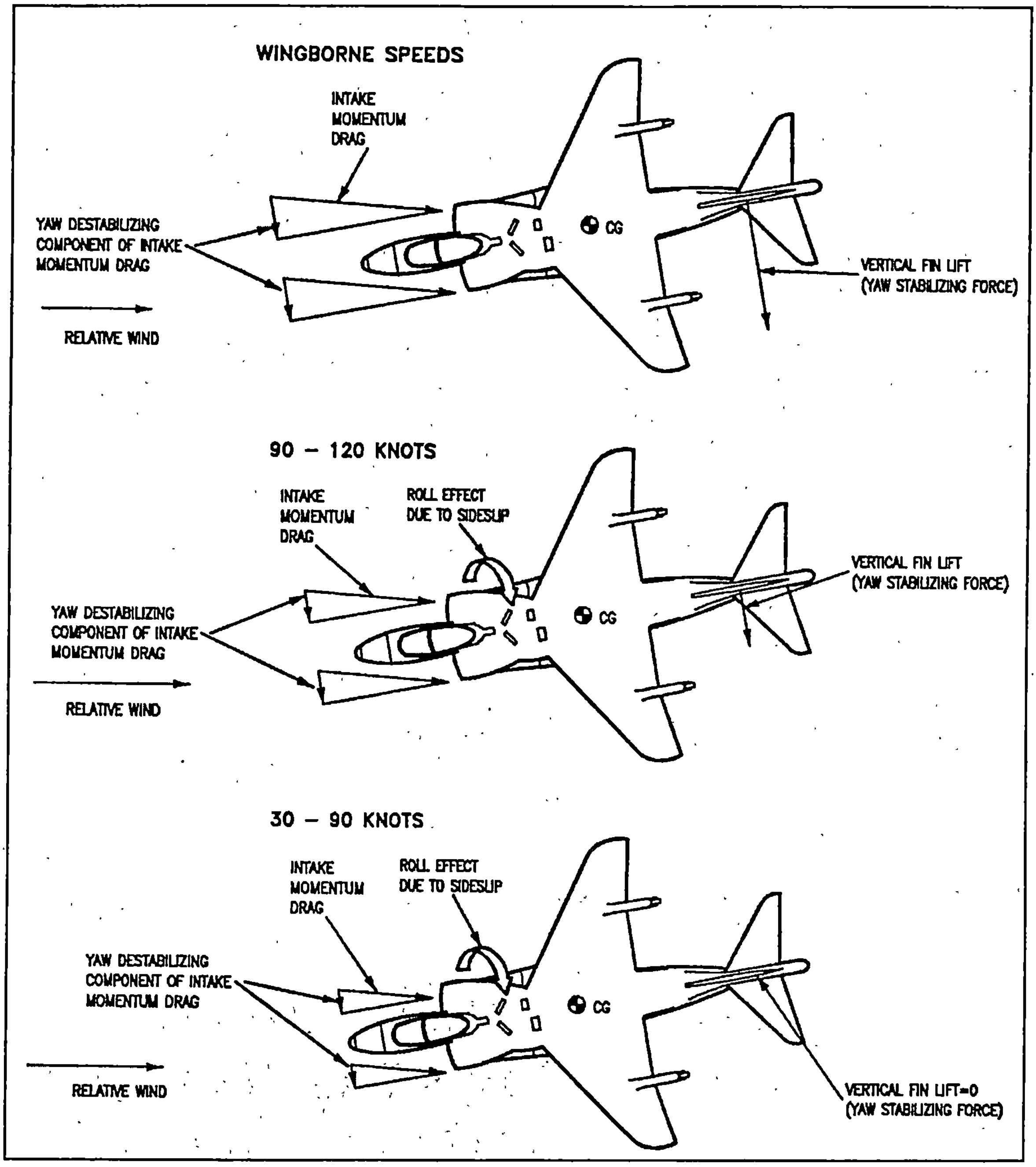


FIGURE A-6 INTAKE MOMENTUM DRAG EFFECT

Source: *V/STOL Flight Characteristics*, AV-8B/TAV-8B NATOPS Flight Manual, A1-AV8BB-NFM-000, 15 September 1990.

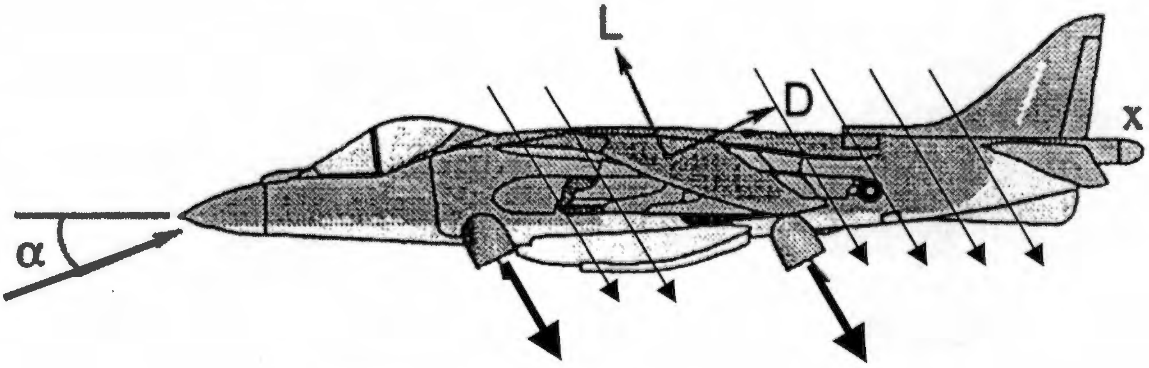


FIGURE A-7 FLOW ENTRAINMENT

Source: Pelikan, Ralph J., *Controllability of a V/STOL Fighter*, International Powered Lift Conference Proceedings, 2 September 1998.

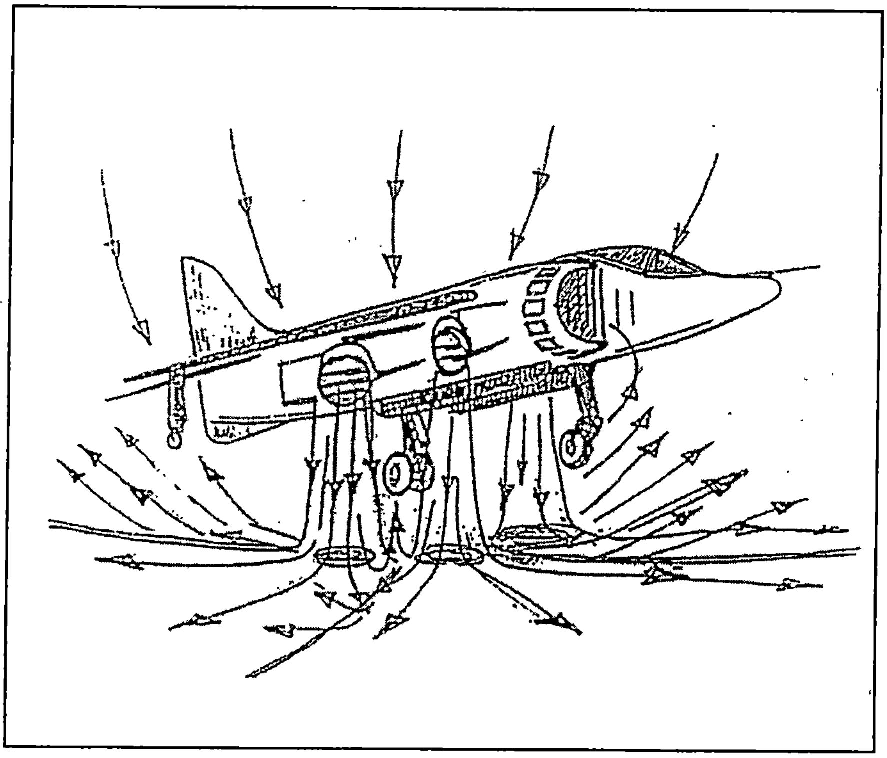


FIGURE A-8 IN GROUND EFFECT SUCKDOWN

Source: Ing, D. N., Knott, P. G., Clark, R., Appleyard, G., *Ground Environment Mat (GEM)*, International Powered Lift Conference Proceedings, 2 September 1998.

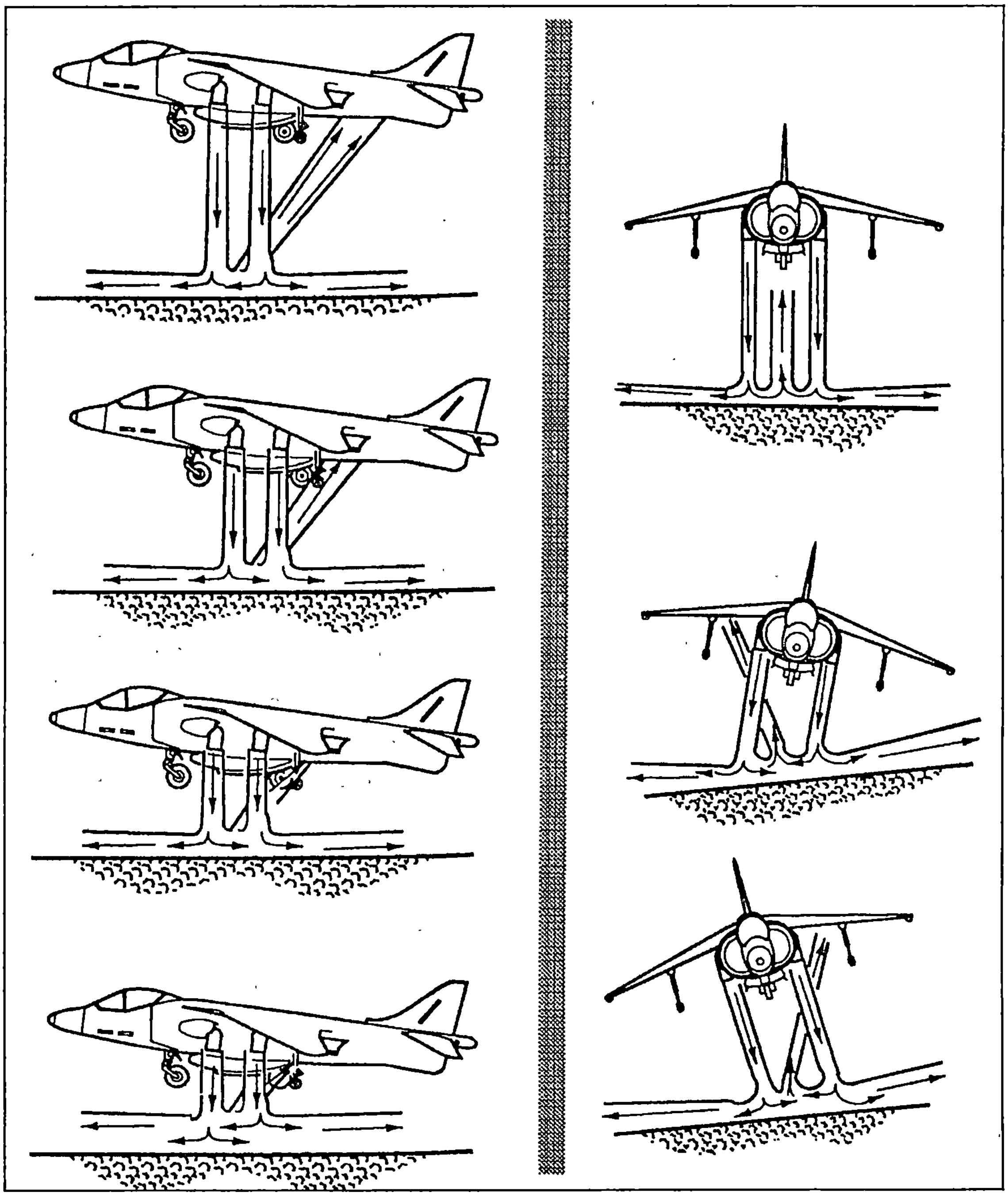


FIGURE A-9 NEAR-FIELD DESTABILIZING FOUNTAIN EFFECT

Source: *V/STOL Flight Characteristics*, AV-8B/TAV-8B NATOPS Flight Manual, A1-AV8BB-NFM-000, 15 September 1990.

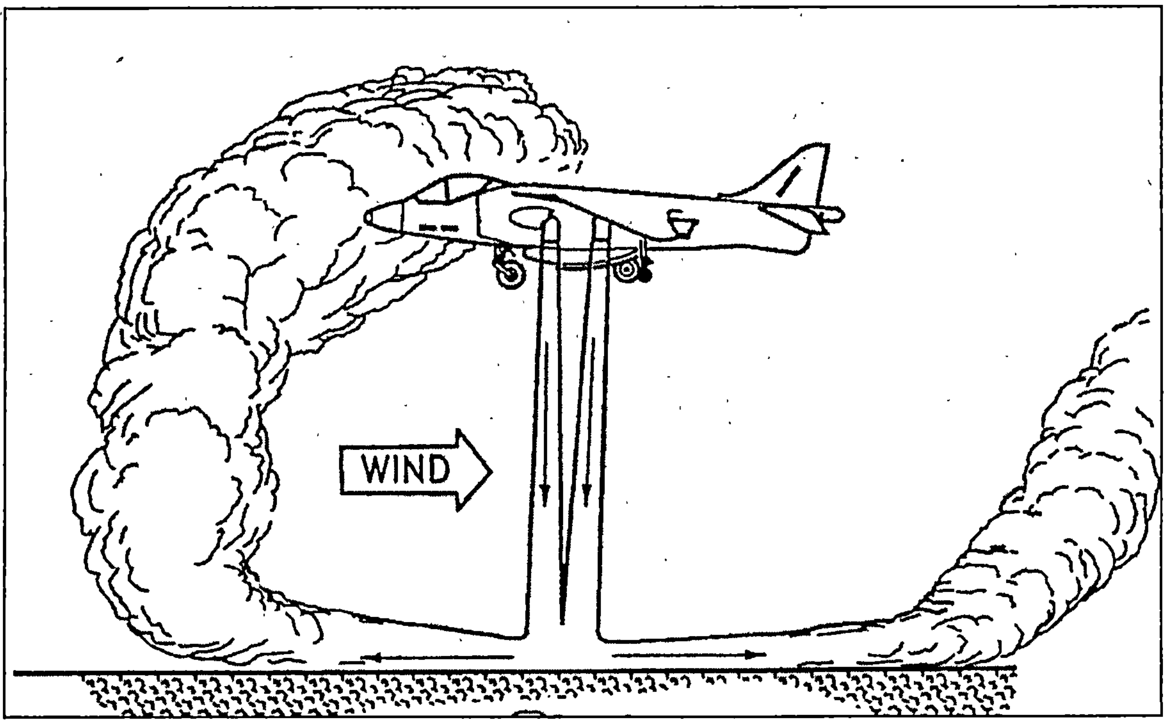


FIGURE A-10 FAR FIELD HOT GAS REINGESTION

Source: *V/STOL Flight Characteristics*, AV-8B/TAV-8B NATOPS Flight Manual, A1-AV8BB-NFM-000, 15 September 1990.

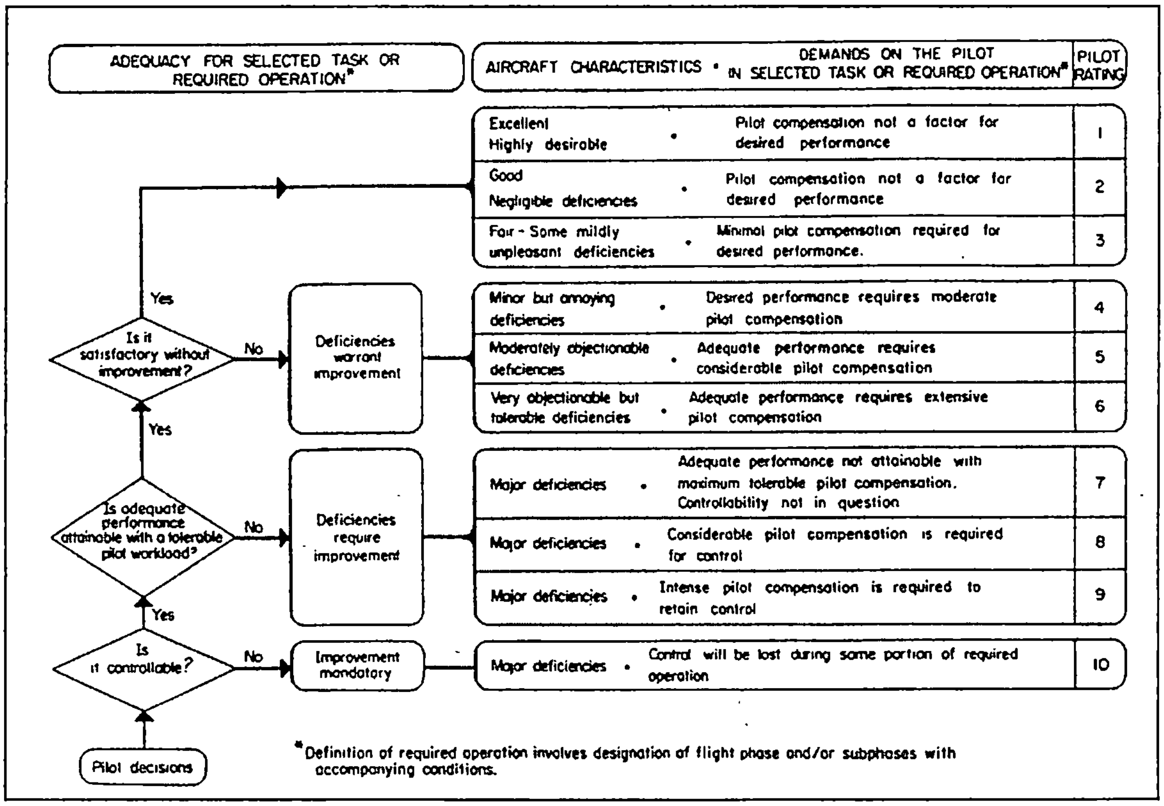


FIGURE A-11 HANDLING QUALITIES RATINGS

Source: Cooper, George E., Harper, Robert P. Jr., *The Use of Pilot Rating in the Evaluation of Aircraft Handing Qualities*, NASA Technical Note D-5153, April 1969.

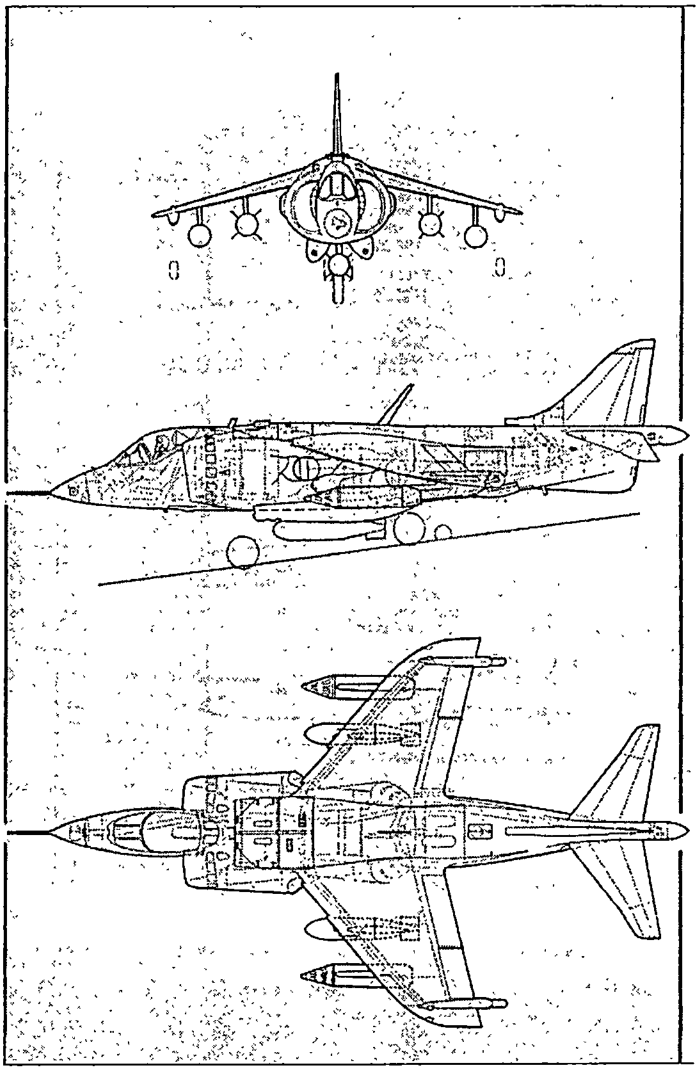


FIGURE A-12 HARRIER GR MK.1

Source: Fozard, John W., *The British Aerospace Harrier, Case Study in Aircraft Design*, American Institute of Aeronautics and Astronautics Professional Study Series, July 1978.

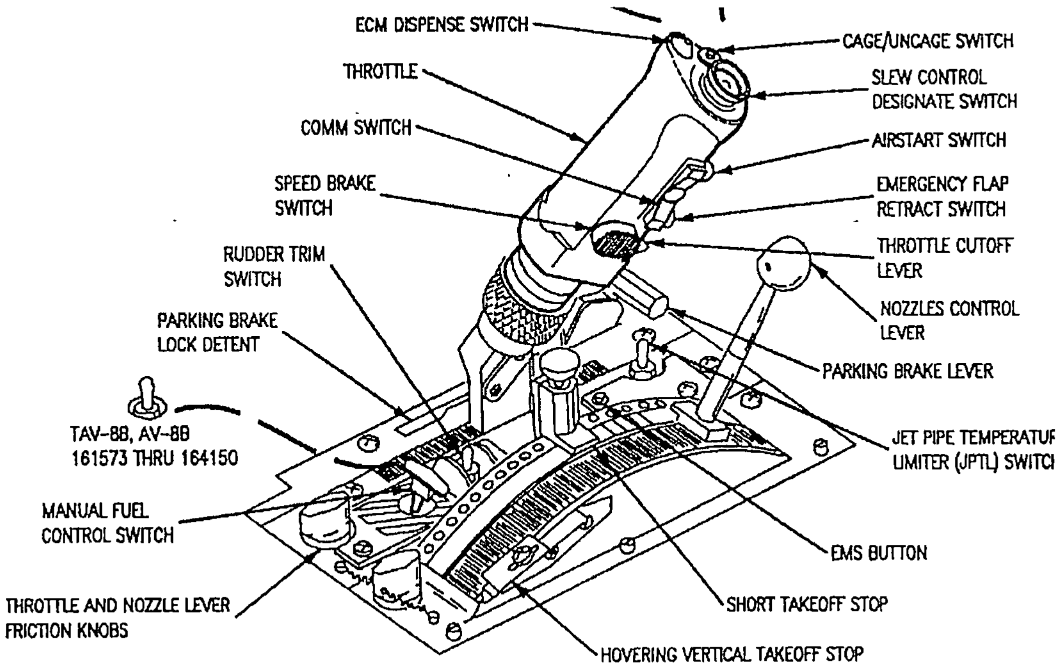


FIGURE A-13 AV-8B HARRIER THROTTLE QUADRANT

Source: *Engine Controls*, AV-8B/TAV-8B NATOPS Flight Manual, A1-AV8BB-NFM-000, 15 September 1990.

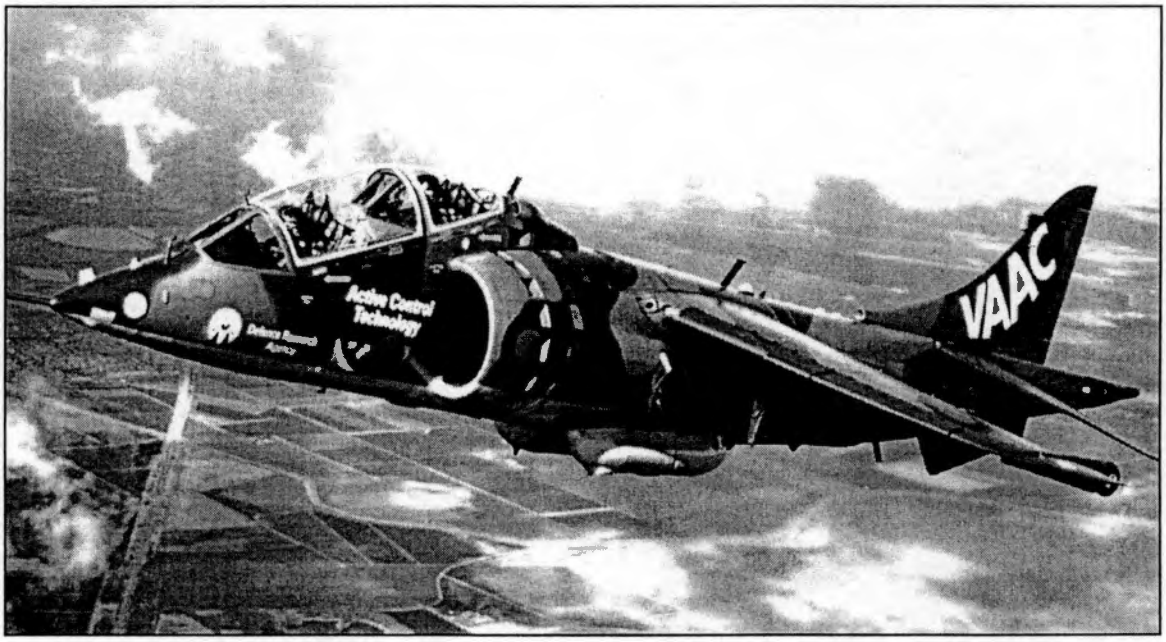


FIGURE A-14 VAAC HARRIER

Source: *Thrusting Forward: VAAC Harrier Flight Test*, Flight International, 2-8 February 1994.

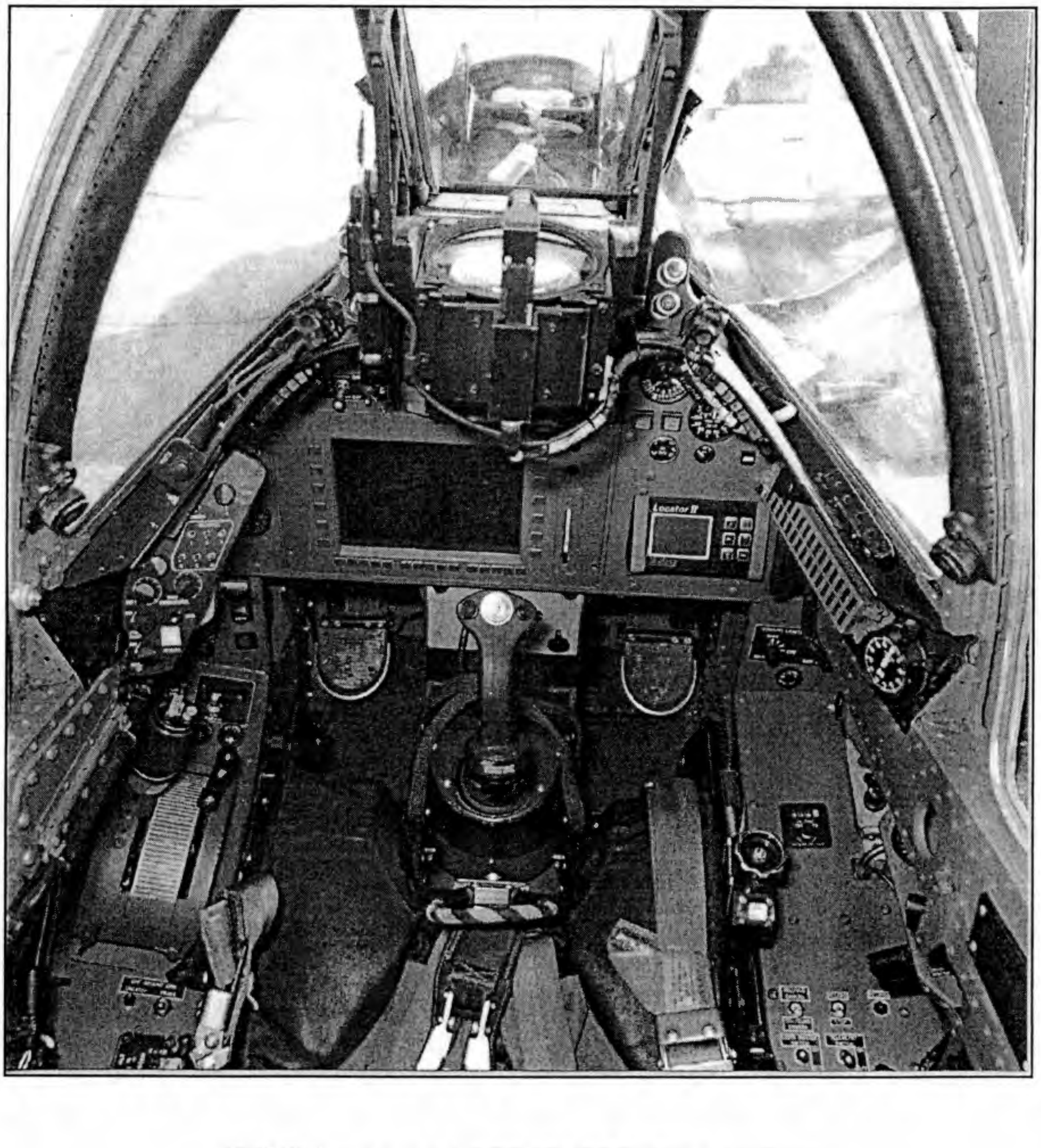


FIGURE A-15 VAAC REAR COCKPIT LAYOUT

Source: Paines, Justin, *VAAC Pilot Briefing Notes*, Experimental Flying Squadron, DERA Boscombe Down, Amesbury, Wiltshire SP4 0JF, December 1998.

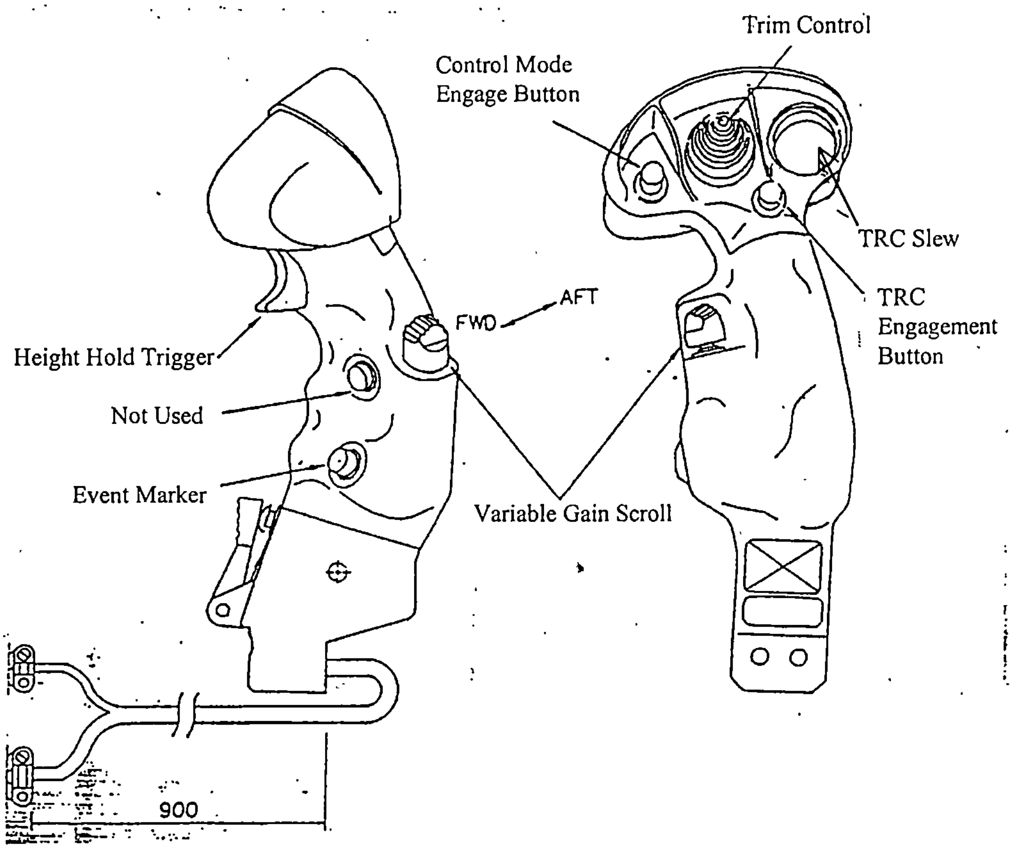
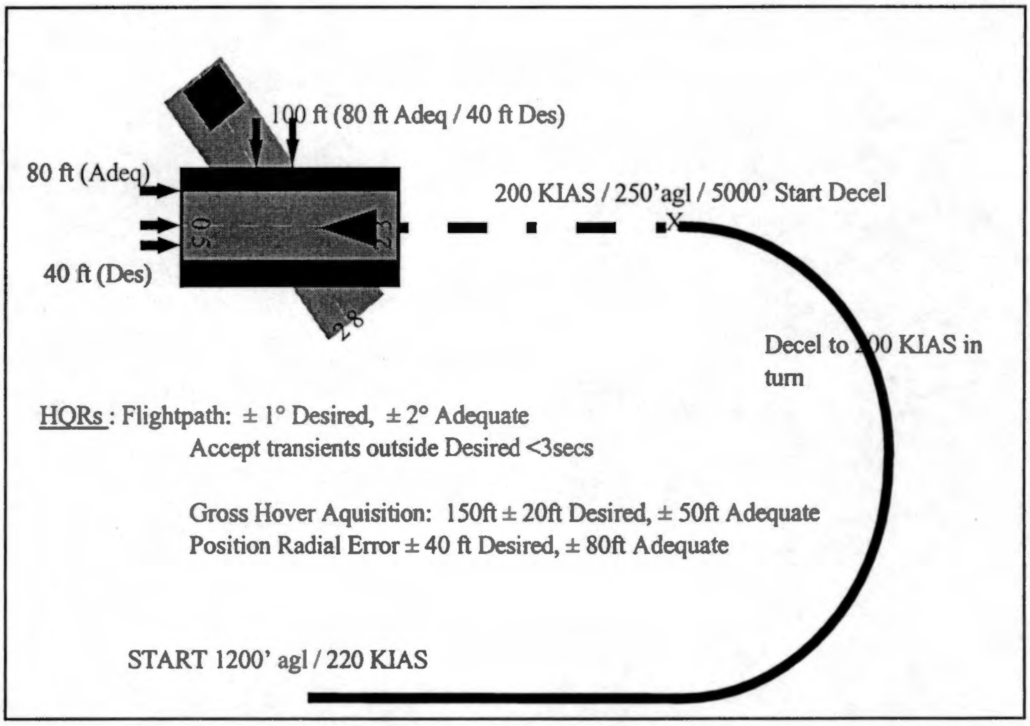


FIGURE A-16 EVALUATED VAAC RIGHT INCEPTOR CONFIGURATION

Source: Paines, Justin, *VAAC Pilot Briefing Notes*, Experimental Flying Squadron, DERA Boscombe Down, Amesbury, Wiltshire SP4 0JF, December 1998.

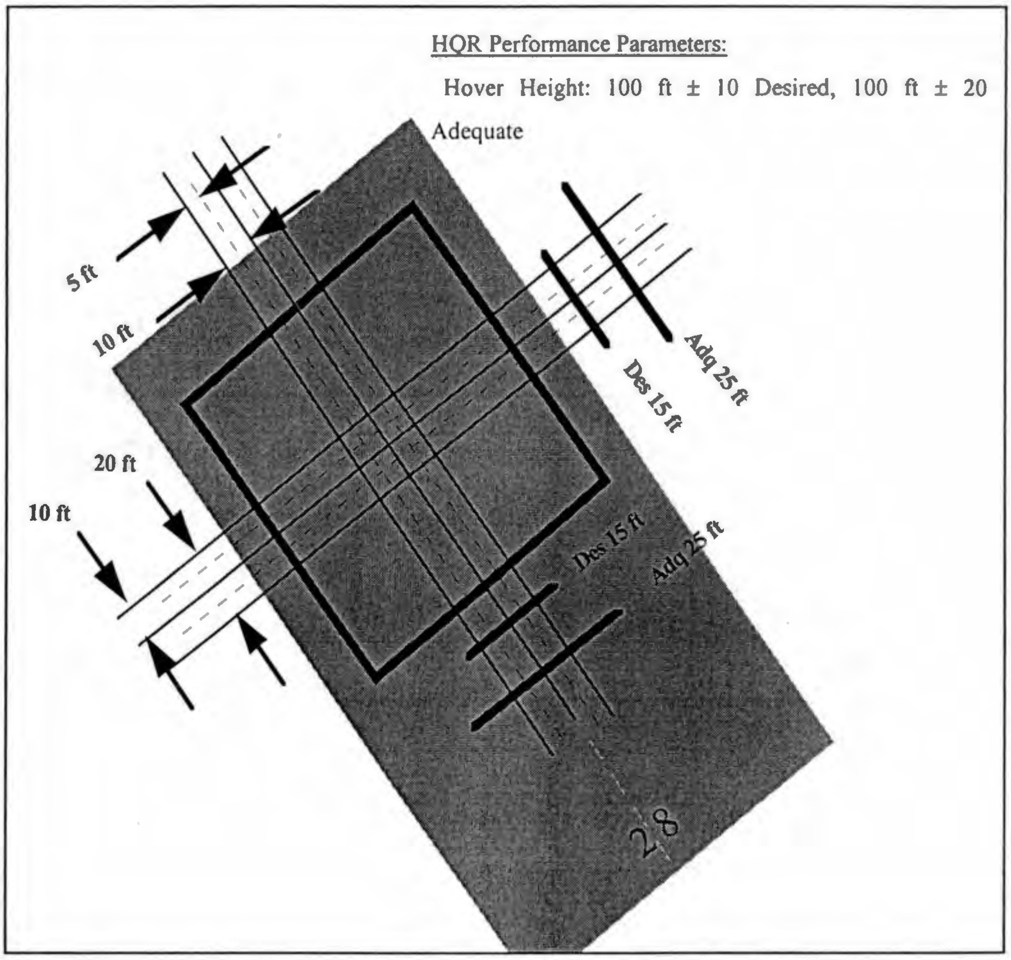


HQRs : Flightpath: ± 1° Desired, ± 2° Adequate
Accept transients outside Desired <3secs

Gross Hover Aquisition: 150ft ± 20ft Desired, ± 50ft Adequate
Position Radial Error ± 40 ft Desired, ± 80ft Adequate

FIGURE A-17 APPROACH AND GROSS ACQUISITION TASK

Source: Paines, Justin, "*VAAC Pilot Briefing Notes*," Experimental Flying Squadron, DERA Boscombe Down, Amesbury, Wiltshire SP4 0JF, December 1998.



HQR Performance Parameters:

Hover Height: 100 ft ± 10 Desired, 100 ft ± 20 Adequate

FIGURE A-18 TRANSITION TO THE PAD TASK

Source: Paines, Justin, "*VAAC Pilot Briefing Notes*," Experimental Flying Squadron, DERA Boscombe Down, Amesbury, Wiltshire SP4 0JF, December 1998.

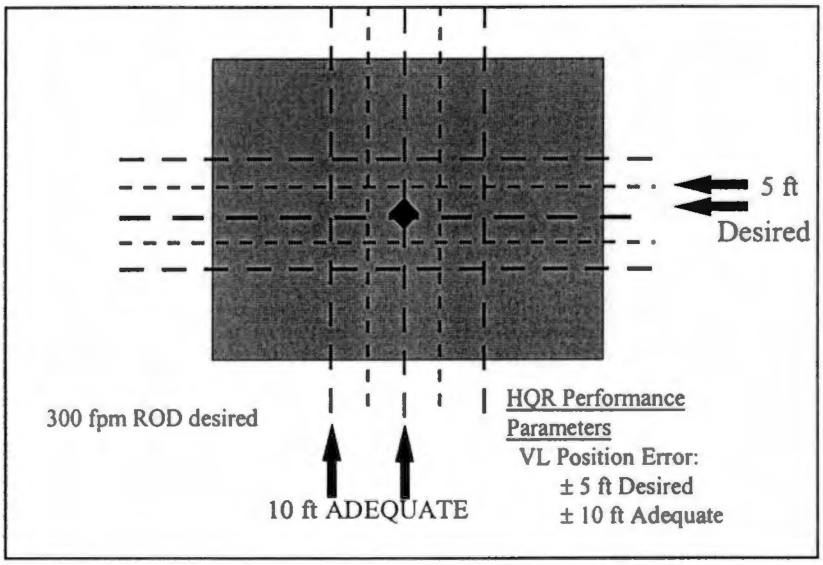


FIGURE A-19 VERTICAL LANDING TASK

Source: Paines, Justin, "*VAAC Pilot Briefing Notes*," Experimental Flying Squadron, DERA Boscombe Down, Amesbury, Wiltshire SP4 0JF, December 1998.

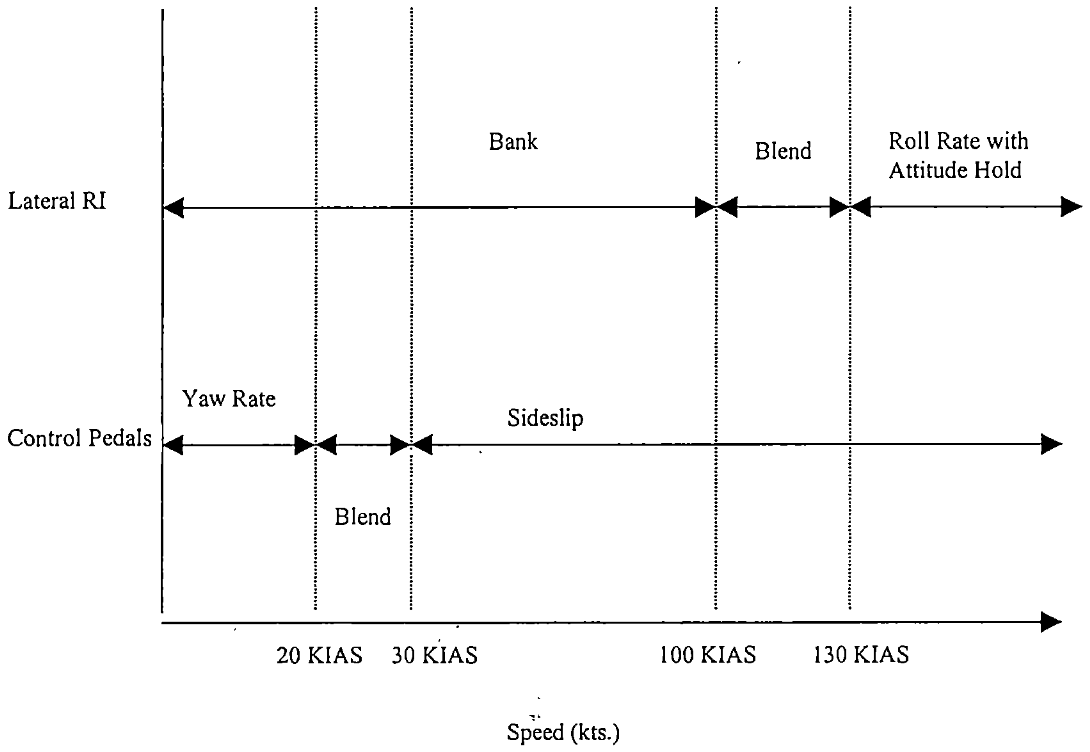


FIGURE A-20 VAAC LATERAL/DIRECTIONAL CONTROL LAWS

Source: Paines, Justin, *VAAC Pilot Briefing Notes*, Experimental Flying Squadron, DERA Boscombe Down, Amesbury, Wiltshire SP4 0JF, December 1998.

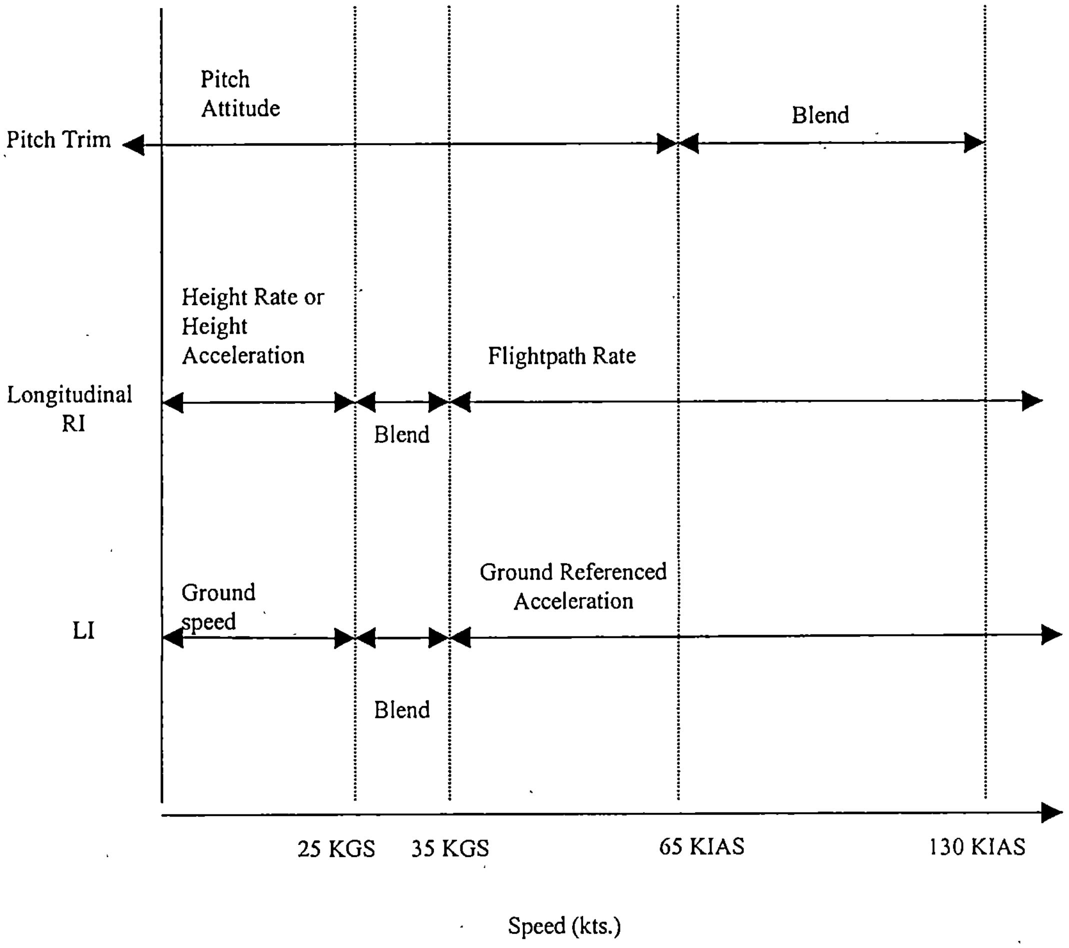


FIGURE A-21 UNIFIED CONTROL MODE

Source: Paines, Justin, "*VAAC Pilot Briefing Notes*," Experimental Flying Squadron, DERA Boscombe Down, Amesbury, Wiltshire SP4 0JF, December 1998.

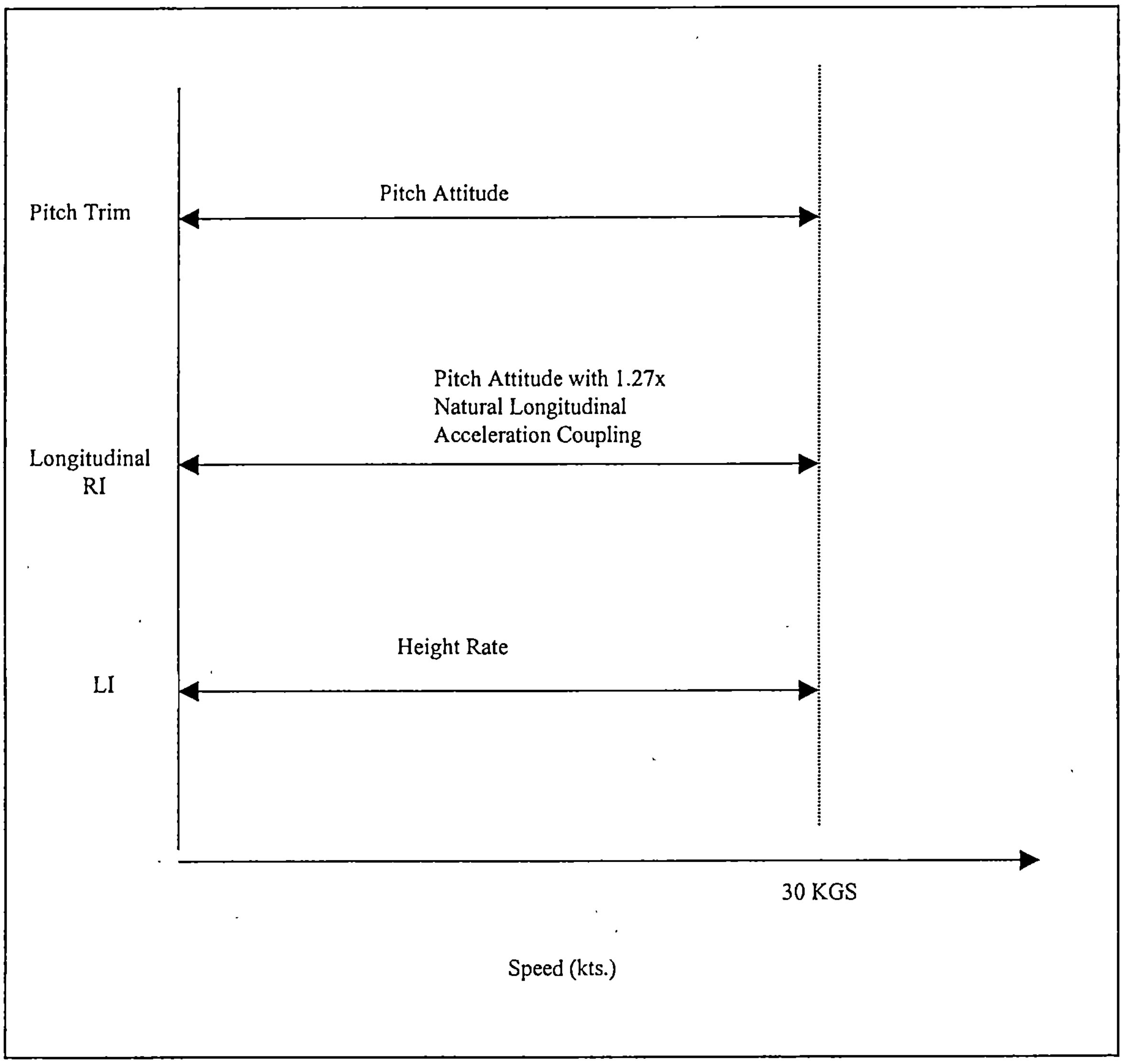


FIGURE A-22 AUGMENTED TAC PORTION OF MODE CHANGE MODE

Source: Paines, Justin, "*VAAC Pilot Briefing Notes*," Experimental Flying Squadron, DERA Boscombe Down, Amesbury, Wiltshire SP4 0JF, December 1998.

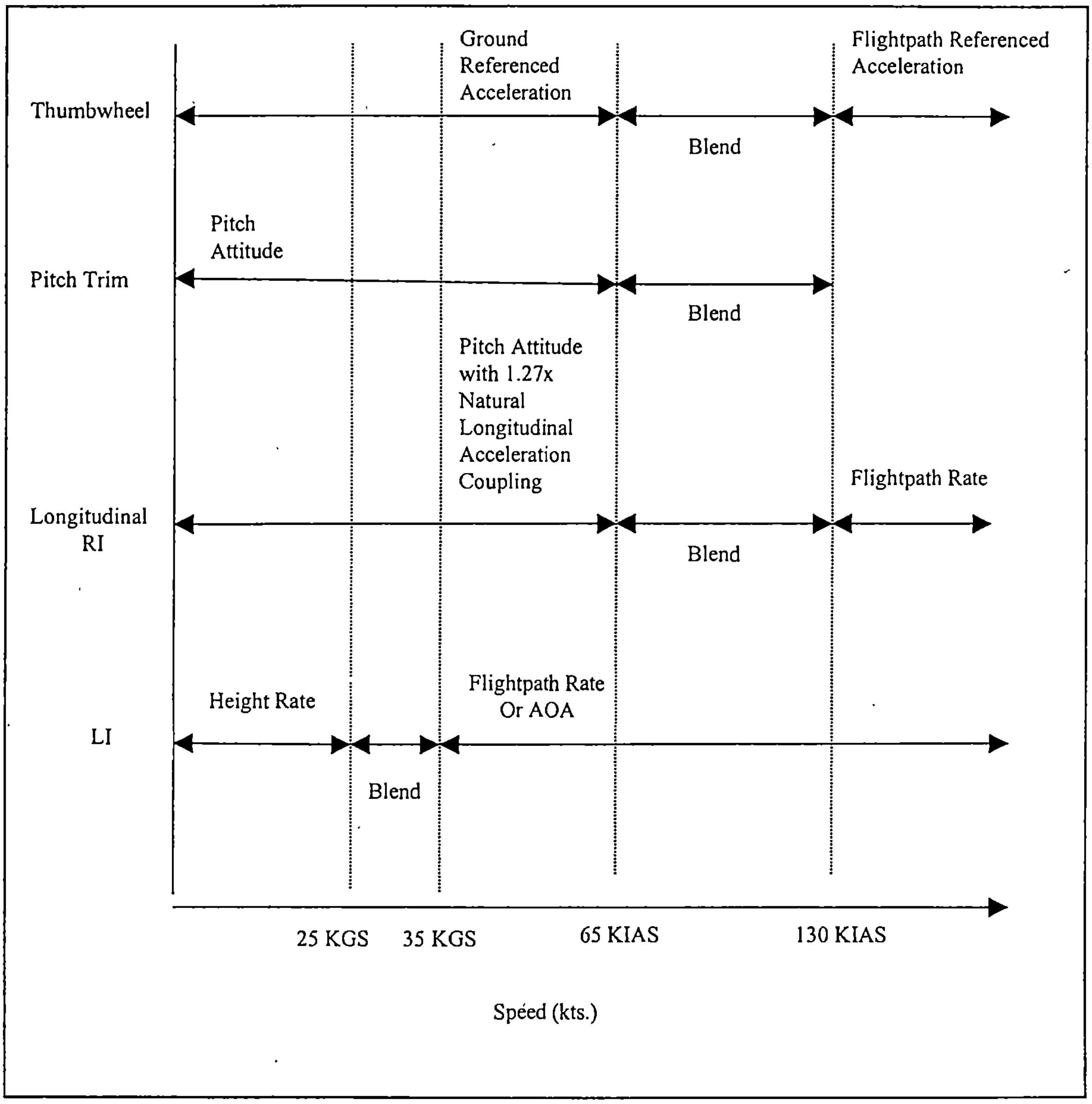


FIGURE A-23 FUSION CONTROL MODE

Source: Paines, Justin, "*VAAC Pilot Briefing Notes*," Experimental Flying Squadron, DERA Boscombe Down, Amesbury, Wiltshire SP4 0JF, December 1998.

VITA

Jeffrey A. Karnes was born in Denver, Colorado on June 14, 1964. He grew up in Colorado, Hawaii, Louisiana, and Indiana, before graduating from Mishawaka, Indiana's Penn High School in 1982. After attending Purdue University in West Lafayette, Indiana, he received his Bachelor of Science degree in Aeronautical and Astronomical Engineering. While at Purdue University, he joined the Naval Reserve Officer Training Corps as a Marine Option, and upon graduation was commissioned as a Second Lieutenant in the United States Marine Corps on August 8, 1986. After initial Marine Corps ground officer training at Quantico, Virginia, he moved to Pensacola, Florida to begin flight training as a Student Naval Aviator. Receiving his wings in August of 1989 at Beeville Naval Air Station, Texas, he was selected to be a V/STOL light attack pilot in the AV-8B Harrier community. After completing transition training at Cherry Point Marine Corps Air Station (MCAS), North Carolina, he served an operational tour at Yuma MCAS, Arizona. Here, he achieved flight designations of Division Leader, Mission Commander, Weapons Training Officer, Flight Standardization Instructor, Post Maintenance Check Pilot, AV-8B Airshow Flight Demonstration Pilot, and V/STOL Landing Site Supervisor. Further designated a Low Altitude Tactics Instructor and Air Combat Tactics Instructor, he returned to the Harrier training squadron at MCAS Cherry Point to be a Harrier instructor. After being selected to attend the U.S. Naval Test Pilot School at Patuxent River Naval Air Station, Maryland, he graduated with class 110 in

December 1997. He currently is currently serving as STOVL test pilot on the Joint Strike Fighter (JSF) Program and F-18 test pilot on various test projects. Involved with the JSF program for three years, he will be flying the Joint Strike Fighter Concept Demonstrator Aircraft sometime in the year 2000.