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Evaluation of at-sea flight testing of the MV-22 Osprey for operational employment

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To the Graduate Council:

I am submitting herewith a thesis written by Christopher C. Seymour entitled "Evaluation of at-sea flight testing of the MV-22 Osprey for operational employment." 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.

Fred Stellar, Major Professor

We have read this thesis and recommend its acceptance:

Ralph D. Kimberlin, U. Peter Solies

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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Ralph D. Kimberlin

Dr. Ralph D. Kimberlin

U Peter Solies

Dr. U. Peter Solies.

Accepted for the Council:

Interim Vice Provost and
Dean of the Graduate School

EVALUATION OF AT-SEA FLIGHT TESTING OF THE MV-22 OSPREY FOR OPERATIONAL EMPLOYMENT

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Christopher Seymour

May 2001

PREFACE

A portion of the information contained within this thesis was obtained during a Naval Air Systems Command sponsored program in conjunction with the Bell and Boeing Corporations. The research, results and discussions, and conclusions 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 States Marine Corps, the Naval Air Systems Command or that of the Bell and Boeing Corporations.

DEDICATION

This thesis is dedicated to the United States Marines lost in the pursuit of tilt rotor aviation. That their service and sacrifice to country and Corps not be forgotten…

I would also like to dedicate this work to my recently deceased father-in-law and friend, Dr. Richard E. Ryan. Whose love of learning, Naval history and people impacted the lives of so many family, friends and students.

May God Bless them all.

ACKNOWLEDGEMENTS

I would like to thank the V-22 integrated test team of many talented test pilots and engineers whose assistance and frank discussions led to the conclusions developed here. I would also like to thank Mr. Bill Geyer and the dedicated team of professionals at the Dynamic Interface office, for all of their assistance and support of this effort.

Additionally I would like to thank my parents Ed and Jackie Seymour, who taught me the precious value of work and whose love and support have been never ending. I particularly would like to thank my father who unintentionally instilled a passion for flying which has led me to this business of aviating.

Finally, I am indebted to my wonderful wife Karen and our five children Megan, Mary, Emily, Travis and Michael for their love and encouragement during this entire experience.

ABSTRACT

The MV-22 “Osprey” tiltrotor aircraft is a radically new air vehicle designed to replace aging helicopters and support the US Marine Corp’s future concept of operational maneuver from the sea. Unfortunately the aircraft has been plagued with political and programmatic delays throughout its 19-year history that prevented early and comprehensive at-sea testing. With an operational evaluation in October 1999, a shortened at-sea test period was required late in the aircraft development in January 1999. This thesis analyzes the compressed developmental test process used to prepare this novel air vehicle for sea service in a short time period.

The dynamic interface testing of Naval aircraft and ships is not new, although the advent of tiltrotors incorporating digital fly-by-wire technology has challenged traditional developmental procedures. The MV-22 required extensive test planning, flying qualities evaluations and engineering tests to define safe operational limits in the shipboard environment. An analysis of a lateral control instability problem encountered during the testing and the subsequent test process innovations for this unique aircraft substantiated the need to conduct comprehensive and extensive developmental testing.

It is the author’s opinion that at-sea testing is risky and the final exam for a Naval aircraft. The risks of a shortened test process were that deficiencies would be uncovered and that uncharted capabilities would not be exploited for operational employment. The documented successes and failures of the MV-22 at-sea test process yield lessons that should be put into practice by future amphibious Vertical Take Off and Landing (VTOL) aircraft such as the Joint Strike Fighter (JSF) and other follow-on VSTOL aircraft.

TABLE OF CONTENTS

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

LIST OF ABBREVIATIONS

AFCS	Auto Flight Control System
APC	Aircraft Pilot Coupling
ADU	Air Data Unit
ADL	Above Deck Level
AGL	Above Ground Level
APLN	Airplane
APU	Auxiliary Power Unit
ATC	Air Traffic Control
BFWS	Blade Fold Wing Stow
CCFDA	Cockpit Control Feel and Drive Actuator
CCPT	Cockpit Control Position Transducer
CCTDA	Cockpit Control Thrust Drive Actuator
CDU	Control Display Unit
CFD	Computational Fluid Dynamics
COEA	Cost and Operational Effectiveness Analysis
CSAR	Combat Search and Rescue
CTDA	Cockpit Thrust Drive Actuator
DCP	Differential Collective Pitch
DI	Dynamic Interface
DOD	Department of Defense
DT	Developmental Test
ECL	Engine Condition Lever
EMC	Electro Magnetic Compatibility
EMD	Engineering Manufacturing and Development
FADEC	Full Authority Digital Electronic Control
FCLP	Field Carrier Landing Practice
FCS	Flight Control System
FCSIR	Flight Control System Integration Rig
FLIR	Forward Looking Infared
FOV	Field Of View
FSD	Full Scale Development
Ft	Feet
FTIP	Flight Test Instrumentation Panel
GPS	Global Positioning System
GTR	Generic Tilt Rotor
HPDU	Hydraulic Power Drive Unit
HQR	Handling Qualities Ratings
HUD	Heads Up Display
HVR	Hover
IG	Inspector General
IGE	In Ground Effect
IEMC	Intersystem Electro Magnetic Compatibility
IFR	Instrument Flight Rules

IMC	Instrument Meteorological Conditions
IR	InfarRed
JSOR	Joint Services Operational Requirements
JVX	Joint Vertical Experimental
KCAS	Knots Calibrated AirSpeed
KTS	Knots
LAV	Light Amphibious Vehicle
LCAC	Landing Craft Air Cushion
LHA	Landing Helicopter Amphibious
LHD	Landing Helicopter Docking
LSE	Landing Signal Enlisted-man
LSG	Lateral Swash plate Gearing
LSO	Landing Signal Officer
LVDT	Linear Variable Differential Transducer
LWINS	Light Weight Inertial Navigation
MC	Mission Computer
MEU	Marine Expeditionary Unit
NAC	Nacelle
NASA	National Aeronautics and Space Administration
Nr	Proprotor Speed (RPM)
NVD	Night Vision Devices
NVG	Night Vision Goggles
OEI	One Engine Inoperative
OGE	Out of Ground Effect
OPEVAL	Operational Evaluation
OSD	Office of Secretary of Defense
OT	Operational Test
PDS	Power Demand System
PFCS	Primary Flight Control System
PFD	Primary Flight Display
PIO	Pilot Induced Oscillation
PRS	Pilot Rating Scale
PUWSS	Pitch Up With Side Slip
ROL	Roll On Landing
RWOD	Relative Wind Over Deck
SFD	Standby Flight Display
SIL	System Integration Lab
SLL	Structural Load Limiting
STO	Short Take Off
TACAN	Tactical Air Navigation
TCL	Thrust Control Lever
TCRS	Thrust Control Regulation System
TM	Telemetry
TRRA	Tilt Rotor Research Aircraft
UCE	Usable Cue Environment

USMC	United States Marine Corps
US	United States
USS	United States Ship
VFR	Visual Flight Rules
VSD	Vertical Situation Display
VSTOL	Vertical Short Take Off/Landing
VTO	Vertical Take Off
VTOL	Vertical Take Off or Landing
WOD	Wind Over Deck

CHAPTER I
INTRODUCTION

The environment in which military aircraft operate can be extremely unforgiving. The amphibious shipboard environment is the most dynamic and challenging of those environments in which pilots are expected to operate. The advent of tilt rotor technology promises to challenge future pilots even further in this environment. The MV-22 Osprey, now in production, is integral to the United States Marine Corps long-term plan for future amphibious operations. Due to the changing nature of military tactics, this air vehicle is being procured to perform its mission safely in adverse weather and nighttime conditions. This radically new aircraft technology will replace the Corps' aging CH-46E tandem rotor combat assault support helicopter. The Osprey is expected to significantly

MV-22 Landing At-Sea
Figure 1-1

outperform the CH-46E, which has been in service since 1964 when it was introduced during the Vietnam conflict. The Marine Corps has extended the CH-46E service life over three times the original design life and is in desperate need of a replacement to fulfill their role in the US strategic policy, Operational Maneuver From The Sea. To that end, it is incumbent upon the acquisition communities to understand the at-sea process and risk of the development of such a novel new aircraft.

The MV-22 "Osprey" tilt rotor aircraft has experienced one of the slowest developmental and acquisition schedules in the history of US air vehicle programs. This novel aircraft is however finally nearing operational deployment scheduled for 2003 in the Mediterranean Sea aboard US Navy amphibious shipping. Because of political and programmatic delays the timeline to flight test and develop the shipboard capabilities was significantly reduced. The compressed nature of this testing substantially affected the test process and the subsequent development of the shipboard capabilities. Unexpected test results in this compressed process precipitated progressive scheduling and innovative test techniques, which were used to produce timely operational envelopes until follow-on testing could be completed. This testing was not without significant, known or unknown risk both to the test aircraft and the future of the program. From Otto Lillienthal who piloted the first manned glider;

"To design an airplane is nothing, to build it is not much, to test it is everything"

Otto Lilienthal
(1848-1896)

Purpose

The purpose of this thesis is to evaluate the shipboard testing process and the relevant issues and steps required to develop a radically new air vehicle for shipboard operational capability. The following chapters will examine the history of tilt rotors, the V-22 program and shipboard testing to provide the reader with the background and insight into the complexity and risk associated with the at-sea test process. A review of pertinent literature and military standards, coupled with the author's extensive personal experience and involvement in this process as an MV-22 test pilot were used as the basis of research.

First discussed is the early development of tilt rotor technology, followed by a brief description of the efforts to keep the controversial V-22 program alive amidst funding instability and a constant threat of cancellation. The complexity of shipboard testing will be analyzed from both historical and subject matter perspectives. Finally the program's shipboard development from 1998 to present is summarized to highlight the delayed and then compressed schedule pressure applied to the testing process. The lessons learned in this arduous task are invaluable and are provided to assist others in the pursuit of future aircraft test efforts.

CHAPTER II
HISTORY AND BACKGROUND

History

Because of the limitations in helicopter speed and range, V/STOL aircraft options were naturally explored as helicopter aviation matured to its limits. The first conceptual tilt rotor design was the British Baynes Heliplane patented in 1937. Heinrich Foche then designed the FA-269 as part of the German war effort, but it too was never developed. It was not until 1945 that the development of the Transcendental Model 1-G occurred under the sponsorship of the US Army. The 1-G was the first air vehicle to explore a conversion mode of flight out to 115 mph with the rotors 70 degrees forward of horizontal. In 1958 Bell developed the XV-3, a tilt rotor that actually flew through the complete conversion from rotor born flight to an airplane mode of flight. The XV-15 eventually followed as a "proof of concept" tilt rotor technology demonstrator in 1979.

The V-22 tilt rotor aircraft and program were conceived in 1981 with the definition of the Joint Services Advanced Rotor Wing Development memo issued by the Secretary of Defense. What followed was a protracted battle against cancellations in the era of post cold war budget wars and acquisition reform. The program grew and was influenced by the mission needs of the Marine Corps, Army and Air Force. In the wake of the Army's infamous "Sgt York's" air defense gun failures and the $700.00 P-3C Orion toilet seat the V-22 program suffered and fluctuated from funding to cancellation four times.

The first contract for military tiltrotor development was let in 1983 to the Bell Boeing partnership for the Joint Vertical Experimental (JVX) program. Again in 1986 they were uncontested and won the V-22 Full Scale Development (FSD) contract award. In January 1987 following the military build up under President Reagan, the program was budgeted to receive funding for 913 V-22's for the Army, Marine Corps, Navy and Air Force. However, before it was actually funded, the Army backed out because of budget priorities for the RAH-66 Comanche and the Air Force reduced their requirement from 80 to 55 aircraft to focus funding on the F-22 Raptor. The program however, continued with revised procurement numbers until a Department of Defense (DoD) attempt to cancel the program in April 1989.

The first cancellation was provoked by an Inspector General (IG) report declaring that Tilt Rotor technology was too risky and a self imposed program office schedule one year slip. Political and legal battles raged between Congress and the DoD over funding and continuation of the program. In the meantime two aircraft crashes occurred one in June 1991 on its first flight and then again in July 1992 following a highly publicized flight from Florida. The crashes were devastating and arguably symptomatic of the erratic funding during development of this novel technology.

The fight to keep the program alive was waged primarily between the Office of the Secretary of Defense (OSD) and the Congressional branches of government. The Marine Corps and Air Force remained staunch advocates along with congressional lobbyists throughout the program. In 1989 OSD was prompted to cancel the program again by a requirement to reduce defense spending by 10 Billion dollars by 1992 to comply with the Gramm Rudman deficit spending limits. Because of a slipping schedule and a negative report released by the DoD, the V-22 program was an easy target for cancellation. The DoD report written by Dr Chu, an outspoken opponent and advisor to then Secretary of Defense Dick Cheney, concluded that a different mix of helicopters would be less expensive and still fulfill the mission requirements. Furthermore the report determined that an alternative helicopter mix, other than the proposed V-22 plan, would be nine billion dollars cheaper making the ten billion dollar V-22 program an easy target to cancel. Congress and contractor advocates however called for and commissioned three independent Cost and Operational Effectiveness Analysis (COEA). The Institute for Defense Analysis (IDA), NASA and Lawrence Livermore Labs COEAs all produced results in favor of the V-22 plan and in direct conflict with Dr. Chu's report.

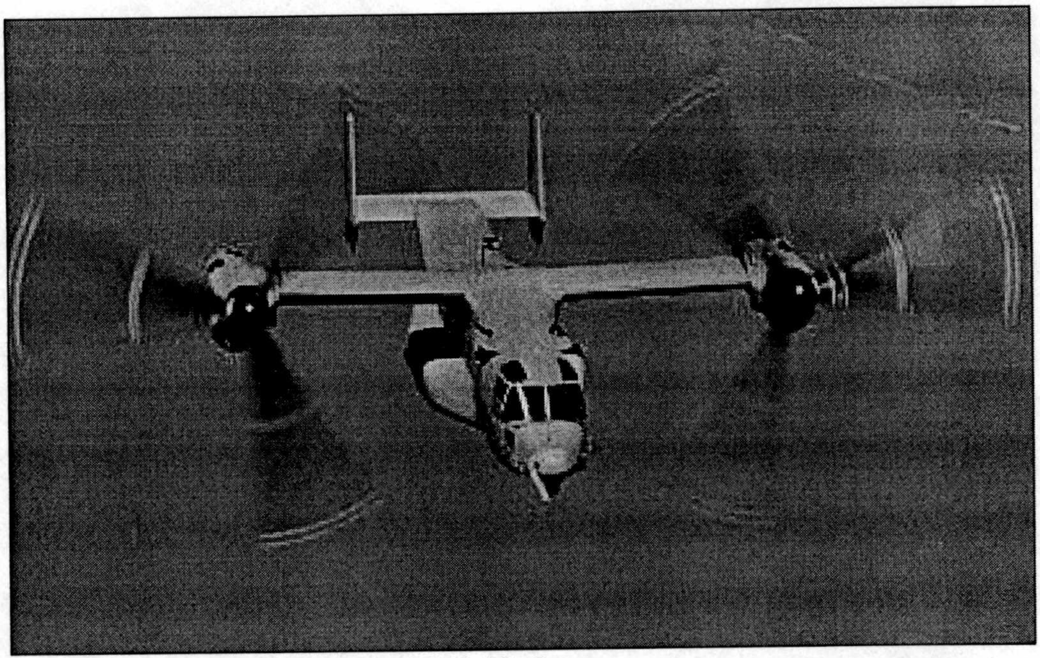
The political conflict continued when the OSD impounded V-22 funding effectively "terminating for convenience" any further long lead production funding. By that point, the results of the COEAs were published and Congress directed that OSD release the funding. Congressman Dellums (CA) stated "In effect OSD is exercising a line item veto of Congress's intent, and that, as we all know, is against the law". The OSD responded by contesting the results of the COEAs and the program was forced to continue under restrictive FSD funding through 1990. In the mean time long lead production money ($200 million) had been dispersed to other DoD programs. A tilt rotor coalition was organized to fight OSD efforts to kill the program. Congressional proponents responded in 1991 with a Desert Storm "Dire Emergency" bill passed to plus up the funding by 790 million dollars and release the DoD withheld long lead production money.

One day after the release of funding FSD aircraft number five crashed on its first flight at the Boeing test facility. The program recovered from the mishap only to face the scrutiny of their strongest proponents (Congress) who wanted to see results. The program was at the end of its six year FSD contract. The problem was that the program was not mature enough to demonstrate satisfactory joint services operational requirements (JSOR). This was primarily because of the funding stalls. The OSD again reattacked and attempted to withhold funding because the failed JSOR thresholds mostly caused by their delays in funding. Again disaster struck on 20 July 1992 when FSD aircraft number four crashed in front of an awaiting crowd of DoD and Bell Boeing officials at Marine Corps Air Station Quantico VA. Because of the programmatic set backs it became apparent that the time and cost goals of producing three operationally representative aircraft were not achievable under the FSD contract.

Two weeks after the Quantico mishap another political attempt to finally end the program was attempted by then Secretary of the Navy Sean O'Keefe. He proposed an alternative FSD II. This was a radically new approach in acquisition. This alternative approach requested of the contractor a proposal, of how many prototypes were necessary and at what cost, knowing that the program only had 790 million dollars. What may have been meant to terminate the program eventually benefited it. Two weeks later the Navy terminated for the convenience of the Government the FSD contract and awarded the 550 million dollar Engineering Manufacturing Development (EMD) contract to Bell Boeing. The EMD contract called for four new V-22 aircraft to meet the medium lift operational requirements.

General Aircraft Description

The MV-22 Figure 2-1 is a Vertical/Short Take-Off and Landing (V/STOL) aircraft powered by two turboshaft engines (6150 SHP) located in wingtip nacelles. The nacelles rotate through 95 degree arcs to power both rotor born and wing born thrust

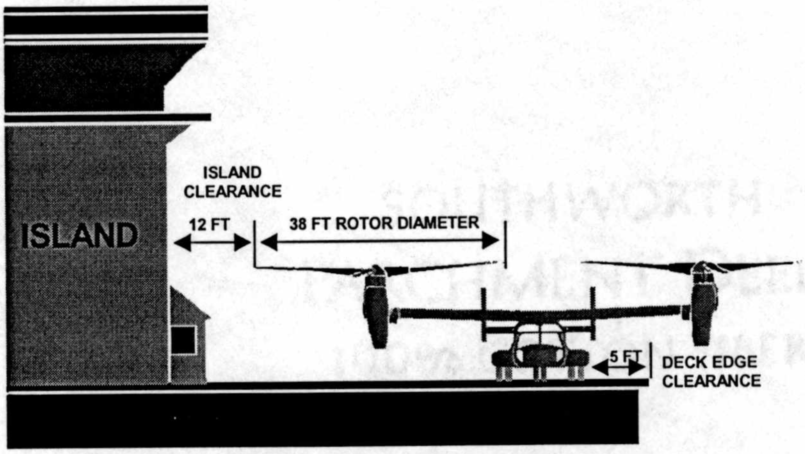


MV-22 Osprey
Figure 2-1

requirements. This aircraft incorporates tilt rotor technology originally developed by the Tilt Rotor Research Aircraft (TRRA) office at NASA Ames that began in 1972. The TRRA office managed a contract to Bell helicopter who built two test aircraft designated the XV-15 that weighed approximately 13,500 lbs. The MV-22 has since capitalized on the TRRA efforts and produced a larger, militarized tilt rotor weighing approximately 52,600 lbs. The MV-22 however, has incorporated progressive composite, metallurgical and digital technologies to achieve its current capability of 52,600 lb Vertical Take Off (VTO) and 60,500 lb maximum self-deployment gross weight performance.

The MV-22 aircraft can rapidly convert from a high disc loaded helicopter configuration to an airplane mode of flight in 12 seconds and cruise at altitudes up to 25,000 ft and 275 Kts. See Appendix A [refs 1, 18] for a more detailed description of the test aircraft. For weight savings, the airframe is over 90% graphite composite material and the flight control system is hydraulically powered at 5000 PSI in titanium tubing. The flight control system incorporates triple redundant, digital fly-by-wire flight control computers that command hydraulically boosted actuators on all control surfaces. The Flight Control System (FCS) consists of both a primary and automatic control capability. See Appendix A for a more detailed description of the flight control system.

Combat safety, durability and survivability were designed into critical aircraft systems with redundancy, dispersion and ballistic tolerances. In the event of a single engine failure the proprotors are interconnected via a tilt axis gearbox and a synchronization shaft located within the wing for transfer of power from the operating engine to the opposite rotor. The MV-22 was point designed to fit and operate on the US Navy LHA class amphibious ship Figure 2-2. Because of this requirement a complex blade fold wing stow (BFWS) design was incorporated allowing it to transform from a compact storage configuration into a helicopter configuration in under two minutes,



Flight Deck Clearance
Figure 2-2

Figure A-3. Additionally the prop rotor design was sized by the clearance to the superstructure of the LHA and the design requirements of the BFWS system.

Amphibious Flight Operations

Amphibious helicopter shipboard operations have been conducted since 1943, when the US Navy landed the XR-4 aboard the Bunker Hill. Since that time thousands of helicopters have operated on US Naval shipping in various capacities. The US Navy utilizes various types of helicopters for missions such as Combat Search And Rescue (CSAR), antisubmarine warfare, minesweeping, vertical onboard delivery general utility and logistics. The USMC has matured the largest fleet of amphibious aircraft for combat assault support. These aircraft work in direct support of theater commanders to assist in the accomplishment of amphibious landings, over the horizon assaults and expeditionary force movements. The aircraft are varied and diverse and must work together within the confines of an amphibious assault support ship.

The US Navy operates a large fleet of L-Class ships for the purpose of supporting the Marine Corps amphibious assault mission. These ships are designated "L" for landing and are followed by an H for helicopter and A for amphibious. The fleet is currently composed of LHA's and LHD's, for Landing Helicopter Docking. Both the LHA and LHD have a floodable well deck beneath the flat landing deck. This well deck is utilized for launch and recovery of other amphibious landing craft such as the Light Amphibious Vehicle (LAV) a convertible boat troop transport and the LCAC hover craft. These ships are up to 1000 feet long and displace over 39,000 tons of water. In addition to the flight deck and well deck they also have large hangar facilities, for maintaining the aircraft and berthing spaces for approximately 1200 infantry troops. These ships also provide facilities and spaces for over 1000 naval personnel who sustain and staff all defensive and support positions for the operation of such a large vessel. See Appendix B [ref 21] for a more detailed description of the LHA-2 (Saipan), the ship used for sea trials of MV-22.

The basic Aviation Combat Element (ACE), of a Marine Expeditionary Unit (MEU), which operates on L-Class ships, consists of approximately 30 aircraft. These aircraft have traditionally consisted of 12 CH-46E Sea Knight and four CH-53E Super Stallion helicopters for Assault Troop support, four AH-1W Cobra, two UH-1N Iroquois helicopters and six AV-8B Harrier Jump-Jets for escort and close air support of the transports. Additionally two CH-46D Navy helicopters are provided for SAR and logistics. When all of these aircraft operate within the confines of a 1000 ft flight deck in conjunction with well deck operations, the environment becomes extremely complex and dangerous. Up to 70% of this small air force operates daily in training and maneuvers and the entire force operates 24 hours a day during sustained combat operations. Each type of aircraft has unique requirements for storage, taxi, launch and recovery limits, as well as fueling, maintenance and armaments.

To safely operate all of the aircraft simultaneously in the shipboard environment a closely coordinated plan, with sound and flexible operating limits is required. The ship must be maneuvered within the appropriate range of the landing area for each vehicle and to within the appropriate Wind Over Deck (WOD) and sea state conditions. Although all aircraft can operate simultaneously, timing is critical for loading, moving and launching all aircraft to successfully accomplish the mission. To further add to the complexity of this environment, operations must continue in darkness and adverse weather so as not to compromise the safety or defense of the ship. Therefore, Instrument Meteorological Conditions (IMC) and Night Vision Goggle (NVG) capabilities must be exercised routinely. These ships operate sophisticated air radars for precision approaches, TACAN stations for non-precision approaches and an entire Air Traffic Control (ATC) facility for coordination and control of the airspace around the busy ships. Finally, NVG compatible flight deck lighting systems and trained ground crews are provided for nighttime operations.

Tilt Rotors on Ships

The first tilt rotor to land on a Navy amphibious ship was the XV-15, when it landed on the USS Tripoli in August of 1982. This was an LPH, an older and smaller L-Class ship operating off of the California coast. Under the TRRA contract the XV-15 was taken to the ship to demonstrate the military application of tilt rotors for the Navy replenishment and Marine shipboard vertical assault missions. Although the XV-15 was a reversible controlled (Mechanical Flight Control System) air vehicle, questions had arisen concerning a deck edge effect. This was specifically concerned with what would the effect of having one rotor in ground effect and one out of ground effect when the aircraft was landing and transitioning over the edge of the flight deck. In addition, prop rotor noise and downwash effects on flight deck personnel during launch and recovery were to be assessed. Although extremely limited in scope, in 54 successful operations the XV-15 performed well in both short and vertical launch and recovery maneuvers. There were no adverse effects from the deck edge effect, or on flight deck personnel.

Again under the JVX program the Full Scale Development aircraft, V-22 numbers 2 and 3 landed aboard the USS Wasp in December 1990. This also was an extremely limited test. Because of immature fly-by-wire technology, and structural evaluations, the ship was positioned in a sterile environment. The ship was essentially not under way, nor generating or radiating any significant electromagnetic energy. This environment was essentially dedicated solely to the V-22, with calm winds, clear weather and no shipboard emitters operating. The test lasted approximately one week and was a demonstration of the V-22's shipboard compatibility. This was an early look at general suitability and potential. The aircraft only completed 14 vertical take offs and landings and 3 planned wave-offs. Additional major milestones were completed such as a successful demonstration of the complex BFWS system and movement of the stowed aircraft configuration below to the hangar deck.

Shipboard Testing

Due to this complex at-sea environment, the Navy took the lead in the development of helicopter shipboard tests through an organization at the Naval Air Test Center Patuxent River identified as Dynamic Interface (DI) established in 1958. Since that time the DI team has conducted over 190 at-sea flight test programs. DI test programs are usually conducted for US Navy, Marine Corps, and Coast guard programs, although some recent tests have been conducted for foreign Naval services and private contractor organizations. DI helicopter testing and analytic efforts are conducted in order to develop, evaluate and optimize all aspects of shipboard rotorcraft operability. These test programs are conducted primarily to quantify operational capabilities under various shipboard flight conditions. These programs also evaluate the adequacy and safety of shipboard aviation facilities and procedures.

The primary task in traditional shipboard DI test operations is the development of launch and recovery wind over deck limits. Several characteristics of the shipboard environment combine to pose additional challenges which are not typically encountered during land based helicopter operations. Fundamentally a vertical take-off is the same as a shipboard launch and a vertical landing is the same as a shipboard recovery. Many factors however, influence a pilot's ability to conduct safe at-sea operations. The size shape and location of the landing area, along with its proximity to shipboard structures and other aircraft, combined with unpredictable ship motion and turbulent air wakes all increase the difficulty of successful shipboard operations. Other aircraft on deck, ambient lighting, degraded aircraft flight control systems and poor aircraft handling qualities further increase the complexity of shipboard helicopter operations. DI testing attempts to systematically measure how each of these factors influence the conduct of operations at sea. The results of these tests define these complex relationships, with the results presented in a format that the fleet user can utilize in an operational environment.

To further improve safety, the DI team also attempts to conduct pretest flight simulation and analysis. The team utilizes the simulator facilities of the perspective aircraft as well as other analytic methods to develop, evaluate and optimize all aspects of shipboard compatibility. This effort normally includes procedural evaluations and definition of both normal and emergency maneuvers. All test pilots that participate in DI programs are usually highly experienced in both the prospective air vehicle and shipboard operations. Their operational experience in the execution of amphibious shipboard operations is invaluable to the test effort. This experience also minimizes unnecessary training and procedural evaluations that are undefined in novel new aircraft, so that the test period can be dedicated to envelope expansion. The simulation efforts also normally include aircraft flying qualities, performance, ship air wake, ship motion, deck handling, obstruction clearance, lighting and markings.

Simulations

Tilt rotor simulation history dates back to the XV-15 and what became known as the Generic Tilt Rotor (GTR) mathematical model. Bell Helicopter's P.B. Harendra, and M.J. Joglekar originally created the GTR in December 1973. This math model has become the basis for all tilt rotor simulations and extensively used throughout the MV-22 developmental period. The original intent of this model was to use it as an evaluation tool for a particular aircraft control system design; as a device for the development of improved generic tilt rotor control laws and to evaluate crew station configurations. Although the original GTR has been extensively developed and modified, it is still used in current production MV-22 and CV-22 training simulators. Since GTR's original conception applications for flight control law software manipulation in the V-22 fly-by-wire system have also been developed to evaluate and modify the complex digital codes. A simulation laboratory has been constructed to also evaluate fly-by-wire control laws and their effect on actual V-22 hardware and electronic interfaces.

Summary

In this chapter the author has provided some essential background information on the aircraft and the environment in which it was tested as well as an historical perspective of the controversial procurement process. Because of the novel new technology and the unpopularized shipboard environment in which the aircraft is designed to operate, this information is essential to the focus of this thesis. All information contained in this chapter and expanded in the appendices will provide the reader with the background and insight into the complexity and risk in the at-sea test process. Next, chapter III explains the preparation and execution of the at-sea test process of the MV-22. The compressed schedule of events will be explained first, to segue the complexity of the procedures development, training and planning required. Finally the execution of the test will be presented as a benchmark for chapter IV where the unexpected problems occurred.

CHAPTER III
PREPARATION AND EXECUTION

General

To complete the EMD phase of the MV-22 program, at-sea testing of the aircraft on board an LHA class ship was required prior to Operational Evaluation (OPEVAL). The preparation for this test and the definition of operational limits was rapidly executed while managing various complex issues. This process was rushed because of several programmatic delays early in the EMD schedule. Table 3-1 is a chronology of events, which outline the compressed process. The original test plan written in 1996 was a contractual requirement with minimal definition in the scope of tests and produced before the aircraft had started any significant flight test in EMD. Once time was dedicated to the task of preparing for flight, several variables affected the planning and execution, such as aircraft availability, simulation, configuration and pilot experience. These issues are explained further in the following paragraphs, to highlight the complexity and difficulty in preparing for and executing such a test program.

Chronology of Shipboard Testing
Table 3-1

Event	Date
Test plan 955 Signed	13 February 1996
Test plan 955 Rev A Signed	18 November 1998
Pre-sail conference with USS SAIPAN	14 December 1998
Sea Trials I testing aboard USS SAIPAN	15 January–8 February 1999
Test Request 37 signed	12 March 1999
Test Request 39 signed	20 April 1999
Test plan 955 Rev B Signed	5 August 1999
Pre-sail conference with USS SAIPAN	29 July 1999
Sea Trials II testing aboard USS SAIPAN	16-27 August 1999
Operational Evaluation	1 October 99 – March 2000

Preparation

In preparation for the at-sea test, the individual tasks and build–up had to be defined. The tasks were initially extracted from previous DI test programs and included early XV-15 and FSD tests mentioned in the historical perspective of Chapter 2. As these baseline tasks were analyzed many additional tasks were added to satisfy the unique requirements of a tilt rotor. Table 3-2 is a baseline of the essential tilt rotor unique tasks needed to meet the testing requirements.

Normal operational procedures were developed in the simulator. Because the V-22 was not yet operational, integration into the operational shipboard environment was a significant unknown. Simple traffic pattern altitudes and airspeeds were still to be evaluated. These were important because the V-22's performance characteristics were dissimilar to the other shipboard aircraft. Altitudes and airspeeds had to be unobtrusive

Tilt Rotor Unique Shipboard Tests
Table 3-2

Task	Description
Launch and Recovery	Wind over deck and sea state limit definition
Short Take Off	Rolling take-off on bow of ship
Self Taxi	Maneuver on flight deck under aircraft power
Exhaust Gas	Measure effects of exhaust on fuel stations and life boats located abeam landing area
Downwash	Measure effect on deck crew and other aircraft
Deck Handling	Maneuverability with tow vehicle, elevator and hanger operations.
External Loads	Lift of netted loads, and light vehicles
Night Vision Goggles	Repeat Launch and recovery, and STO using NVG
BFWS	Evaluate reliability and suitability on flight, hanger deck, and elevator in all positions (Helo, Maint, and Stowed)
Pilot Training	FCLP
OEI	One Engine Inoperative (OEI) landing

to other aircraft so that simultaneous operations could be conducted. The speeds and altitudes were also critical for emergency procedures in the event of engine failures and system degradations. The final approach profile and departure technique were closely evaluated for the same reasons. An engine failure on departure was found to be catastrophic in the simulator because of the power requirements for out of ground effect performance. The Short Take Off (STO) procedure and self-taxi capability were also maneuvers that were evaluated. Up to this point the only aircraft to taxi aboard amphibious ships was the AV-8 Harrier, which was not a helicopter. Self-taxi of a V-22 tilt rotor aboard a moving ship deck among operating V-22's and other helicopters is dangerous, requiring closely coordinated procedures between pilots and ground crew. See Appendix C for descriptions of the tested maneuvers.

Because of delays, most of the procedural development, training and practice were performed in the simulator. Additionally because of the unknown accuracy in the simulator fidelity, procedures and techniques were verified and evaluated in the aircraft. These tasks required close management with maintenance, prerequisite testing and pilot training.

A normal currency and proficiency requirement for all Navy and Marine pilots is to complete a minimum number of Field Carrier Landing Practices (FCLP) within two weeks of operating on a Naval ship. This simple requirement is levied on both fixed wing and rotary wing pilots, because of the demanding nature and complex procedural proficiency required to safely land aboard a ship under way. To fulfill this requirement a detailed flight deck profile was painted on a runway, see Figure B-2, at the test center with accurately scaled deck markings for landing areas and obstacles. This deck was used accordingly for flight evaluations and training where simulated approaches and departures were made in both VTOL and STO configurations. The other use for this flight deck profile was verification of ground handling procedures for deck crews to experience down wash, taxi, towing and storage techniques.

Because none of the test pilots or operational evaluation crews had ever flown a tilt rotor aboard a ship, that invaluable pilot experience in the DI effort was missing and training was a critical requirement. The four Developmental Test (DT) pilots had never flown the V-22 aboard the ship so they were required to complete initial qualifications. There were also six Operational Test (OT) evaluation pilots that needed initial ship qualifications and training in the V-22 before their OPEVAL period eight months later. A significant issue of concern was in determining at what point in envelope expansion was the aircraft ready to complete the OT pilot training. This was a concern that became significant to the OPEVAL phase of the program also.

After the baseline tasks to operate on the ship were defined, a long list of prerequisite engineering and classic flight tests from other EMD test plans were to be completed. These tests, as the shipboard tasks, were initially described by referring to vintage aircraft plans and reports. Table 3-3 lists the tests, which were unique to shipboard tilt rotor tasks and essential to complete before attempting any at-sea operations.

Although largely dependent on the successful completion of prerequisite testing, some of the tasks were also dependent on aircraft configuration. For example, before simple launch and recovery testing could be accomplished, structural landings up to eight feet per second were required. When this test was finally completed a modification to landing gear doors was required to withstand the high sink rate landings aboard ship. Because of the delay in this testing, the aircraft was taken to sea with the landing gear doors removed. This configuration change questioned the validity of some test results. Additional configuration concerns included the Flight Control System (FCS) software and the relocation of the flight test instrumentation panel. This panel was a flight test requirement throughout EMD; however, for shipboard operations it seriously blocked the primary egress route for the cockpit crew and had to be moved to the cabin area, which required an airframe modification.

Tilt Rotor Unique Shipboard Tests
Table 3-3

TEST	NACELLE ANGLE (Deg)	CONDITION	COMMENTS
Intersystem Electromagnetic Compatibility (IEMC)	60 & 90	As Required	APU BFWS Vulnerability
BFWS	N/A	Parked	Reliability, Suitability in Stowed, Helo, and Maintenance positions
Critical Azimuth	90	30 ft AGL	Evaluate Pitch Up with Sideslip, Vibrations, Handling Qualities
Hover Ladder	90	IGE up to OGE	Hover Power Verification, and baseline.
Engine Exhaust Deflectors	90	Ambient	Collect Data using: IR Thermal Imaging Level Fuselage Deflectors On/Off
Structural Landings	90	As Required	8 FPS Max.
Slope Landing	As Required	9 Deg Roll, Pitch	Evaluate Brakes, HQ's, and Nacelle Clearances
External Loads	60 Min	150 KCAS Max	Netted Load, HMMV Single Point, Dual Point
Avionics System Checkout	As Required	As Required	Qualitative Evaluation during FCLP'S: FLIR, NVG, HUD, TACAN
Short Take Off	60 & 75	Up to 52000 Lb	Verify Procedures, Min Deck Length, Min Nose Gear Lift Off, OEI Ground Roll

Another prerequisite test which was contentious, was Electromagnetic Compatibility (EMC). The compatibility of the fly-by-wire Osprey in the shipboard environment was critical because of the large amounts of radiant energy in that environment. The effects of radar, high frequency radio and power generation signals on the Osprey's digital flight control systems, displays and mission computers were unknown. This testing required hours of shore based aircraft run time under simulated shipboard emitters. Again, because of the flight test delays, build-up and training requirements, completion of this testing became impossible within the compressed schedule. A complex compromise was necessary to take the aircraft to the ship, which limited some shipboard emitter frequencies and some aircraft configurations. For example the Osprey was not cleared to fly in airplane mode within one mile of the ship because no EMC testing was done in that configuration.

Finally taking the aircraft to sea aboard a US warship was not a small task. Requests and scheduling of this type of national asset required very high-level approval. When the USS Saipan (LHA-2) was finally scheduled, it was just returning from a six-month deployment to the Mediterranean. Needless to say the Captain and sailors were not overly enthusiastic about returning to sea so soon to support one temperamental test aircraft. A crew of over 1000 men and women operated the ship for the test team of approximately 150 people including civilian contractors and military personnel. The integrated team of civilians and Marines included both engineering and technical professionals as well as skilled mechanics and technicians. One of the contractor maintenance crews were also members of a powerful labor union and demanded special treatment. In the close living quarters of a Navy ship, satisfying this diverse team was difficult.

Compressed Time period

As previously stated the programmatic purpose of this test was to develop operational limitations of a production representative aircraft for the fleet users to successfully employ during the coming OPEVAL phase of the program. These same limits would also be used for subsequent deployments scheduled for January 2003. This final developmental at-sea test effort was scheduled for approximately three weeks from 15 January to 8 February 1999, with the OPEVAL to begin 1 October 1999 only eight months after testing. The scheduled start date of OPEVAL was programmed as the final evaluation of the production representative aircraft prior to full-scale production and initial operational capability. The primary focus of the at-sea tests was to create effective launch and recovery envelopes, including STOs, in the limited amount of allotted time. This was later discovered to be short sighted and resulted in significant limitations to the aircraft's full potential.

Execution

The planned priority for the at-sea testing was to develop launch and recovery envelopes for the L-class ship landing spots. There were ten potential spots on the test ship, however only six were identified as priorities, spots 2,3,4,7,8,9. Figure B-2. Table 3-4 shows the priorities of the tests required, some of which could be accomplished concurrent with the launch and recovery testing. The process of developing these envelopes utilized classic flight test methodologies. This was in a deliberate build-up fashion, from the most benign condition to expectedly hazardous conditions. Since the launch and recoveries were the priority and the majority of the work to be accomplished in the V-22 at-sea test program, a detailed description of the maneuvers is defined. All other maneuvers tested on the ship are provided in Appendix C, [refs 29-32].

The operational procedures determined in the build up and training preparations, closely mirrored those of the CH-46E. See Figure B-4 for a graphic depiction of the flight pattern around the ship. The take-off is a multiple maneuver event including; a vertical lift-off, a 10 ft stable hover, followed by a lateral slide out over the deck edge and a simultaneous transition to forward flight. The departure then continues with a shallow climbing acceleration to 300 ft and 80 KCAS in the upwind and then a standard rate turn to a downwind leg. When the aircraft reaches a position abeam the assigned landing spot, a normal turn to final and a shallow descending decelerating approach is established. This final descending approach is on a 45 degree bearing relative to the ships course. As the aircraft approaches the deck edge, a turn to align with the ships

Test Priorities
Table 3-4

Test/Task	Priority
Deck Landing Qualification	1
Launch and Recovery envelope expansion	1
STO	2
Self Taxi	2
Exhaust Gas	Concurrent
Downwash	Concurrent
Deck Handling	2
External Loads	3
Night Vision Goggles	2
BFWS	2
Pilot Training	3

course is made as a 10-15 ft hover is established. The hover is followed by a vertical landing into three 2 square foot boxes painted on the flight deck, see Figure B-3. This later became the most difficult task to complete, particularly under Night Vision Devices (NVD) and high wind and sea state conditions.

The flight test methods for this type of maneuver are complex, requiring both quantitative and qualitative evaluations. All aspects of the launch and recovery task must be evaluated. The DI group has refined this method over years of testing to include the Pilot Rating Scale (PRS) shown in Table 3-5 below. This scale simply allows the pilot to qualitatively summarize the entire task as specified by the individual ratings. The quantitative part of the evaluation is accomplished by measuring average and maximum power requirements throughout the task, as well as simultaneous measurement of ship state information. A test rig is placed on the ship to measure relative wind speed and pitch and roll data, which can be GPS time synchronized to the aircraft state information.

Pilot Rating Scale
Table 3-5

PRS No.	Pilot Effort Adjective	Remarks
1	Slight	No problems; minimal pilot effort required.
2	Moderate	Consistently safe launch/recovery operations under these conditions are possible. These points define the fleet limits recommended by NAVAIR 4.11.3.2.
3	Maximum	Landings and takeoffs successfully conducted through maximum effort of experienced test pilots under controlled test conditions. These evolutions could not be consistently repeated by fleet pilots under operational conditions. Loss of aircraft or ship system is likely to raise pilot effort beyond capabilities of average fleet pilot.
4	Unsatisfactory	Pilot effort and/or controllability reach critical levels, and repeated safe landings and takeoffs by experienced test pilots are not possible, even under controlled test conditions.

Aircraft state information is post processed from onboard digital monitoring of 1553 data bus traffic. Additionally video cameras are placed throughout the ship and aircraft for real time recording of each event. The testing began as FSD and XV-15 tested, in calm wind and sea state conditions. As confidence in crew and aircraft performance were established the conditions were changed to expand the operating envelope. The shipboard environment affords some control over relative Wind Over Deck (WOD) conditions. A simple geometric calculation of ambient winds, ship speed and course are used to adjust the WOD, magnitude and azimuth. The build-up plan specified an increase in magnitude and azimuth in small increments of 10 knots and 10 degrees relative. See Appendix C and Figure C-2 for more details on the build up plan. This method was used for all handling qualities testing including STO self taxi and external loads. Generally as the speed and relative wind on the ship increased the pitch and roll conditions increased as well.

The STO and self-taxi tests, which were tilt rotor unique, were conducted in the same traditional manner. STO's were unknown, but because of the enhancing performance characteristics of the V-22, were relatively easy to execute and evaluate. Self-taxi however was challenging because of the complex flight control system and its effect on turn radius and nose wheel steering. Close coordination and slow deliberate speeds were utilized particularly in high sea state conditions. Detailed descriptions of V-22 specific test procedures are provided in Appendix C.

Summary

When the testing finally began, the scope of the tests had grown out of proportion, and it became obvious that it was going to be nearly impossible to complete all the planned events in the allotted time. The variables involved in the day-to-day management of tasks were incalculable and affected the teams' daily productivity. Factors such as weather conditions were a significant consideration in WOD envelope development. Initially calm winds were necessary to start the build-up and training, then as time went on higher magnitude winds were necessary to expand the WOD envelope. The maintenance status of the aircraft was also a factor in the day's events. If the V-22 was not flight worthy because of one inoperable part not located on the ship the entire test force was at a standstill until it was delivered. Test equipment for the downwash and exhaust gas measurements were also a factor; the testing was dependent on their up status. Given the expansive scope of tests to be accomplished, planning and managing day-to-day events were very cumbersome.

CHAPTER IV
PROBLEMS IDENTIFIED

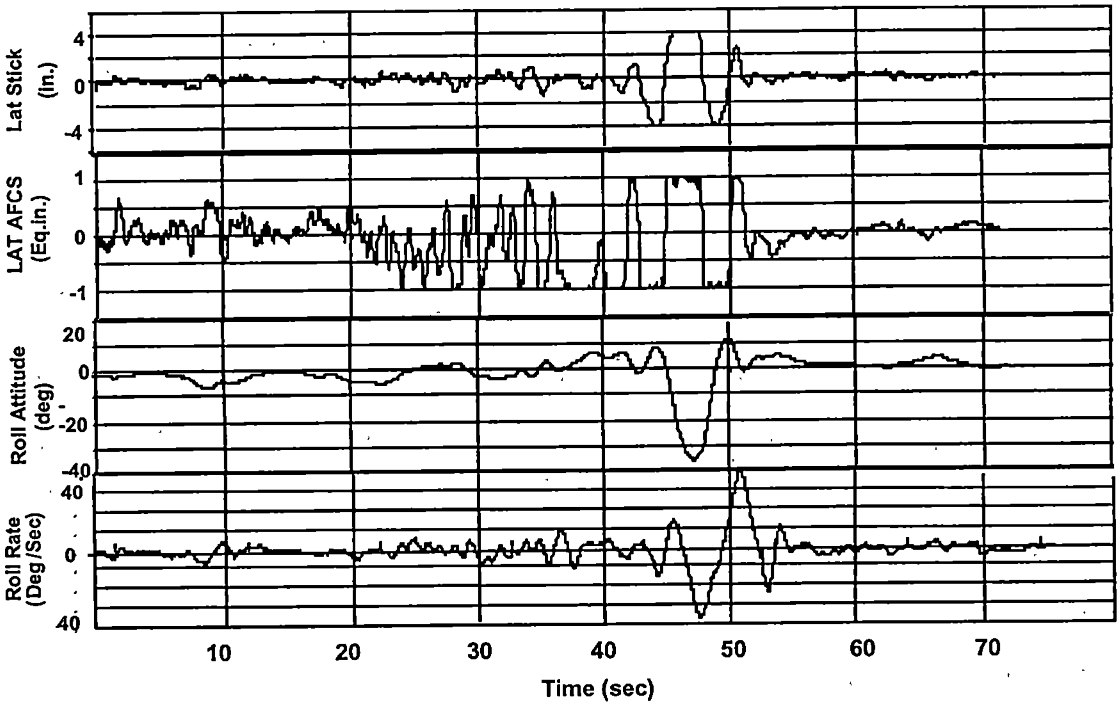
General

During the first at-sea test period, several problems were identified. Some of these problems were deficiencies with the aircraft handling qualities and others with the interface of the shipboard environment. Most were not significant enough to warrant major concern, however one near catastrophic problem in particular, prompted cessation of shipboard testing at a critical time in the program schedule. This handling qualities deficiency was unexpected and potentially devastating to the aircraft, crew and the future of the program.

Lateral Instability

After 20 successful test flights completing 56 flight hours and 233 takeoffs and landings, the V-22 experienced an instability in the roll axis, which was nearly catastrophic. An aircraft-to-pilot coupling occurred in the lateral control axis, which resulted in a 37 degree roll attitude, at approximately 9 feet Above Deck Level (ADL). Figure 4-1 below is a time history of the pilot inputs in the lateral axis, with reference to roll attitude, roll rate and augmentation inputs (AFCS). The event occurred on spot 7 (Figure B-2) during a normal landing by the pilot in the left seat, well within previously tested WOD conditions. This landing attempt was part of the daily build-up and proficiency flying before starting envelope expansion. The WOD was 10 degrees to port (left crosswind relative azimuth) at 22 kts, well within normal operational limits. This was not at the edge of the flight envelope, but a typical environment every shipboard aircraft operates in routinely. Testing was promptly terminated until a detailed analysis could be made of the occurrence. The aircraft was carefully inspected for mechanical failures or malfunctions and none were found. Then it was flown off of the ship, from its pier-side location, back to the test center for further analysis.

The analysis of the event was intense and every effort was made to identify the source of the problem. The lateral flight data indicated that the AFCS system was saturated, indicating that its full authority was in demand and insufficient to satisfy the flight conditions. See Figure 4-1 from 36-52 seconds. This indicated that a powerful unknown aerodynamic influence was affecting the aircraft. The resultant effect could not be adequately controlled through the combination of pilot controls, FCS and rotor system. Because fly-by-wire aircraft are by design non-linear systems, the exact cause was not immediately obvious. Other time history data from similar landing conditions were then



Time History of Lateral Instability
Figure 4-1

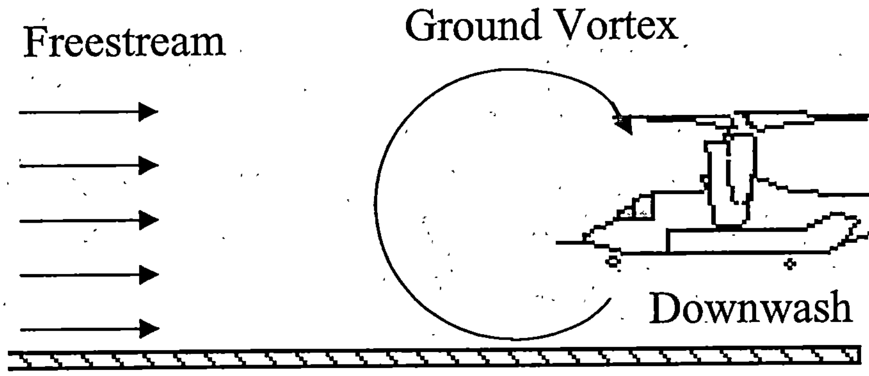
analyzed and indicated very similar conditions on previous landing attempts particularly on the same spot.

Landings on spot 7 had been identified as high workload during the course of the testing by all the pilots who had flown to that spot. Between the four separate developmental pilots who were evaluating the recoveries and landings, PRS values varied for each pilot, but trended in the same direction on that spot. Telemetry flight data, that was routine in most shore based testing, was not utilized at-sea because of EMC considerations discovered early in the planning. Lack of telemetry did not allow for real time monitoring (TM) of the flight control system and aircraft state data such as AFCS commands and pilot control positions. The rapid daily at-sea testing also did not allow adequate time to review flight data after the testing was complete. Generally the AFCS saturation was a parameter closely watched during flying qualities tests because of its transparency to the pilots. A flying qualities engineer well versed in the FCS would have quickly identified the AFCS saturation trend.

Because four separate test pilots were evaluating the launch and recovery tests, there were distinct paradigms in their evaluations, which were clearly indicative of their flying backgrounds. The four evaluation pilots came from three different operational flying backgrounds, including the CH-46E, CH-53E and the AV-8B. Each with their own experiences outside of tilt rotor flying that affected their techniques. Generally the CH-46 pilots flew shallow fast approaches, the result of their experience flying a limited power aircraft. The CH-53 pilot flew slow, high pitch attitude, steep approaches, because of his experience operating an aircraft with seemingly unlimited power and a typically aft center of gravity. The AV-8B pilot flew high approaches to high hovers and quickly followed by fast hard vertical landings. This was his technique required in the Harrier procedures because of the significant jet wash effects and severely limited FOV for hover tasks. The qualitative test results then were subjective and caused significant data scatter which demonstrated that the build-up and training effort was short sighted.

The final portion of the recovery was also closely scrutinized. The hover and vertical landing maneuver tolerances were identified in the build-up and planning stage of the process. They were quantified as requiring the pilot to maintain the hover position within +/-2 ft longitudinally, +/-3 ft laterally and vertically as desired, and +/-2 ft and +/-4 ft respectively as adequate. The tolerances were based on rotor clearances from shipboard structures, other aircraft and structural limitations of the flight deck. There was no metric for accountability of pilot performance however and post video and data analysis indicated that the four pilots also had differing perceptions of the tolerances, particularly when assigning PRS values. Because the PRS scale was generalized this was not considered unusual, except for the fact that the scale was based on average fleet pilots experience. This did not exist in the V-22 community because there was no fleet established and hence no fleet pilots.

A scientific analysis was commissioned to evaluate the aircraft aerodynamic environment while hovering over spot 7 of an LHA. One was a wind tunnel test conducted at NASA Ames which produced a ground vortex in front of the right rotor, Figure 4-2. This ground vortex caused by the superstructure and flight deck, precipitated an inflow effect on the inboard rotor. The second analysis was a Computational Fluid Dynamics (CFD) analysis conducted on the air wake interaction with the ships hull, flight deck and superstructure. The parameters were simulated to the exact WOD and ship



Ground Vortex
Figure 4-2

state at the time of the incident. This analysis indicated a wave effect originating at the bow and organizing into a rolling formation just prior to spot 7. When the two analyses were combined an interesting inboard rolling effect on the aircraft was hypothesized.

Other Problems

Several other lesser deficiencies were discovered in the launch and recovery testing prior to the lateral instability event. A transient pitching up of the aircraft occurred during the transition maneuver over the deck edge, which substantially reduced the longitudinal control margins. This characteristic had been discovered and quantified in prerequisite critical azimuth tests before shipboard testing. This was characterized as Pitch Up With Side Slip (PUWSS), because it was caused by sideslip that resulted in the high velocity rotor downwash impinging on the horizontal tail, causing a pitch moment. This was affecting the vertical take-off and landing phases of flight in clearly quantifiable crosswind conditions. The PUWSS problem was anticipated and preoccupied the test teams' attention, diverting it away from being aware of the high lateral workload trends.

Some other problems that demanded the teams' attention focused on BFWS, ground handling and cockpit FOV. Because the BFWS endurance testing was never completed in the prerequisite tests, consistent and dependable BFWS configuration changes were not occurring at-sea. This problem caused significant maintenance delays. The Flight Control Computers were rendered unusable when the wing was in the stowed configuration because the Global Positioning System (GPS) antenna was masked. The GPS is used to align the Light weight Inertial Navigation System (LWINS) that provided aircraft state information to the Flight Control Computers (FCC's). Without this information the FCC's would prevent the LWINS from aligning autonomously and prohibited unfolding the wing and rotors. Engine wash locations, critical in salt-water environments, were not accessible when the aircraft was unfolded on operational spots. Additionally, the specialized tow vehicle used to position aircraft in the hanger decks was unable to maneuver around the refueling probe. This significantly limited the ground handling of the aircraft in tight quarters of the ship. Finally the Field Of View (FOV) from the cockpit was limited because of the lack of lower peripheral view windscreens generally found on rotorcraft. This affected the pilots' ability to perform precision maneuvers over the tightly confining landing area.

Summary

The problems identified during this complex test process demonstrated several significant issues, perhaps unique to novel technology air vehicles. The near catastrophic lateral instability further identified errors in both the test process and the technological assumptions. The extensive simulation utilized in the build-up and development of procedures, did not provide a prelude to any of the problems that were actually identified on the ship. This was caused by an unacknowledged limitation of the fidelity (technology), in the flying qualities and the visual and aerodynamic shipboard simulation models. Anything more complex than general procedures training was not accurately modeled in the simulator and was of little use to the development of operational limits. Another indication of the simulation fidelity deficiencies was that it prevented accurate evaluations of flying qualities and did not provide a means to detect the differences in pilot techniques. The delays in build-up testing of BFWS and EMC had obvious impacts on the results and outcomes of this test. The incomplete BFWS endurance and reliability tests caused significant delays in an expensive test. The incomplete EMC testing prevented the use of invaluable real time telemetry, which was routine in most modern flight test programs and an effective tool for identifying divergent handling qualities. The extensive number of assumptions with regard to simulation, prerequisite tests and build-up demonstrates the extent of unknown variables introduced in the development of a new aircraft technology and the success oriented methodology that assumed no deficiencies would be discovered.

CHAPTER V
ROAD TO RECOVERY

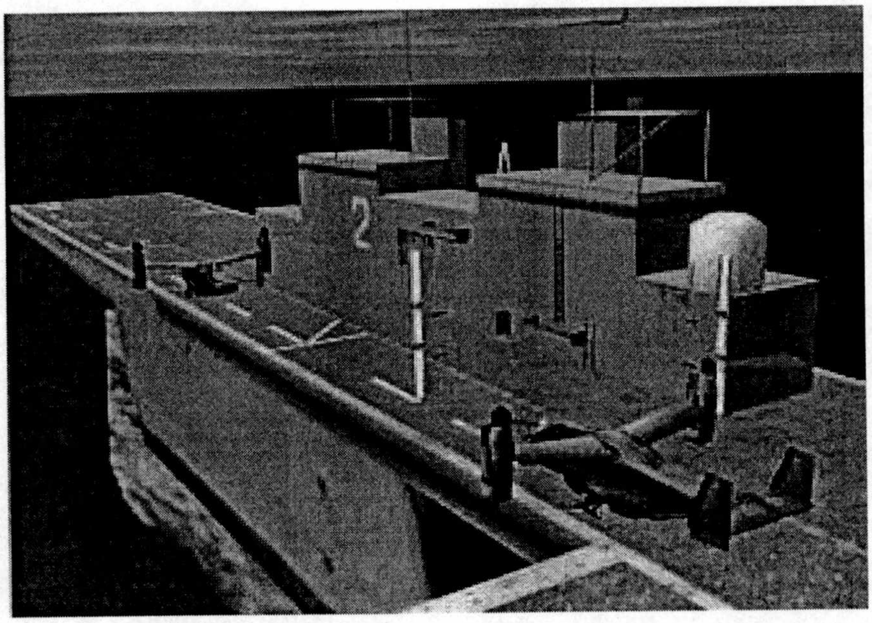
General

To recover from this potentially devastating setback in the program, all manner of resources converged to correct the problem. The V-22 program was the number one aviation acquisition program for the Marine Corps and a Category 1-A Major Defense Program. The problem was technically complex and required an innovative iteration in simulation and flight test before returning to sea. The accelerated process designed for success had hit a major roadblock. Therefore, in the tradition of the V-22 program, a plan to recover was established on a timeline with measurable milestones to ensure success. The problem was to be identified, corrected and validated before the 1 October 1999 start date of OPEVAL. This schedule was difficult to meet because it was not in the original program plan and all test data gathered in the preparation process were brought into question by the late occurrence of such a problem. The problem arguably questioned whether the Osprey would be able to perform its designed mission, which was to operate at-sea on an L-Class Naval ship.

> *"Nothing is more difficult to carry out, nor more doubtful of success, nor more dangerous to handle, than to initiate a new order of things"*
>
> -Niccolo Machiavelli
> (1469-1527)

Simulation

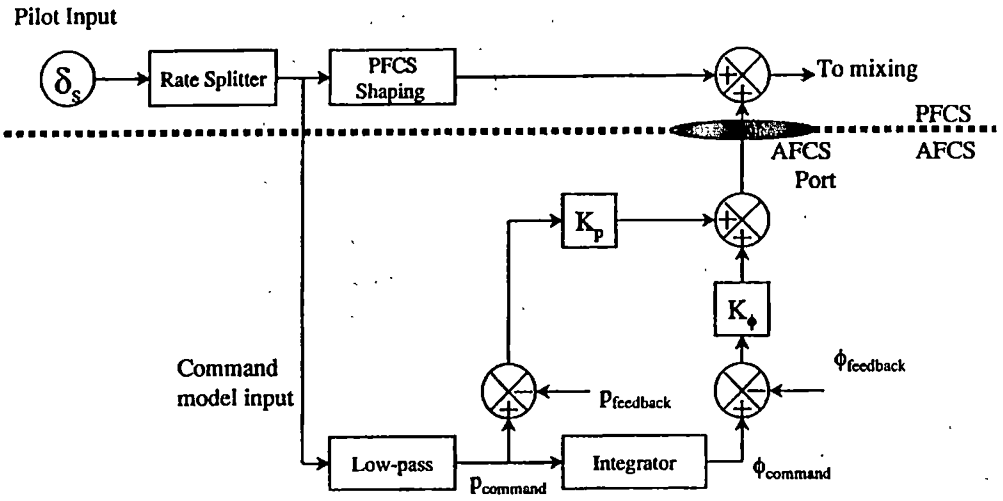
Because of the high safety risk of exploring the dangerous instability in the aircraft, the simulator was chosen as the tool to analyze the event. In a basic reverse engineering technique the simulation used the flight test data to recreate an extremely sterile replica of the shipboard environment. The environment where the instability occurred was not simulated with complex aerodynamic modeling or ship interface algorithms. The handling qualities were recreated; by offsetting the lateral center of gravity to an extremely unrealistic limit and inducing a standard turbulence model which was only effective below 15 ft ADL. This simulator configuration produced the closest approximation to the observed, at-sea event in the shortest time. With this approximation, flying qualities and flight control engineers were able to evaluate FCS software design changes in an attempt to correct the problem. A lateral repositioning task was developed based on handling qualities specifications for fly-by-wire rotorcraft, ADS-33 [ref 54]. This task closely simulated the terminal phase of the final approach to a stabilized hover, but only analyzed one axis of the recovery maneuver. The task was a lateral hover displacement from left to right to capture the lateral alignment cues while



Simulated Lateral Reposition Task
Figure 5-1

maintaining altitude and longitudinal alignment. This lateral repositioning task was placed within the simulator's piloted shipboard visual model at the same location, spot-7 of an L-class ship, Figure 5-1.

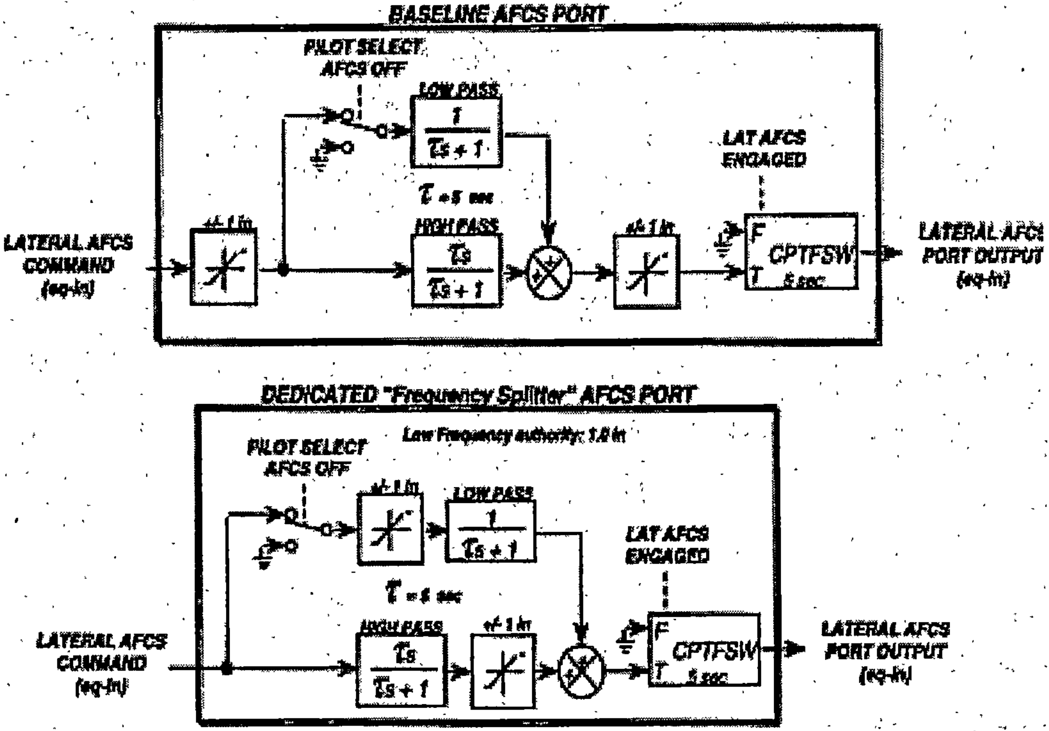
After hours of simulation, using many different test pilots, the control laws were analyzed to determine their effect on the instability. The aircraft's primary problem was a complete saturation of the AFCS authority. This was earlier identified as an aerodynamic response to the shipboard environment, particularly in the WOD conditions encountered during the instability event. The Primary Flight Control System (PFCS) responded to this saturation with significantly degraded response predictability and complete loss of AFCS rate stabilization that required larger pilot inputs. Also within the control laws was a lateral stick rate splitter implemented to protect against airframe



Lateral Flight Control Law Diagram
Figure 5-2

structural damages. This is part of the Structural Load Limiting (SLL) function of the FCS described in Appendix A. Figure 5-2 is a simple block diagram, which illustrates the rate splitter and AFCS port in relation to the PFCS and AFCS augmentation inputs. This rate splitter protected against damages which could result from high rate responses to large lateral control inputs. The resultant larger pilot inputs further aggravated by this rate limiter, contributed to the unpredictability and hence the instability.

The simulation laboratory afforded the luxury of real time control law changes and analysis. The changes in Figure 5-3 below illustrate the simplified roll axis control laws implemented in an attempt to increase phase and bandwidth. The Baseline AFCS port was redesigned with dedicated frequency splitters acting on the low pass and high pass augmentations independently. The ADS-33 type lateral reposition task described

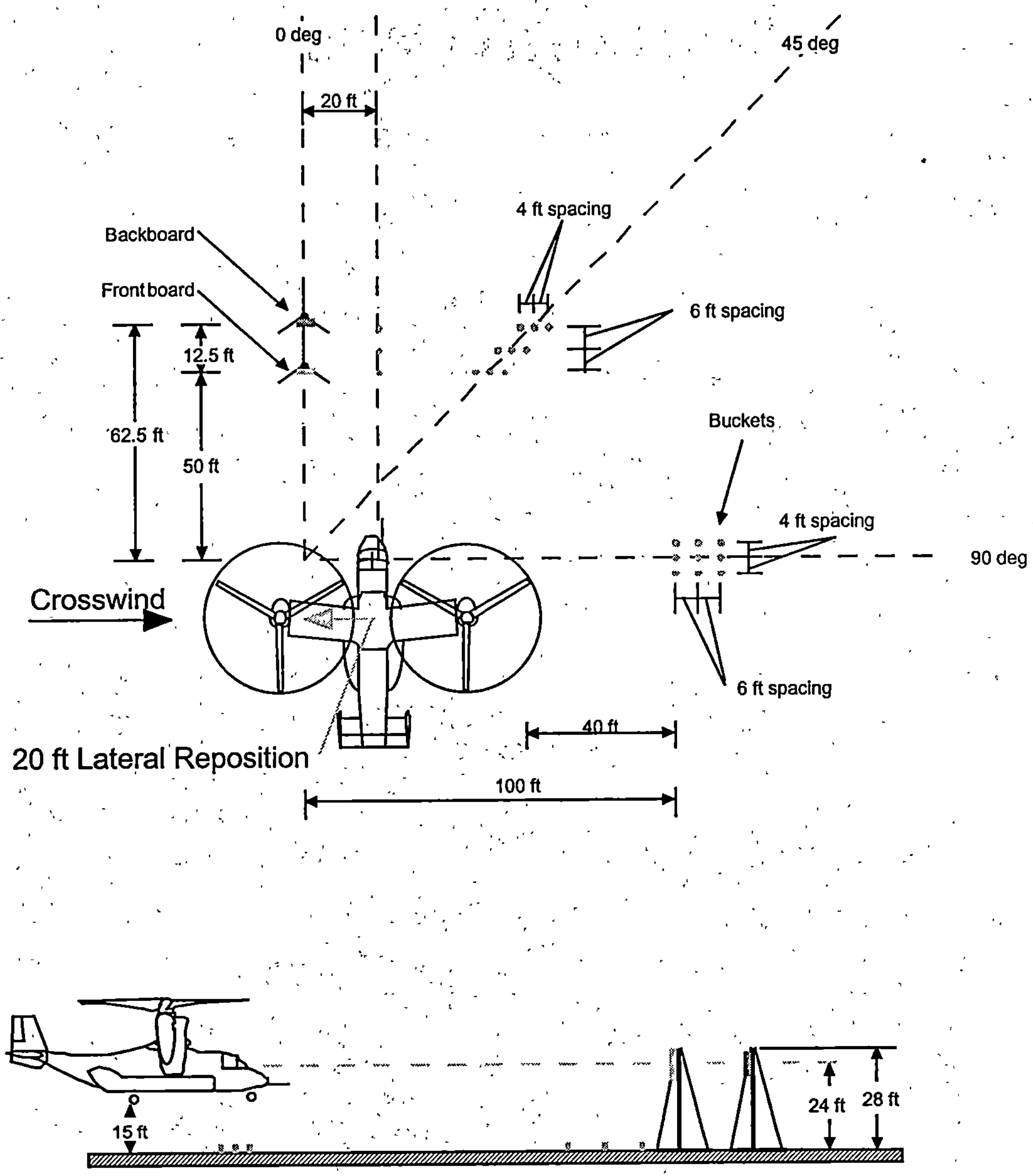


Simplified Roll Axis Control Laws
Figure 5-3

above were flown by several different test pilots to measure the changes. With statistical satisfaction that the change was accurate in the simulation; the aircraft flight control computer software was modified for flight test. Before this proposed design could be flight tested, another complex simulation with actual hardware and software in the loop was tested. This testing has become industry standard in fly-by-wire aircraft, in some cases referred to as "Iron Bird" testing, where an actual aircraft replica is used with modeled aerodynamic loads applied. The testing used in this process was accomplished in a synergistic laboratory tie-in attempt utilizing three separate laboratories. An avionics System Integration Lab (SIL), with actual aircraft flight control computers (FCC) was digitally linked to the flight control system integration rig (FCSIR), which modeled actual aircraft control surface actuators. These two laboratories were then coupled to the piloted flight simulation created to replicate the shipboard environment. The tests produced unstable results in the lateral axis as well, but were discounted because of tie-in and interface latencies occurring between the simulator, the SIL and FCSIR laboratories.

The software was loaded into the aircraft for evaluation. The in-flight evaluations were to be conducted on the same ADS-33 type course, lateral repositioning task. Figure 5-4 below illustrates the layout of the test with the same general lateral reposition methods used in the simulator. Again the testing was conducted with several different test pilots, building up in translation rates. The lateral translation was expected to simulate the aerodynamic effect on the V-22's FCS effectively saturating the AFCS as in the instability event. The results were consistently poor and produced divergently unstable conditions again. The net effect from the new design was that poorer flying qualities were produced than previously predicted in the simulation laboratory.

Configuration 2
V-22 Lateral Reposition Course (derived from ADS-33D)



Center of Board Height = 24 ft
15 ft MG AGL + 2.7 ft MG Extned + 7.7 ft skin to WLCG (166 in) - 1.4 ft eyepoint below WLCG

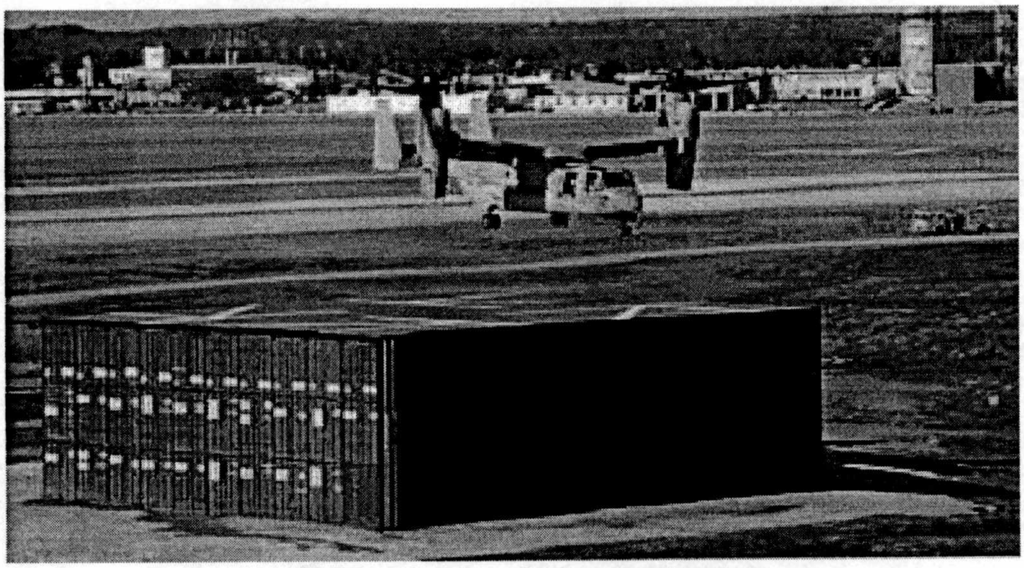
Lateral Reposition Course
Figure 5-4

The subsequent analysis of in-flight test data demonstrated that the cause of the divergent instability characteristics was that the new design was commanding unlimited swash plate actuator rates. The actual mechanical limits of the swash plate actuators however, were approximately eight inches per second. The complex simulation attempts had inaccurately modeled the aircraft swash plate actuators. This effect was demonstrated in the FCSIR tie-in attempt, but was discounted because of the processing and interface latencies.

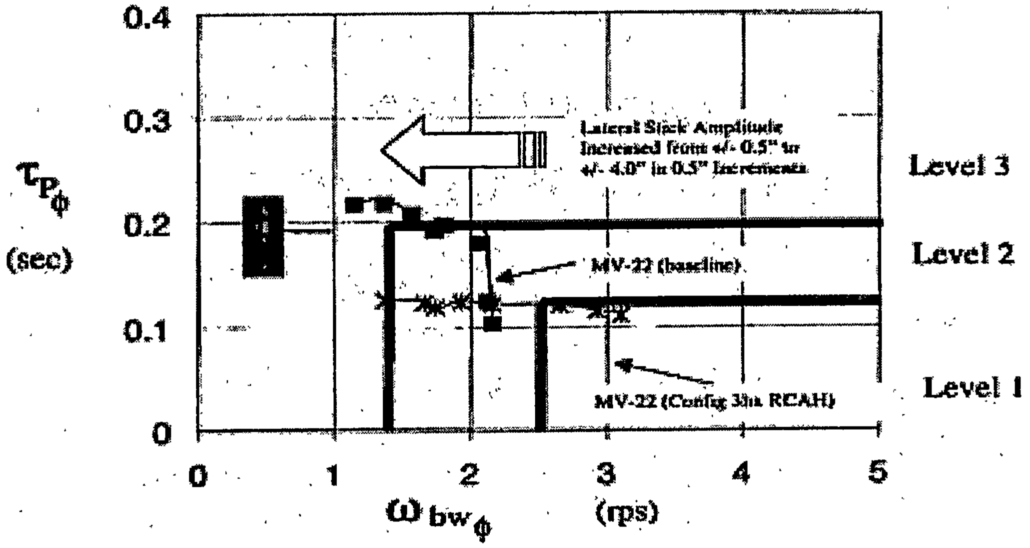
The entire process was then repeated by returning to the simulation laboratories and implementing realistic hardware limits. However, actual hardware limits had never been fully quantified or tested. Therefore, lateral frequency sweeps were required to measure the aircraft's full system responses. This data was implemented into the simulation labs, modeled and reevaluated in the simulated lateral repositioning tasks. Unfortunately with real data the task of correcting the instability became more difficult than general flight control law changes. The lateral control strategy of the V-22 had to be completely reconsidered.

As described in Appendix B the lateral control strategy of the V-22 was accomplished by two separate mechanisms. The Lateral Swash plate Gearing (LSG), and Differential Collective Pitch (DCP) mechanisms had to be optimized to satisfy the stability requirements of such a complex maneuver. This optimization involved multiple iterations of redistributed amounts of swash plate actuator rates for DCP and LSG. With accurately quantified actuator rates for simulation an effort to effectively apportion them within the two control mechanisms was attempted. Several iterations with various pilots in the simulator were required to accurately model the swash plate movement. These tests produced varied results in handling qualities ratings among the pilots. Therefore, a Flight Test Instrumentation Panel (FTIP) implementation was made to allow real time changes of this delicate swash plate actuator rate apportionment in the aircraft. The FTIP would allow the pilots to evaluate each finely tuned design in flight by activating a specific FTIP switch.

The best three simulated designs were then taken to the aircraft for flight test. This time however they were not only evaluated in the lateral reposition task (Figure 5-4), but also on an elevated platform, used as an attempt to simulate deck edge effects, Figure 5-5. This expensive requirement was levied on the test organization to mitigate risk and satisfy the notion that an IGE, OGE rotor effects contributed to the instability. Unfortunately the platform was extremely limited in utility, because of its inherent lack of fidelity to a complex shipboard environment. Again statistical analyses of the results



Elevated Platform Testing
Figure 5-5



Phase Delay vs. Bandwidth
Figure 5-6

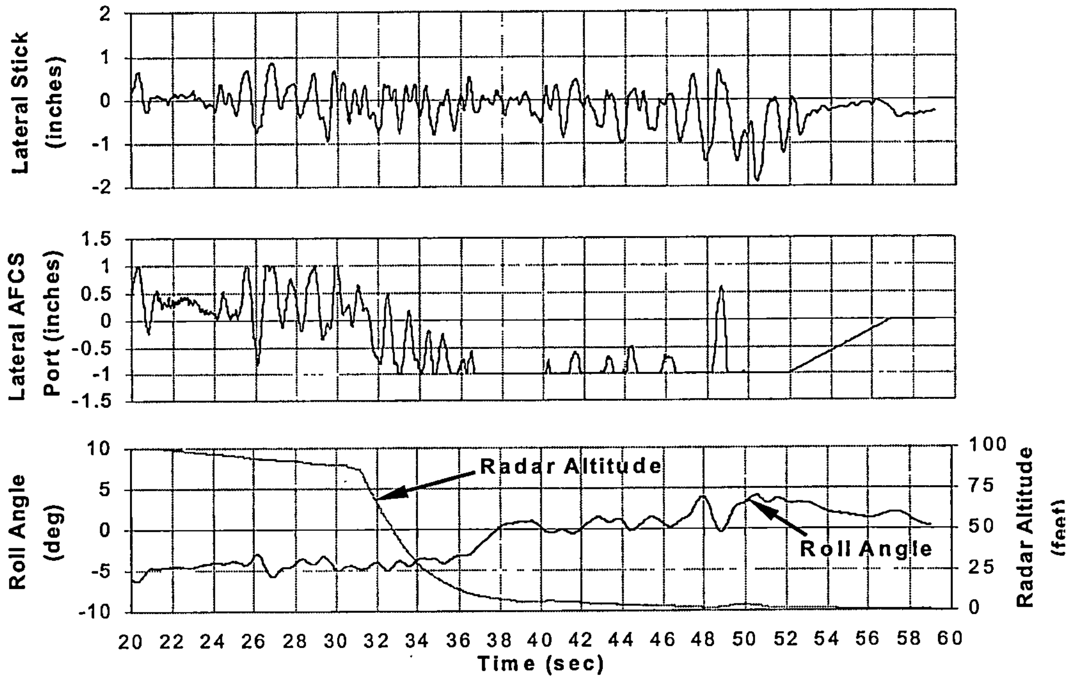
were considered and a decision was made which produced the best results. Figure 5-6 above illustrates the improvements made in the handling qualities from level III in the baseline to level I in the redesign configuration 3hx.

During the redesign process structural engineers also reevaluated the stick rate splitter discussed above. This splitter aggravated the problem because it limited lateral stick inputs to prevent overstressing the composite airframe. The airframe components of concern were in the "Wing Cove" area, located where the wing joins the fuselage. This stick rate splitter was effectively removed from the LSG path and remained in the DCP path, somewhat reducing it's effectiveness, but not changing the limits protected in the airframe, Figure 5-3 above.

Return To Sea

When satisfactory land based test results were finally acquired, a decision to return to sea was made. The reactionary yet innovative developmental process had produced sufficient data and was validated in a series of land based flight tests. Regression testing at-sea then required serious consideration. The validity of the first at-sea test results, was of concern. Unfortunately a large amount of expensive data in the envelope development process during the first test period had been acquired. The validity of these data demanded consideration as to whether to completely discount it or accept it. Because of the extensive delays in the schedule, there was implicit pressure to accept the data with minimal regression tests and validation. Also, because of the short time available to complete testing, a rapid analysis was required to produce a product for the OPEVAL period. Figure 5-7 below is a time history of nearly the same landing conditions that originally stopped the first at-sea testing. Figure 5-8 is a landing at the same conditions with the improved design software (3hx). Note the difference in lateral AFCS and control margin for roll rate augmentation. This data was used to mitigate the risk and minimize regression tests.

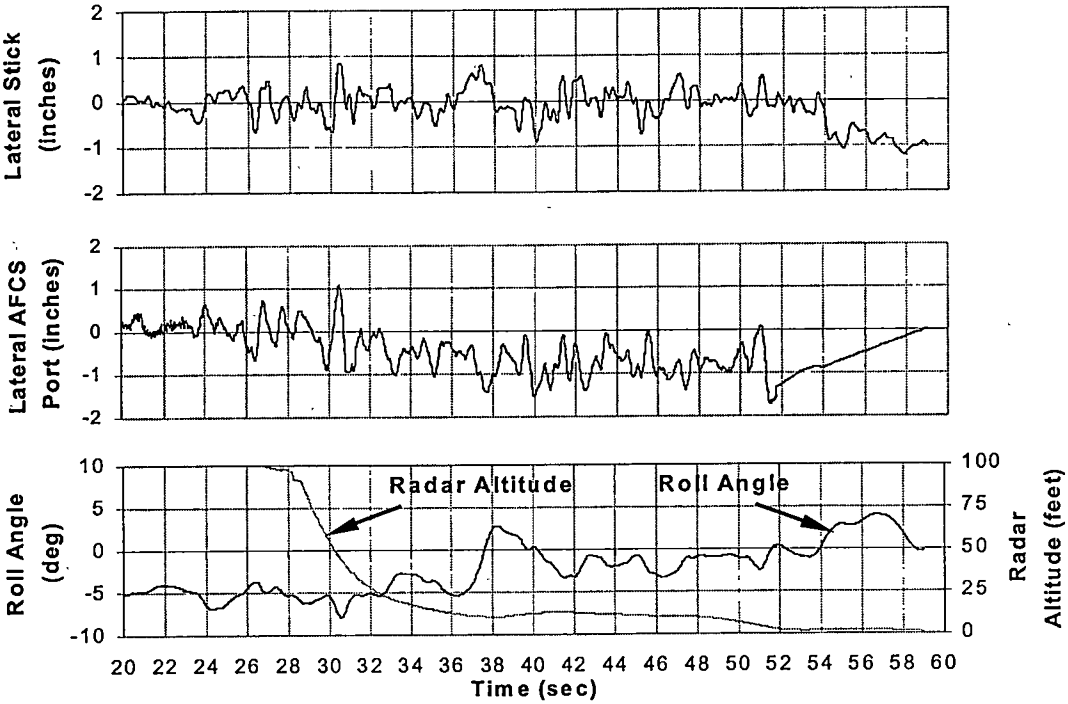
The second at-sea test period, similar to the first, was extremely large in scope. Not only was regression testing required, but also a more thorough evaluation of the launch and recovery events was necessary. More compromises were negotiated with the Naval ship directorate so that telemetry equipment could be used on board. The telemetry equipment was used to monitor critical flight control system parameters real time, particularly the AFCS activity. Additionally a more detailed breakdown of the maneuver was made to isolate more specific tolerances. This enabled the pilots to assign



Original FCS Control Response
Figure 5-7

Handling Qualities Ratings (HQR) Figure C-1, in sub tasks, which were becoming difficult to fly. These HQR's were used in conjunction with the PRS ratings assigned, to assist in the analysis of the data to determine operational limits.

To assist the pilots with the last phase of the recovery maneuver, a measurement was made after each vertical landing. This was done because of the critical limitations on flight deck structural integrity and proprotor clearances. Because of the limited FOV, an outside observer provided real time feedback on each landing with respect to the distance of each wheel from the center of the landing boxes. This was to assist in the assignment of PRS and HQRs. This measure was necessary because of the subjective interpretations of the different pilots during the first at-sea testing. This was an arguably contentious process, but innovatively necessary with a new tilt rotor aircraft and not without



Improved Flight Control Response
Figure 5-8

precedence. In fixed wing air carrier recoveries, a Landing Signals Officer (LSO) who is also a pilot provides immediate feedback on landing performance with regard to centerline distance and which of the four arrestment cables are captured. However contentious, this measure provided a metric and another dimension in the analysis of assigned PRS ratings, in this novel aircraft. This method effectively base-lined the operational expectations of the aircraft, even though there was no operational community from which to draw experience from.

Summary

A high workload hovering task, combined with an undefined shipboard aerodynamic environment contributed to the lateral instability of this aircraft . However, the complexity of digital fly-by-wire flight controls afforded an unexpected luxury in the development of an improvement. What might be considered an elegant flight control system repair to system software was actually complex in real world terms to safely test and validate. Because of complex manufacturing processes and delays in development, a classic flight control change in mechanical hardware was not an option in this particular case and necessitated an innovation in developmental procedures.

The integrated test team incorporated innovative developmental test methods in a short period of time to solve a serious problem. This shortened at-sea process validated the assumed success methodology of the V-22 program, which was heavily dependent on simulation. This simulation however, lacked requisite fidelity to substantiate real conclusions or assumptions and proved that flight test was essential.

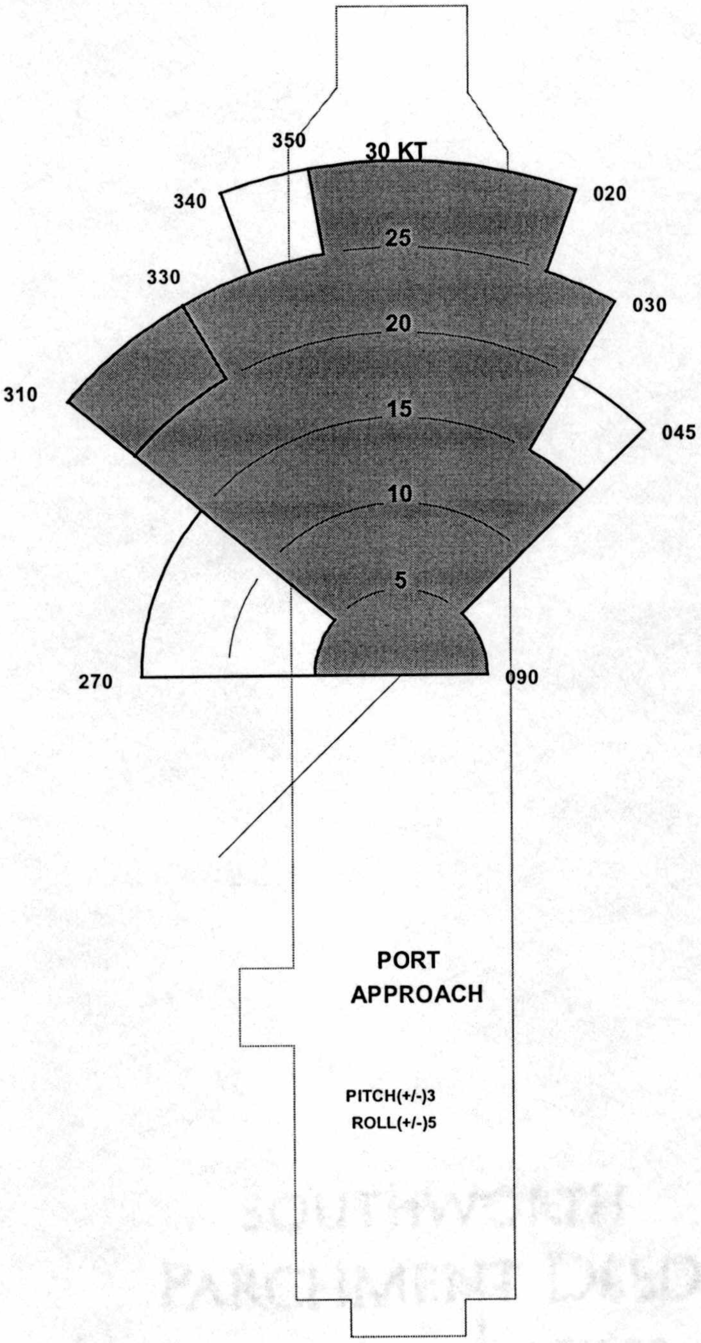
CHAPTER VI
FINAL ANALYSIS OF PROCESS

General

In what was expected to be a quick last minute test period, the at-sea evaluation of the V-22 demonstrated the necessity for more flight test. The process was designed for success and assumed that any problems were already known and accounted for through simulation and analysis. However, when a major deficiency was discovered necessity produced results. The real limitation in those results however, was a focused effort to correct one problem. With the short amount of time to certify the aircraft for OPEVAL there was no time to explore possible corrections to the other less significant deficiencies, or potentially enhancing capabilities. The innovation in the correction of the instability problem was remarkable but wasted valuable time in the exploration of new test or operational procedures which could dramatically improve the safe employment of tilt rotor aircraft on amphibious ships.

Operational Limits

A conservative approach to envelope development was necessary in the final analysis of the results. Because of the focused effort in the majority of testing, the launch and recovery maneuver was the primary envelope to be provided to the operational community. Figure 6-1 below is an example of the product of such an arduous task. The intent was to clearly describe the WOD limits so that both a pilot in flight and a landing controller could quickly ascertain if the current environmental conditions were safe for landing. The same product is provided for every spot tested on the L-class ship for both day and night NVG landings and takeoffs. To responsibly produce these products, a



Sample Launch and Recovery Operational Envelope
Figure 6-1

detailed analysis of all test results is necessary. Results including PRS, HQR, landing performance and ship state conditions must be considered in this complex analysis. Other dimensions in the V-22 analysis included flight control system parameters, such as the AFCS inputs, control margins and nacelle angle. Additionally, the power requirements are considered to ensure acceptable performance and handling qualities margins. Unfortunately all possible variables were not factored into this analysis. Factors such as FCS state, left or right seat pilot location and effects from other operating aircraft, which were traditionally discounted, could have more serious consequences in the development of a radical new aircraft such as the V-22.

The complexity of the V-22 afforded many other variables and configurations in the test process which were not considered in the preparations. An example of a variable not tested or cleared, was a FCS production design capability which allowed the pilot to change the lateral control system to an attitude controller, vice the rate controller tested. Appendix-A provides a general description of this capability. To thoroughly investigate this system, in light of most recent results, would require repeating the entire launch and recover conditions in the attitude mode of flight. This would effectively double the test conditions in an already rushed program. Additionally, because of the limited FOV described in Chapter IV, the left seat pilot on a normal landing to the port side spots has a severely restrictive Usable Cue Environment (UCE). This limited FOV affects the development of operational procedures, in that a caution, note, or warning is required in the operating manual to alert pilots of the restrictive UCE.

Other tilt rotor unique characteristics were not explored in detail, limiting operational potential. The Short Take Off characteristics of a tilt rotor are expected to be enhancing because of the safe flying conditions quickly achieved. STO departures were demonstrated to be single engine capable at mission gross weights where traditional VTOL departures were not. Why then would an operational unit routinely transporting passengers, not want to exploit this capability? Evaluation of this unique capability was not permitted due to the short test period scheduled. Day VFR STO's were the only conditions investigated and determined to be enhancing. One specifically oriented development for operational missions was a V-22 unique STO line (Figure B-2), which afforded more critical deck space for aircraft storage. There was no time to complete night or NVG STO testing, which unnecessarily restricted operational limits, seriously jeopardizing safety.

In conjunction with STO operations, an innovative operational method was conceived, but not tested. This unique method incorporated an assembly line technique to tilt rotor operations, which may improve safety and productivity in a combat environment requiring the simultaneous operation of diverse aircraft. This method would generally be described as V-22's completing vertical or run-on landings on the stern of the ship followed by a self taxi forward to abeam the super structure where passengers and equipment could quickly be loaded. The operations would continue with another self-taxi forward to the V-22 STO line for an immediate and safer STO departure off of the bow. The applications for this flight technique are seemingly limitless, and would afford more operational flexibility and safety to the complex and dangerous shipboard environment. Because of the unique characteristic of the tilt rotor, these types of scenarios are numerous and demand further development to enhance safe operational employment of this type aircraft.

Although the PUWSS condition, previously described in Chapter IV, was quantified before taking the Osprey to sea, the real limitations to operations were unknown. When the results were compiled for OPEVAL, this flying quality deficiency significantly restricted WOD limits. A concerted effort to improve this deficiency was not considered because of rushed testing within program time constraints. However, the road to recovery for the lateral instability demonstrated the remarkable capabilities and resolve of a weary program to get results. The fly-by-wire technology and innovation of the program are the basic ingredients to improve these conditions. A filter, or switch for preset conditions might be a basic starting point to improve this condition and refinement could be found in the multitude of flight control methodologies available in fly-by-wire.

The restrictive FOV in the Osprey, less commonplace in vintage rotorcraft, was reported as a deficiency and was a contributing factor in the lateral instability. However, this deficiency warranted research into the design of flight deck markings (Figure B-3) that were originally conceived for Vietnam era helicopter designs. Those aircraft were not expected to operate with Night Vision Devices (NVD) that severely restrict pilot UCE and FOV. These unchanged deck markings could be optimized for both NVG operations as well as V-22 operations and significantly improve pilot performance in vertical landings. The cues currently incorporated are scaled to provide peripheral cueing for precision hover tasks, such as landing in confined spots. If optimized for the V-22 the marks could improve far field views to enhance the same precision tasks and effectively improve NVG operations for all participating aircraft. This again was discovered during a fast paced test period with no additional time to explore the possibilities.

Other possible innovative recovery aids were considered but never explored. Simple lighting aides installed in the flight deck or on the super structure could be designed to enhance landing characteristics. Additionally low frequency transmitters, assigned to each landing spot could be installed, which transmit position information to the V-22. The on-board LWINS and GPS could correlate this low frequency signal and provide flight director signals or coupled flight controls to ensure safe landings within assigned areas.

However arduous the at-sea test process was for the V-22, it proved very productive relative to recently tested aircraft. Within the span of a very short time the V-22 was able to qualify a new aircraft to operate in relatively expansive WOD envelopes on six of nine possible L-class ship spots. This was remarkable when compared to the CH-53E that tested in the late 1980's and only qualified on four spots with less WOD capability. The CH-53E helicopter was innovative; however it was not as radically different as a tilt rotor and certainly did not incorporate the technological innovations of the V-22. The reason for the relative success in the V-22 effort was the level of attention given to correcting a dangerous problem as demonstrated in the road to recovery in Chapter V.

Proposed Guidelines For At-Sea Tests

The following guidelines are provided to outline lessons learned throughout this process.

1. When developing an air vehicle such as a tiltrotor, acknowledging the risk associated with revolutionary technology and acting appropriately can significantly improve the likelihood for success. For at-sea tests, this can be accomplished by an

incremental developmental period, allowing for several shorter at-sea test events well in advance of the OPEVAL. This would help in the development of effective operational procedures for such a new technology. An interim air vehicle for at-sea testing only, without the full mission system complexity; i.e. BFWS, avionics and NVG, would reduce the costs in both schedule and time. This could be an incremental process to evaluate changes caused by system complexity and would serve to evaluate those systems effect on the shipboard tasks.

2. When testing new technology, event based testing has to be the over arching requirement. Resisting the need to satisfy calendar based milestones will allow for innovative testing, which will potentially uncover enhancing capabilities.

3. When stepping out into uncharted environments, do not become complacent about test requirements. In compressed hasty test programs, pressure is implied to extrapolate available data into untested conditions and environments for operational uses. Resisting this temptation is essential because the unknown conditions and factors that may affect the air vehicle in that environment are uncontrollable in real world operational situations.

4. Testing in simulation should be considered as a tool not nearly accurate enough to completely eliminate flight test. This principle applies particularly to revolutionary air machines such as the V-22. Non-linear responses in flying qualities are not completely defined and therefore cannot be accurately modeled in simulation without flight test and significant validation.

5. Capitalize on applied technology in flight test as the V-22 program did. Fly-by-wire offers tremendous flexibility to modify deficient aircraft characteristics. Early

implementation of a conduit to the FCS, which affords modifications in control laws, will save time and dollars in the test effort.

6. Utilize simulations and shore based testing to experiment with progressive new operational procedures. As in the lateral instability event, a shore-based test course can be scaled to analyze innovative concepts, saving valuable shipboard test time. This will prevent the testers from putting revolutionary technology "in a box" early, limiting its potential.

7. Never pass up the opportunity for real time monitoring (TM) of critical flight parameters in an untested environment. The large numbers of variables are unmanageable by an aircrew or outside team without this capability, particularly in nonlinear fly-by-wire systems.

8. When utilizing high value support test assets such as a Naval war ship, provide for multiple test articles and crews. This will more effectively model the dynamic amphibious shipboard environment. This should also apply to parts, spares and maintenance equipment. The time and burden on operational assets are monumental and demand the highest amount of priority and flexibility.

9. Standardization of test methods is a complex matrix of variables in a new multi-piloted aircraft. Directing and managing the talents and evaluations of test pilots from various backgrounds is critical to prevent wide deviations in quantifiable data. This also applies to invaluable input on various methods employed in other aircraft communities. Provide thoughtful accurate metrics to quantify theses variations in performance and subjectively evaluate the results early so that changes in the test process can be made if required.

10. Do not stereotype new aircraft technology with respect to operational employment procedures. In long developmental programs, capabilities diverge from initial requirements and change the profile of the mission and environment. Expect limitations and search for work-a-rounds and innovations.

11. The testers involved with the at-sea evaluation of a new amphibious aircraft need to be keenly aware of the dynamic environment in which they are testing. This is essential to better assess the aircraft's potential to operate in an environment with a great many variables. This awareness should provide a respect for the aircrew and passengers expected to operate there and allow for as much flexibility as possible, so that they can safely execute their mission.

Summary

The scope of tests, for this unique new aircraft were seemingly limitless because of the many novel technologies incorporated in the aircraft design. The level of attention focused on this program, required a limited scope of testing which would reasonably clear suitable mission envelopes for the coming OPEVAL and ensure political success. The lateral instability event highlighted an unacknowledged risk to the aircraft and identified the extent of unknown characteristics of this new air machine. This effectively tempered the analysis of data and limited the teams' ability to extrapolate any operational conditions not tested. The analysis of this process provides insight into the level of detail unexplored in the V-22 program and provides proposed guidelines for future test efforts. This information could serve to assist in the preparations and scheduling of the testing of future amphibious shipboard aircraft.

CHAPTER VII
CONCLUSIONS AND RECOMMENDATIONS

General

At-sea testing of a Naval aircraft is the final culmination of years of research, design and development and is the last milestone before advanced procurement efforts are funded. Although hastily prosecuted in the MV-22 program this test process was critical to the success or failure of a very long and complex program. There were significant risks both explicit and implicit, which were ineffectively addressed for such a high priority test. Some of the traditional risks were mitigated by flight simulation for schedule and cost savings, however the revolutionary tilt rotor technology added more unknown and unacknowledged risk. The discovery of a near catastrophic deficiency identified most of these risks and certainly substantiated the need for more comprehensive planning and testing of such a new technology aircraft. The impact of compressed at-sea testing is monumental in a modern day program such as the V-22. The complexity of such a task is widely misunderstood and therefore taken for granted in the management of VTOL aircraft development. The analysis and conclusions of this thesis, serve to assist others in the future development of revolutionary new air vehicles.

Risk

The risk associated with the at-sea flight test of the revolutionary MV-22 was not appropriately managed. The approach to risk although deliberate with regard to traditional methods was too casual with respect to tilt rotor technology, as evidenced by the short amount of time allotted for this test, scheduled late in the EMD program. The program plan optimistically implied that this was simply a verification of previous demonstrations, simulations, and expectations. Nowhere was time allotted in this complex task for deficiency identification and correction, which would have effectively acknowledged the technological leap in all aspects of the aircraft design. A replanning effort was risky to the timeline for success and the political climate of the program. The test process was expected to produce traditional operational envelopes in a short period of time so that the program could present the aircraft to the user community for final operational evaluation (OPEVAL) on schedule. As presented in this thesis however, the actual progress and methods were not traditional or expected. Acquisition reform initiatives such as "faster, better, and cheaper" [ref 48], may apply more appropriately to evolutionary programs, such as a new model fighter or helicopter which employ demonstrated "off the shelf" [ref 48] technologies.

Because of the stormy acquisition history, political pressure was silently understood by everyone in the integrated test team that the EMD program must be successfully completed on schedule and budget. Acknowledging the significant amount of risk involved in this test would have required reprioritizing the general EMD test plans and eliminating many other important tests to the program. This would have effectively signaled technological complications that would jeopardize future funding and were not in keeping with sweeping new acquisition reform initiatives. Because of production delays and deficiencies, the EMD schedule was rewritten several times to eliminate or delay previously contracted tests. In most cases simulation and analysis were used to justify the reduced flight test requirements. There was never an admission that the program was falling short of projected timelines and a request for an extension or additional test articles submitted. Asking for more time or money would have been an acknowledgment that the program was under funded, too ambitiously scheduled and was perceived to be devastating to the programs future.

Similar to basic design deficiencies, another unknown risk was that of unexplored potential capabilities. The test team quickly realized that traditional operational methods would limit the capabilities this novel aircraft afforded. With such a compressed plan to execute in a short period of time, there was no flexibility in the schedule for investigations of innovative employment methods. Innovative methods such as the assembly line launch and recovery technique, NVG STO and a technological fix for PUWSS, which warranted further investigation. These methods, if further explored would have certainly demonstrated more operational capability or deficiencies than expected and effected operational limitations. In some cases, traditional test methods and procedures planned for a V-22 were untenable. The risk in this case was that of unnecessarily restrictive and complex limitations required to compensate for shortcomings born of traditional test methods.

Production of confident results for operational employment was extremely challenging in a compressed test program. The team was faced with unnecessarily restricting the operational community, or unknowingly clearing them for a dangerous condition. Because of all the unknowns in this particular environment, made poignantly obvious in the lateral instability, there was no flexibility for liberal interpretation of the data when producing operational envelopes. The compressed nature of this test justified the means and actually produced useable results. However, the operational evaluation team was disappointed with the conservative limitations and likewise not impressed with expansive traditional launch and recovery wind over deck envelopes provided that did not really help them operationally. This was because they were also quick to realize the flexibility and innovative potential in at-sea operations. The net effect was that limits were imposed which restricted their efforts to evaluate the aircraft's mission effectiveness for non-traditional operating methods better suited for the V-22.

Simulation

Simulation is not a panacea for reducing the scope of the flight test effort and analysis. There was an over confidence in simulation analysis that placed the test team in a riskier position than having no simulations at all. Throughout the process the use of simulators was too extensive and fostered a sense that data produced there were realistic and unquestionable. In the sea trials preparation and follow-on testing the over dependence on simulation was precipitated by a lack of real test assets to fly and evaluate. This was a programmatic approach to simulation, which financially justified the elimination of invaluable flight test, considered too costly in both schedule and dollars. This was a mistake, because the simulation fidelity was inadequate for such a dynamic environment. Simulation advocates simply do not understand the dynamic nature of at-sea testing, which requires unrealistically high fidelity in both environmental modeling and hardware. This level of fidelity is required to recreate the complex aerodynamic and mechanical situation that dramatically affects non-linear flying qualities at sea. Using limited simulation is short sighted and produces inaccurate test results. Extensive use of simulation also creates a systemic complacency throughout modern day large-scale programs and unintentionally disguises serious technical problems.

In the case of tilt rotor simulators the computer models are nonlinear and are hence reverse engineered. The complex aerodynamic and environmental models were built early in the program using modified XV-15 results and never fully validated or corrected with real V-22 flight test data. The lateral instability problem identified this oversight in the application of developmental simulation. The problem had to be created in the simulator, using real time flight test data. Historically this has always been the method utilized. However, contrary to the V-22 accepted use of simulation, the simulator analyses were unable to predict problems before hand. The simulation analyses were not only unable to autonomously simulate the visual environment but were also unable to accurately drive hardware in the loop at the actual aircraft rates. These simulator deficiencies brought into question all data collected by simulated means and sometimes used to eliminate invaluable flight testing.

Complex Aircraft Require More Tests

Complex novel aircraft require significantly more testing than vintage aircraft to complete proper evaluations. The complex flight control system of the MV-22 added innumerable variables to the test process than vintage mechanically controlled aircraft. For example, the production design configuration of the FCS, which allowed for in-flight changes of the lateral control strategy, from a rate controller to an attitude controller, was never fully explored. Because of the other FCS challenges, thorough investigations into the capabilities or limitations of the attitude control side of that system were not conducted. As discovered in the lateral instability, the capability is available to analyze and correct inherent flying qualities deficiencies.

Novel aircraft characteristics, which interface with the shipboard environment, require investigation to thoroughly understand their limitations and to exploit all the operational capabilities available. Maneuvers characteristic of tiltrotors such as self-taxi, STO and ROL should be explored as thoroughly as vertical take-off and landings and require deliberate planned test procedures to understand their limitations. Simple configuration changes such as left or right seat pilot landings can no longer be taken for granted. The restrictive FOV on the V-22 limits the Usable Cue Environment (UCE) and the visual aids to shipboard landings and take-offs differ when viewed from two separate locations on the aircraft. The location and orientation of visual landing aids directly affect handling qualities in confined landing areas. The downwash and exhaust gases from a highly loaded rotor disk dramatically affect the deck crew and the landing environment. These and many other tiltrotor specific characteristics require attention and additional flight test time.

Crisis necessitated the need for more thorough testing and schedule adjustments to correct the problem. The lateral instability crisis, like many others throughout the program's history have derailed plans and distracted the testers and operators. This type of reactionary management style has been symptomatic of the V-22 program throughout its history. This distinguished style was born of necessity because of the politicized program history and revolutionary changes in technology and acquisition management. This determination to succeed was observed in every facet of the at-sea test process including planning, execution and recovery from the lateral instability event. In the analysis of the lateral instability, a decision was made that the technology was available to fix the problem and then aggressively pursued on regimented timelines to a point of measured success. When the problem was acknowledged, innovation took advantage of technology to fix technical problems as well as operational limitations. This is not always the case in large programs, because getting the level of attention focused on a deficiency requires a near-catastrophic event and extreme programmatic consequences. In the end, the product for the fleet user was more credible and useful, only because of the discoveries in this complex process.

The interoperability of the MV-22 with other aircraft and the ship was not fully tested. Many important tests such as downwash and jet wash effects from other helicopters and the AV-8 Harrier were not completely explored. Since the downwash was a contributing factor in the lateral instability, there was concern that further investigation of aircraft-to-aircraft interoperability be evaluated. The downwash effects of other aircraft on the FCS and the mechanical limitations of the rotor could prove to be problematic in a full-scale operational environment that routinely operates over 25 various aircraft simultaneously. Unfortunately the limited number of test assets available during the at-sea test period, allowed for only one V-22.

Recommendations

Although the author has provided recommendations throughout this thesis, specific guidelines are presented in Chapter VI. The pursuit of excellence is every testers ambition and the guidelines are provided to assist in that endeavor. The most important recommendation for at-sea testing of novel technology aircraft however, is to seek to understand the shipboard environment and all risks associated with operating there.

PROLUGUE

The MV-22 Osprey completed its operational evaluation period on schedule. Arguably the EMD program including the OPEVAL was considered successful. However, in the course of OPEVAL another V-22 crashed in April 2000 and the lives of 23 Marines were lost during a land based, tactical assault evaluation utilizing NVGs. The cause of the mishap was determined to be a vortex ring state encountered during a high rate of decent in excess of published limits in helicopter mode. Additionally, the OPEVAL period included two short at-sea evaluations, which were extremely limited in scope because of aircraft availability and reliability. Fortunately no problems were recorded during those test periods, which were not already identified in development. Regardless of these events, the aircraft was considered operationally effective and suitable.

Reasonable questions were produced in the wake of the first mishap, which concerned the amount of testing done on the aircraft prior to OPEVAL. Specifically questions were raised on how the decent rate limits were determined and was this vortex ring state condition known. Again in December of 2000 after fleet introduction, another Osprey crashed and four more Marines were killed during a routine training event. The mishap investigation results indicate that a failure mode in the FCS was inadequate to accommodate an isolated hydraulic system malfunction. Obvious questions were again directed at the amount of testing and verification of these complex systems to determine the extent of FCS limitations before delivery to operational users. The answers to both of these recent mishap questions are still unknown. However, it is the authors' opinion that it is the responsibility of the test community to test to exhaustion all possible conditions and acquire data with complete immunity from political implications. The ultimate consequence for oversight and shortcuts is severe and should not be taken lightly.

The future lies in the first operational Marine Expeditionary Unit deployment, where every aspect of the dynamic shipboard environment will be experienced. The potential and likelihood then exists that more unknown conditions not considered by the testers will be experienced. The hope is that by that time more at-sea testing can be conducted and a better definition of the capabilities and limitations of the V-22 will be known.

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Appendix

Appendix A

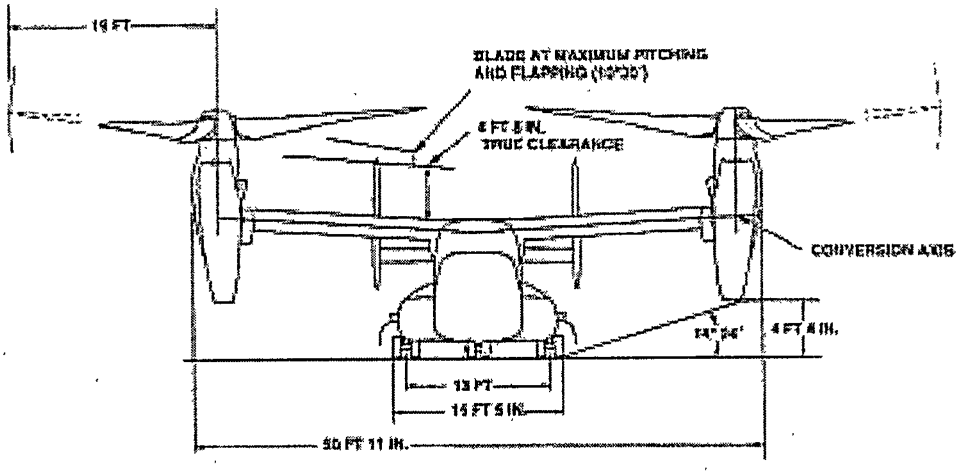
AIRCRAFT DESRIPTION

General

The MV-22B Osprey, built by Bell Helicopter Textron and Boeing Defense & Space Group, Helicopter Division, is a tiltrotor aircraft. The advantage of a tilt rotor design is that the flight envelope encompassed the envelopes of the helicopter and turboprop airplane. The aircraft design consists of a fuselage with a high wing and twin vertical stabilizers. The fuselage is designed to seat 2 pilots, 2 crewmembers and 24 troops. Twin 3 bladed proprotors are located at each end of the wing and are 38.08 feet in diameter. A dimensional drawing is presented in figure A-1 Below. The proprotors are mounted on a gimbaled hub and powered by two Allison T406-AD-400 turboshaft engines. Each engine is capable of producing 6150 shaft-horsepower and employ FADEC technology. The nacelle located at each end of the wing houses an engine, a proprotor gearbox, and a tiltaxis gearbox. The nacelles are designed to rotate about the wing from 0 to 95 degrees, momentary to 97 degrees, relative to the aircraft longitudinal axis in order for the proprotors to provide thrust in airplane mode and lift in helicopter mode. Figure A-1 provides a dimensional illustration of the aircraft. In the event of a single engine failure, the proprotors are interconnected via the tilt axis gearbox and the synchronization shaft located in the wing enabling the transfer of power from the operating engine to the opposite proprotor. The pilots controlled the aircraft via a "fly-by-wire" flight control system. The flight control system is triple redundant and consists of the PFCS and the AFCS. The PFCS provides basic aircraft control, thrust/power management, force feel, and trim control. The AFCS provides full time rate stabilization and selectable attitude stabilization and flight director system. The VMS integrated the flight control system with the hydraulic system and enable the crew to control the aircraft in all modes of flight. The mission computer software is termed JASS and controlled avionics and nonavionics subsystems. The aircraft employs a retractable, tricycle landing gear. A brake pallet system is installed as a workaround to provide hydraulic power to the brakes while the aircraft is not hydraulically powered. Nonpowered brakes were necessary for aircraft movement on the hangar deck and would be incorporated into production aircraft. The maximum VTOL gross weight is 52,600 pounds at sea level and maximum self-deploy gross weight is 60,500 pounds. The aircraft featured a BFWS system to reduce the aircraft footprint for storage on the flight deck and hangar deck. The BFWS system was designed to index the blades, fold the rotors, rotate the nacelles to the 0 deg position, and stow the wing in less than 90 seconds.

Vehicle Management System (VMS)

The term Vehicle Management System (VMS) is used to describe the integration of the hydraulic systems and Flight Control System (FCS). The integration of the FCS sensors, computers, and cockpit mechanical controls with the hydraulic systems and control surfaces enable the crew to control the aircraft in all modes of flight.



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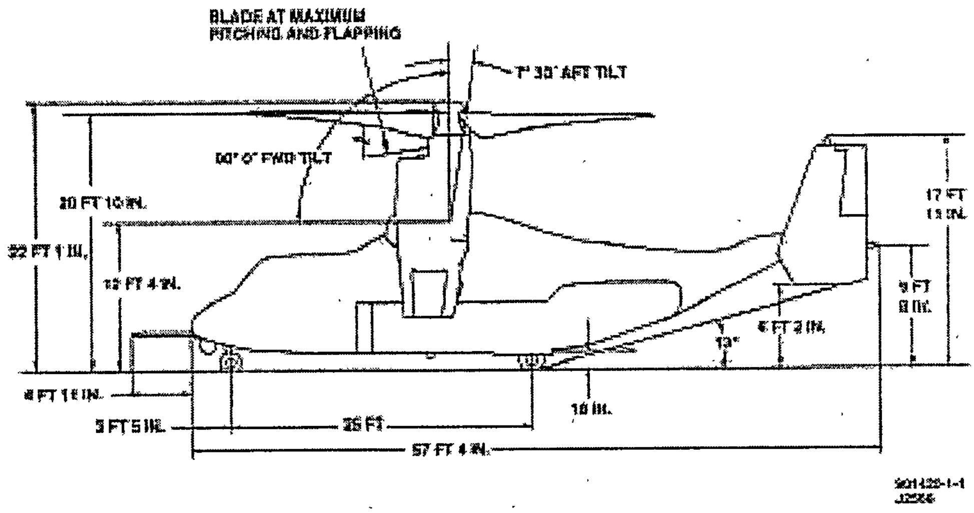


Dimensional Drawing
Figure A-1

Hydraulic Systems

Hydraulic power is provided by three independent 5000 psi systems. Systems No.1 and No.2 are identical, dedicated flight control systems. System No.3 serves as a backup to certain flight control systems, provides ground check pressure to the flight control actuators, and provides pressure to power the utility systems. Hydraulic power to the rotor system controls and control surfaces is triple redundant (swashplate actuators are dual-stage with system No.3 providing backup). Failure of one system does not degrade system operation, and failure of a second system will not result in a hazardous loss of control response. System pressures and fluid levels are monitored by the FCCs. Switching logic in the FCCs will automatically attempt to isolate a defective system when loss of pressure or fluid is detected. Four thermal controls modules (one each for system No.1 and No.2 and two for system No.3) are used to rapidly warm up the hydraulic fluid during cold weather operations.

Flight Control System (FCS)

The V-22 Flight Control System (FCS) consists of mechanical cockpit controls, sensors, computing devices, and actuators which enables the aircrew to control the aircraft. The FCS is a triple redundant, "Fly-By-Wire" system. Mechanical controls are limited to the cockpit and cockpit under-floor area. The FCS generates commands to the control actuators by processing signals from cockpit controls and various aircraft data sensors. All flight control actuator commands are computer generated. The FCS consists of two systems, the Primary Flight Control System (PFCS) and the Automatic Flight Control System (AFCS).

Structural Loads Limiting (SLL)

Structural Loads Limiting (SLL) is a flight control design approach that integrates handling qualities, performance and load limiting requirements into the basic flight control software. The SLL control laws capitalize on the flexibility of the digital flight control system. The parameter scheduling capability of a digital control system allows the designer to modify the aircraft's control response for only those flight conditions where the potential for load exceedences exists. The SLL control laws protect critical proprotor, drivetrain, and airframe loading. SLL allows the pilot to focus on mission tasks without constant monitoring and control of structural loads. The SLL control laws are only fully effective when the FCS has no failures present. Faults and failures in the FCS may degrade the effectiveness of the SLL control laws. A STRL LOAD LIMIT FAIL caution or a STRL LOAD LIMIT FLT advisory is displayed when the FCS has experienced a degradation in the SLL capability.

Primary Flight Control System (PFCS)

The PFCS is a triple redundant digital flight control system that enables the aircrew to control basic flight control functions. The PFCS provides basic aircraft control, thrust/power management, force feel, and trim control. The PFCS processes aircraft state information (air-speed, angular rate, flapping, engine torque and rpm, control actuator position) and pilot input. It performs digital computations, and outputs drive signals to the control surfaces, swashplate and nacelle actuators. It also outputs commands to the engine control system. The FCS interfaces with the 1553B data bus in two ways: digital system interface and analog system interface. The PFCS functions in the 1553B data bus are controlled by the FCCs and the Cockpit Interface Units (CIU).

Flight Control Computers (FCCs)

The FCCs are located in the avionics bays: No.1 and No.2 in the left bay, No.3 in the right bay. The FCCs contain both the PFCS and the AFCS modules. The computers are both self and cross-channel monitored; the others monitor the performance of each. The FCCs receive information from the cockpit controls, the MCs, aircraft data systems and FADECs for processing and output data to the control actuators, and the FADECs. Each FCC controls a set of actuators that is capable of providing flight control via that FCS.

PFCS Operation

The primary flight control system is comprised of the cockpit mechanical flight controls, the electro-hydraulic servo actuators, and the electronic flight control computers and sensors. Pilot inputs to the mechanical cockpit controls are converted to analog electrical signals by control position transducers. The electrical signals are digitized and then processed by the redundant FCCs. Digital computer outputs are converted to analog signals and transmitted by wire to the flight control servo actuators and engine controls. Complete flight control system redundancy (computers, sensors, data buses, hydraulic and electrical power sources, and control actuation) is provided. Components, buses, hydraulic lines and wiring are physically separated as far as possible to reduce exposure to ballistic or other damage. Three dual tandem hydraulic actuators are connected to the stationary swashplate in each nacelle. Three pitch links, connected to the rotating swashplate, transmit the swashplate movement to the proprotor blades. When all three actuators extend or retract equally the swash-plate moves axially on the proprotor mast, increasing or decreasing the blade pitch angle collectively, causing the thrust vector to increase or decrease. Movement of the swashplate actuators is commanded by the FCCs to maintain a constant proprotor rpm in response to increased or decreased engine power output. When actuator movement is unequal, the swashplate tilts with respect to the rotor mast and the pitch angle of each rotor blade changes cyclically as the rotating swashplate ring turns. This cyclic pitch change causes the rotor disk to tilt, producing a longitudinal or lateral thrust vector. These vectors need not be equal, nor in the same direction. The combined TCL and cyclic inputs provide pitch, roll, yaw, and velocity control in the VTOL mode. Differential collective pitch (thrust), Figure A-2, produces roll. Cyclic (tilt) inputs produce pitch, yaw, and sideward flight. Airspeed or rate of response is a function of the magnitude of the control input (power demand). In VTOL mode, the longitudinal cyclic pitch is used to control the aircraft's pitch. Roll is controlled using lateral cyclic and differential collective pitch. Differential longitudinal cyclic is utilized to control yaw. During transition to APLN mode, the cyclic proprotor controls are gradually phased out. The longitudinal cyclic pitch command is reduced as the nacelle angle decreases from 90 to 0 degrees. The differential longitudinal cyclic command is phased out between 85 and 45 degrees nacelle. The lateral cyclic command is phased out between 75 and 60 degrees nacelle. The differential collective pitch command is reduced as the nacelle angle drops from 60 to 0 degrees; however, it is not completely eliminated like the cyclic commands.

As the aircraft reaches APLN mode, pitch, roll, and yaw are primarily controlled by the elevator, flaperons, and rudders respectively. Nr is reduced after transition from 100 percent (397 rpm) in VTOL mode to 84 percent (333 rpm) in APLN mode. The decrease in Nr occurs when the nacelle angle reaches 0 degrees and the pilot releases the nacelle switch, then momentarily beeps forward again. This is known as "autobeep." When converting out of the APLN mode, the momentary activation of the nacelle switch aft causes Nr to increase (autobeep) to 100 percent. Subsequent activation of the nacelle switch aft will cause the nacelles to move upward. TCL input is used to maintain constant proprotor/power turbine rpm throughout the full range of nacelle travel.

The mechanical flight controls consist of the cockpit mechanical controls and the electro-hydraulic mechanical flight controls. The cockpit mechanical controls consist of a conventional pitch and roll control stick (cyclic), rudder pedals for yaw control, and a TCL for throttle/collective pitch control, and associated link-ages under the cockpit flooring. The electro-hydraulic mechanical controls are the electro-hydraulic actuators at the flight control surfaces.

Thrust Control Levers (TCL)

Two TCLs are mounted to the left of each pilot seat and are interconnected by linkages to the FCS. The TCL has a travel of 6 inches. 0 to 4 inches is for normal power (100 percent mast torque) and interim power (109 percent mast torque) operations. 4 to 6 inches, or overtravel, is provided to compensate for power loss from a dual simultaneous mast torque sensor failure. Shear rivets in the linkage to the individual components (at electronic components) protect against jammed controls or a frozen component. A friction knob is installed below the right TCL. The TCL sends electrical signals to the Cockpit Thrust Drive Actuator (CTDA) to feed engine power demand signals through the FCCs to the FADECs.

Cyclic Control Sticks

There are two cyclic sticks installed in the cockpit, one in front of each pilot seat. Each stick provides lateral and longitudinal input to the FCCs by pilot control input.

Directional Pedals

The pilot and copilot directional pedals are independently adjustable, fore and aft, using the pedal adjust switch on the respective side console. Power for the pedal adjustment actuators is supplied by DC bus No.1 through the PEDAL ACTR circuit breaker in the overhead panel. The pedals are also used to control the nose wheel steering and wheel brake systems.

Electro-hydraulic Controls

Input signals from the electronic FCCs are sent to the flight control actuators. These actuators move the control surfaces (swashplates, elevator, flaperons, and rudders). Flight critical controls (proprotor, conversion, elevator, and flaperon) are triple redundant.

Flaperon Actuators

Roll control in the APLN mode is provided by two flaperons on each wing. In the APLN mode the flaperons operate as conventional ailerons, providing roll deflection of 25° up and 40° down. During VTOL flight, approach, and landing, the surfaces can be positioned as flaps with a maximum deflection of 73°. In any manual flap setting, the roll control function is still available, except that the flaperons opposite the turn direction are limited to 47° down (full 30° roll control). In the VTOL mode, the flaperons are normally positioned at 73° to reduce proprotor wash download. Each of the four flaperons is powered by two actuators, only one of which is required to move the surface. Each of the two actuators are powered by different hydraulic systems. The hydraulic sources are selected so that failure of a single hydraulic system will not effect operation of the flaperons.

Elevator Actuators

Pitch control in the APLN mode is provided by a single elevator. Three piston actuators power the single elevator. Each actuator is supplied by a different hydraulic system. A single actuator is capable of operating the elevator in typical flight conditions. The elevator deflection range is 30 degrees up and 20 degrees down.

Rudder Actuators

Yaw control in the APLN mode is provided by dual rudders, each powered by a single actuator. The left rudder is supplied by flight control hydraulic system No.1, the right by system No.2. Rudder deflection is 20 degrees either side of neutral. Dual hydraulic failure will result in loss of rudder control, however, the rudder is not flight critical in this aircraft.

Swashplate Actuators

Each swashplate actuator is a jam-proof, dual tandem actuator normally powered by hydraulic systems No.1 and No.2, and controlled by FCC No.1, No.2, and No.3. In the event of hydraulic system No.1 or No.2 failure, the FCC will supply hydraulic system No.3 power to the affected swashplate actuators. Fault logic in the FCC monitors hydraulic system pressure and fluid quantity and will automatically isolate a defective system to prevent fluid loss.

Conversion Actuators

The conversion actuators are located at the outboard end of each wing. One end is attached to the nacelle, and the other end is attached to the wing. The actuators provide 97.5 degrees of travel between the APLN (0°) position and the VTOL position. Each actuator screw is normally driven by two Hydraulic Power Drive Units (HPDU) powered by flight control hydraulic systems No.1 and No.2 and is controlled by FCC No.1, No.2, and No.3. Hydraulic system No.3 provides backup power to each conversion actuator.

PFCS Sensors

The PFCS requires sensor inputs of control position, airspeed, nacelle angle, roll rate, and engine/proprotor status. Signals from these sensors are processed by each FCC, in accordance with programmed control laws, and sent to the control servo actuators and engine controls.

Cockpit Control Thrust Drive Actuator (CCTDA)

A CCTDA connected to the TCL linkage supplies motorized drive of the power control from manual or automatic inputs. It also provides position holding friction proportional to the adjustment setting. The friction control knob is on the pilot armrest.

Cockpit Control Feel And Drive Actuator (CCFDA)

Three CCFDAs, one in each control axis, provide programmable breakout and gradient forces for manual control feel and perform the magnetic brake function for pitch, roll, and yaw manual trim. The control feel and drive actuators also supply motorized drive in each axis from manual or automatic inputs.

Cockpit Control Position Transducers (CCPT)

Cockpit control position is provided to the FCC by 16 Linear Variable Differential Transducers (LVDT). Four LVDTs are connected in each control axis (pitch, roll, yaw, and thrust). Each transducer supplies a dedicated signal to a single FCC.

Nacelle Position Sensors

Four nacelle position sensors in the left nacelle and four in the right nacelle are driven by gear segments on the conversion spindles. These sensors provide nacelle angle to the FCCs for control law scheduling, feedback signals to the actuators, and cockpit indication on the HVR, VSD, PFD and SFD. The FCC compares the nacelle positions and limits their angular difference to 0.5°, stopping the leading actuator until the slower actuator is within limits.

Rotating System Sensors

Sensors installed in the proprotor mast slip ring assembly and on the rotor hub provide mast torque, rotor rpm, rotor azimuth, and rotor blade flapping angle signals to the FCCs. Mast torque and rotor rpm are supplied by the FCCs to the MCs for cockpit display.

PFCS Flight Control Laws

Each flight mode has control laws that supply the command processing and operating logic necessary for governing the desired handling qualities. These laws provide the input/anticipation/feedback loop for pilot input to minimizes lags in control response due to aircraft inertia. The response to pilot TCL input is shaped to improve response time when the VTOL mode and to desensitize the response to abrupt stick inputs in APLN mode. The control laws are automatically scheduled as a function of nacelle angle and airspeed.

Longitudinal (Pitch) Control

The PFCS provides stick input shaping, AFCS input, swashplate and elevator control gearing, flapping control, and pitch damping in both thrust/power and nacelle angle coupling.

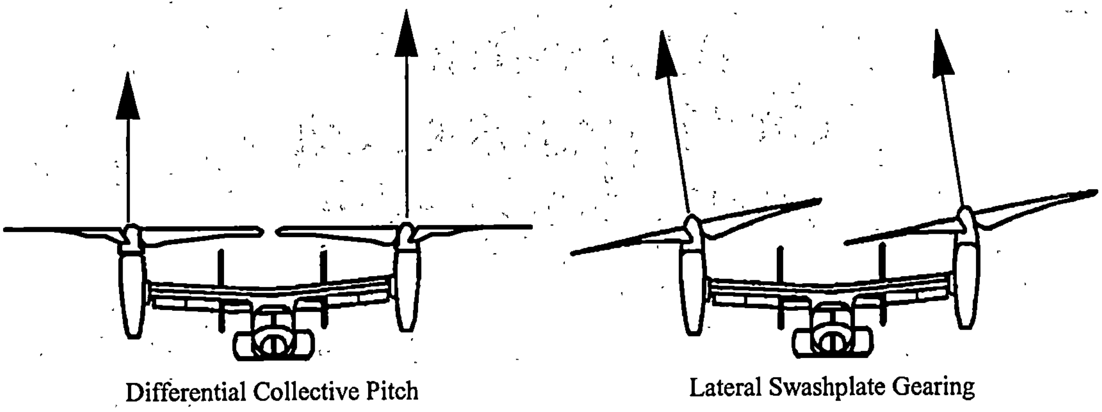
1. Gearing provides consistent control sensitivity for the elevator over the APLN speed range; making the elevator more responsive at low speeds and less responsive at higher speeds.
2. Longitudinal stick commands rotor flapping for low speed control when nacelle angle is greater than 45°. As airspeed increases and the elevators become effective, flapping is reduced to alleviate blade loads. Elevator is commanded as the primary pitch control at higher effective airspeeds for nacelle angles below 45°.
3. The control laws reduce pitch power coupling caused by the thrust line being located above the longitudinal axis causing the nose down-pitch response to increased power application or decreasing nacelle angle.
4. Elevator gearing causes more elevator deflection at low speed than at high speed for consistent pitch sensitivity throughout the airspeed envelope.

Lateral (Roll) Control

The PFCS lateral control law combines lateral cyclic input, pitch rate gyro, control shaping, roll rate damping, and AFCS input. This provides lateral swashplate gearing and collective gearing (as a function of nacelle angle) for VTOL control, and aileron gearing (as a function of airspeed) for APLN control.

1. Lateral cyclic inputs command differential collective pitch roll commands to both swashplates, increasing one and decreasing the other, Figure A-2. The lateral trim input is ramped out as the nacelle angle decreases to 60°.
2. Differential flaperon control is provided in APLN mode. When the flaps are beyond 40°, additional flap down command from a roll command will result in a reduced down command to the opposite flaperon to preserve roll control at large flap deflections.
3. Aileron gearing causes more aileron deflection at low speed than at high speed for consistent roll sensitivity throughout the airspeed envelope.

The FCS allows for pilot selection of either an attitude commanded or rate commanded attitude hold capability. This feature is available to allow the plots to select their preferred control strategy both in helicopter and airplane modes of flight.



Lateral Control Strategy
Figure A-2

Directional (Yaw) Control

Directional control combines pedal input shaping and AFCS input, to provide swashplate gearing as a function of nacelle angle and airspeed in VTOL and rudder gearing as a function of airspeed in APLN. Gearing is applied to yaw and rudder control.
1. In the VTOL mode the rudder pedals command differential longitudinal cyclic.
2. During flight in conversion and APLN mode, differential swashplate control is washed out and the rudders provide control. Rudder gearing provides consistent sensitivity throughout the flight envelope.

Thrust/Power Control

The thrust/power control generates Power Demand Signal (PDS) commands to the engines and collective pitch commands to the proprotors. The aircraft uses blade pitch governing (BETA governing) as the means of Nr control. With the low inertia proprotor bearing unable to absorb sudden changes in load, significant rpm excursions would result if a pure throttle governor were used. In the VTOL mode, movement of the TCL will result in both throttle and collective blade pitch commands. In VTOL mode, throttle and collective command quickeners reduce pilot workload for precision hover. Nr signals are fed back to the collective governor to maintain desired/commanded Nr. In APLN mode, movement of the TCL results in throttle command and some reduced collective command.

Torque Command Regulating System (TCRS)

The TCRS, an element within the thrust/power control, generates engine and proprotor commands to provide mast torque response to thrust-axis input commands, up to specified mast torque limits. TCRS works in conjunction with the rotor governor to drive both mast torque error and Nr error towards zero. TCRS also reduces torque response transient overshoot due to rapid application of full forward TCL. Mast torque reduction can occur due to a single engine failure or deduction in PDS to one engine due to ECL position (simulated engine failure). Any loss of mast torque is automatically compensated for by the TCRS system by adding the necessary PDS to restore the currently commanded mast torque up to remaining emergency rated engine performance limits. TCRS authority is designed to be the minimum required to provide adequate single engine compensation and mast torque overshoot protection throughout the operating envelope. TCL over-travel and ECL position selection provides sufficient pilot override capability in case of undetected mast torque sensor failures.

Automatic Flight Control System (AFCS)

The AFCS interfaces with the PFCS to enhance the basic control functions and provide improved handling qualities. The AFCS provides improved flying qualities, expanded mission capability, and reduced pilot workload through zero steady state outputs (nulls). Stability augmentation through rate and attitude feedback, and authority and rate limiting. AFCS provides full time (core) automatic flight control stability inputs and selectable AFCS functions through the flight director system, and is a single fail/operate system. The AFCS incorporates three identical digital modules which are located with the PFCS processors in the flight control computers. The AFCS processors operate in parallel, each receiving sensor inputs describing aircraft airspeed, attitude, acceleration, and control commands. The inputs to each processor are compared via a cross-channel data link. If an input is out of tolerance, it is ignored and a sensor malfunction is recorded via the central integrated checkout system. All AFCS outputs are checked and must be approved by the PFCS, which produces all commands to the flight control actuators. When the pilot commands a change in attitude through the cockpit controls, the command is routed for quickening through the shaping loop in the PFCS and rate command and the attitude command modules in the AFCS. Both modules pass their signal through measured rate gyros separately to another module for rate and amplitude gain. The signals are then summed. The resulting signal is processed by an authority limiter. From the limiter, the signal goes to the PFCS for action. Authority of the AFCS is 20 percent in each axis.

AFCS Control

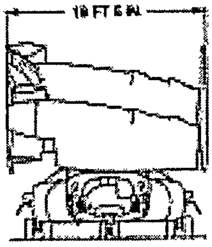
The AFCS is controlled by switches on the flight control panel on the overhead console, CDUs, and by the trim release and altitude hold switches on the cyclic and TCL grips. The AFCS ON switch on the flight control panel is normally ON (light on). A system malfunction will cause the adjacent AFCS RESET light to blink RESET. If pressing RESET clears the problem, the light will go out. If the problem remains after attempting to reset, the RESET light will remain on.

Full Time (Core) AFCS Functions

The AFCS functions are both full-time and pilot selectable. The full time core AFCS functions are an integral part in the structural load limiting approach.
1. Stability control - Pitch, roll, and yaw rate damping are provided full time. When AFCS is selected ON, vertical damping as well as attitude stability is provided.
2. Turn coordination - At airspeeds of 50 KCAS or higher, turn coordination is provided full time.
3. Attitude hold - When AFCS is selected ON and the cyclic controls are not displaced more than 0.1 inch from trim reference, attitude hold is provided.
4. Heading hold - Core AFCS heading Hold functions at all airspeeds. There are two primary AFCS control strategies for heading hold: 1) At low speeds (less than 80 knots), heading hold commands are elicited through the directional AFCS, and 2) At high speeds, heading hold elicits lateral AFCS commands. No lateral AFCS commands are elicited below 45 knots; likewise no directional AFCS commands are elicited above 80 knots.

Blade Fold/Wing Stow System (BFWS)

The BFWS system is designed to automatically fold the proprotor blades, rotate the nacelles to the horizontal position, and stow the wing to reduce the overall dimensions of the aircraft for shipboard operations and hanger storage Figure A-2 below. The proprotor blades can be folded, and the nacelles can be rotated to the horizontal position without stowing the wing to provide access for maintenance. The automatic procedures are controlled by the Blade Fold/Wing Stow control layer, and activated by pressing and holding the blade fold/wing stow push-button switch on the left overhead console. Releasing the switch will stop the sequence, and cause the operator to have to press the RETRY key and press the blade fold/wing stow switch again.



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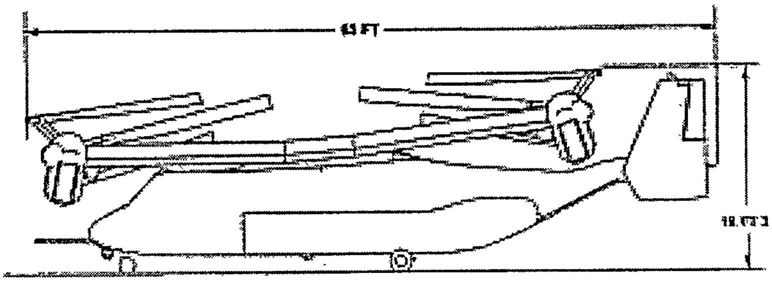

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Blade Fold Wing Stow Configuration
Figure A-3

Blade Fold

The blade fold system provides proprotor indexing and locking for BFWS operations. A blade fold control unit, located on each proprotor central deice distributor, controls and sequences the operation of the blade fold system by responding to signals from the MCs, inputs from the blade fold proximity sensors. An electric power module located inside each blade bolt folds the blades. Operating power for the power modules is supplied by the BFCUs.

Wing Stow

The wing is rotated on a stowring by a capstan drive actuator. The capstan drive actuator uses a cable to rotate the wing from flight, stow, and intermediate positions. Four lock pins lock the wing in the flight position, and one is used to lock the wing in the stow position. The wing stow mechanism consists of a capstan drive actuator and lock pin actuators that are powered by the No.3 hydraulic system.

Appendix B

SHIPBOARD DESCRIPTION

General

USS SAIPAN (LHA 2) belonged to the USS TARAWA (LHA 1) class of amphibious assault ships. These ships displaced 39,300 tons when fully loaded. Overall length was 820 feet and beam was 106 feet. The flight deck was 118 feet wide. Propulsion was provided by two Westinghouse geared turbines that had an output of 70,000 shaft horsepower each. Maximum ship speed was approximately 24 knots. Aircraft were moved below the flight deck via elevators located on the port side amidships and on the stern. The stern elevator was capable of 80,000 pounds, and the port elevator was capable of 41,000 pounds. The flight deck had ten landing spots: one centered on the bow, three on the starboard side, and six on the port side. The guns on the port and starboard sides of the bow were removed. A plan form drawing of the flight deck and photograph are presented in Figures B-1 and B-2. The LHA operated the following emitters: TACAN, SLQ 32V EW, SPS 52C, SPS 40B, SPS 10F, LN 66, SPG 9A, and UHF and HF communications. Ship flight deck and hangar deck strength analyses were shown to be adequate for MV-22B operations.

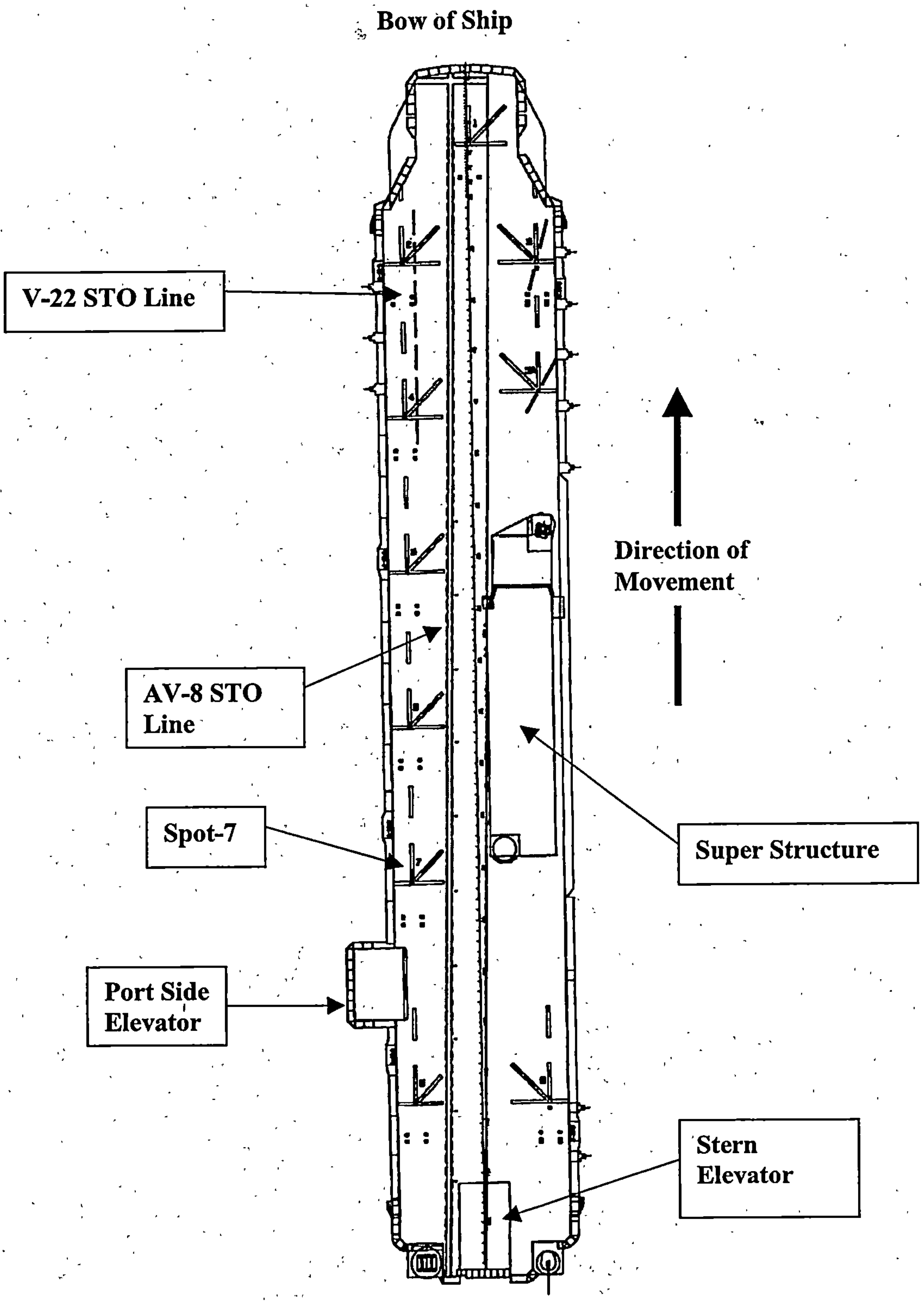
Landing Environment

The landing environment of an LHA class ship includes the entire landing deck presented in Figure B-1. The 820 foot flight deck contains markings for landing on nine separate areas. A plan form view of the flight deck is provided in Figure B-2. A description of the V-22 landing area is provided in Figure B-3. There are three 2 square foot boxes painted relative to a geometric landing aid design, commonly referred to as the "Crows Foot". The crows' foot provides line up markings for the approach with a line extending from the center outward at a 45 degree angle relative to the ships centerline. There is an "Athwart ships" line, which runs perpendicular to the ships course, used by pilots to judge longitudinal line-up distances from the spots. Finally there is also the lateral deviation line, which is parallel to the ships centerline used to estimate distance laterally from the landing spots.

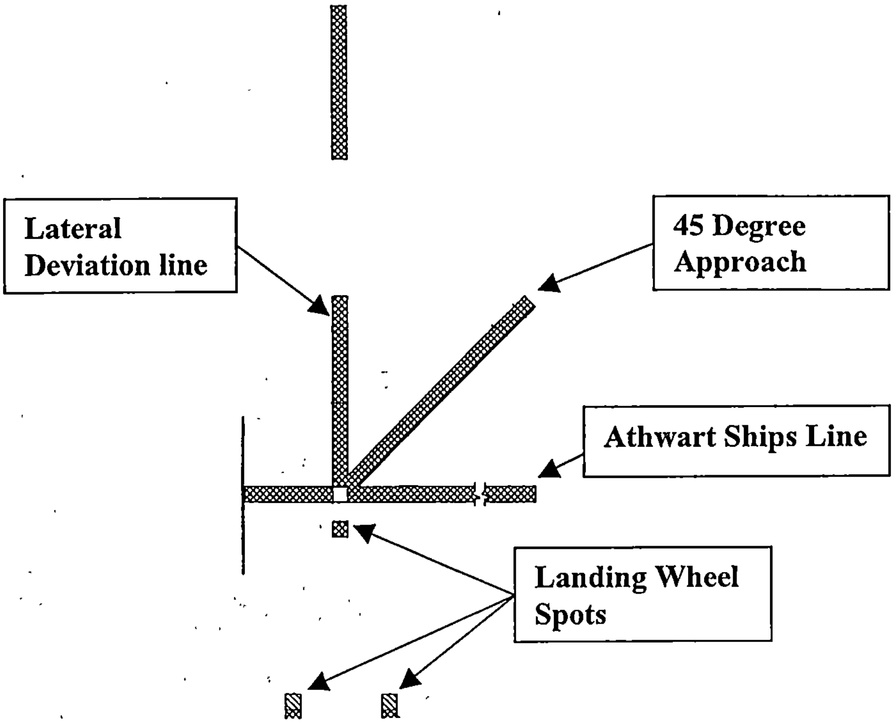
Landing Pattern

The V-22 landing pattern was modeled after current operational helicopters, which operate on the LHA. Figure B-4 describes the V-22 pattern in detail and illustrates the entry profile as well as the recovery patterns for various landing areas on the left side of the ship.

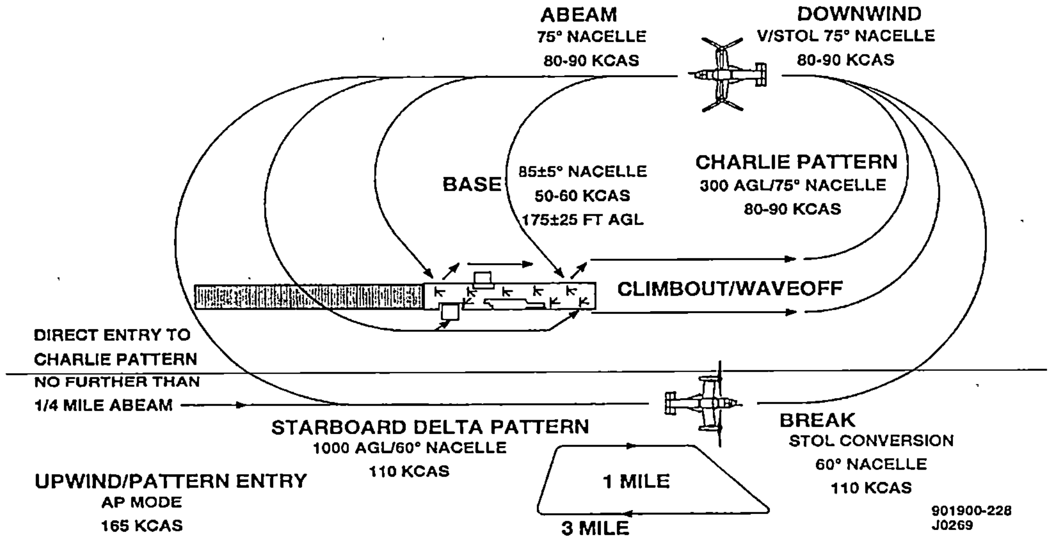
USS Saipan LHA-2
Figure B-1



Plan Form View of Flight Deck
Figure B-2



V-22 Landing Area and Spots
Figure B-3



LHA/LHD Launch and Recovery Pattern
Figure B-4

Shipboard Taxi

Shipboard self taxi may be utilized for flight operations with the following exceptions: 1) The aircraft shall not be taxied while the ship is in a turn, and 2) backwards taxi shall not be conducted shipboard.

Taxiing aboard ship must be conducted under the positive control of the aircraft director. Any signal from the aircraft director above the waist is intended for the pilot and any signal below the waist is intended for deck handling personnel. The aircraft director signals shall be followed explicitly with large immediate directional pedal inputs when directed.

When taxiing aboard ship, nacelle angle shall not be modulated to control aircraft speed, due to the deck motion. Instead, a combination of setting a nacelle angle and modulation of brake pressure is used to control speed.

Prior to removal of chocks and chains, the aircraft shall have both engines operating, AFCS on, and be flight ready with takeoff and lineup checks complete. Pilots shall monitor land/launch frequency during taxi. Personnel with chocks and chains shall be readily available during aircraft taxi. These personnel shall remain far enough away from the aircraft to allow for immediate takeoff. However, upon signal from the LSE they will be prepared to immediately install chocks and chains.

After taxi is complete, the pilot shall center the nose gear. The aircraft director shall signal the pilot that the nose gear is centered, before chocks and chains are installed.

1. Brakes – Apply and hold
2. Nacelles – 80°

When directed by LSE:

3. Brakes – Release

Note: If the aircraft comes to a stop (or rolls backwards) due to ship motion, do not increase power or lower nacelles to continue taxi motion. Apply brakes and hold until the ship motion allows the aircraft to roll forward again. Release brakes and continue to taxi.

4. Use aircraft brakes to control speed
5. LSE turn signals – Follow with large and immediate pedal input

When taxi complete:

6. Brakes – Apply
7. Nosewheel – Center.

Shipboard STO

The recommended configuration for shipboard STO is 70° nacelle, nosewheel centered and unlocked, and brakes held until just prior to a smooth application of full TCL in 2 to 3 seconds.

1. Takeoff checks – Complete prior to taxi

After taxi:

2. NOSE LOCK – Momentarily ON, then off

Note: Momentarily selecting NOSE LOCK will ensure that the nosewheel is centered.

After LSE signals nosewheel centered:

3. PWR STEER – Off
4. Nacelles - 70°
After LSE performs final checks (flaps, nacelles, leaks, etc…), give thumbs-up/salute, moves clear of aircraft:
5. Takeoff checklist – Verify complete
6. Cyclic – Verify near longitudinal center
7. LSE – Ensure final thumbs-up
8 Brakes – Release
Note: Time brake release to occure on upward motion of ship's deck.
9. TCL – Smoothly apply maximum power (target full application in 2 to 3 seconds)
At liftoff:
10. Attitude – 3-5° nose up
Passing 200 ft:
11. Nacelles - 75°
12. After takeoff checks – Complete.

Shipboard Landing OEI

All approaches will be made to a no-hover landing on an aft spot.
1. Request course and speed from ship for best possible wind over deck
2. FUEL DUMP – As required
3. Landing Checklist – Complete
4. Parking Brake – Off
5. Airspeed – Maintain ≥ 80KCAS until landing assured
On final:
6. Attitude – 2 to 3° nose up
7. Airspeed – 25 to 30 KCAS until over the deck
Crossing the deck edge:
8. Nacelles – 85 to 90° to slow rate of closure
9. Airspeed – Decrease to slowest controllable
10. Nacelle/cyclic – As required to decelerate just prior to touchdown
11. TCL – As required to cushion touchdown
12. Wheel brakes – Apply to minimize deck roll.

Appendix C

FLIGHT TEST METHODS
Handling Quality Task Definitions and Tolerances

Task tolerances are provided for each task definition below. In some cases, the methods to measure task tolerances are readily available (i.e. aircraft parameters displayed on the MFD, refueling boom alignment to ship markings, etc.). Tolerances that are not uniquely measured and requiring "pilot calibration" (i.e. x-y position over the spot) will be assessed during land based FCLPs. The cues (for each seat position) used by the pilots to verify that these tolerances are met, will be documented for future reference (with the understanding that these cues may be pilot specific). Though there are multiple task tolerances assigned for each task definition, there will only be one HQR given for each event with the understanding that the HQR will reflect the worst subtask (i.e., the one producing the highest rating).

Ship Vertical Takeoff (Launch)

- From the ship deck perform a vertical takeoff maintaining the listed tolerances.

Vertical Takeoff Tolerances
Table C-1

Parameter	Desired tolerances	Adequate tolerances
pitch attitude	0° ≤ θ ≤ 5°	0° ≤ θ ≤ 8°
x position (over the spot)	± 3 ft	± 4 ft
y position (over the spot)	± 2 ft	± 3 ft
aircraft/ship alignment	± 2 deg	± 5 deg

Steady State Hover

- Establish a steady (~ 10 sec) ~15 ft hover over the spot maintaining the listed tolerances.

- The purpose of this condition is to collect control margin data.

Hover Tolerances
Table C-2

Parameter	Desired tolerances	Adequate tolerances
pitch attitude	-3° ≤ θ ≤ 5°	-3° ≤ θ ≤ 8°
x position (over the spot)	± 3 ft	± 4 ft

y position (over the spot)	± 2 ft	± 3 ft
aircraft/ship alignment	± 2 deg	± 5 deg

Ship Departure

- Depart from the hover with a lateral translation and forward acceleration maintaining the listed tolerances.

Departure Tolerances
Table C-3

Parameter	Desired tolerances	Adequate tolerances
pitch attitude	$-3^\circ \le \theta \le 5^\circ$	$-3^\circ \le \theta \le 8^\circ$
climb angle/rate	≥ 500 fpm	≥ 0 fpm

Approaches (Recoveries)
Ship Case I Approach

- On a left downwind, abeam: 300 ft altitude, 80 kts, 80 ±5 deg nacelle
- Turn left on to 45 deg bearing to the cleared spot #: 175 ft altitude, 50-65 kts, nacelle as required.
- Acquire alignment with ship, descend and decelerate maintaining consistent closure.
- Perform pedal turn as appropriate based on wind conditions and transition to a ~15 ft hover (not necessarily steady) over the spot prior to landing.
- Note: The technique to minimize the effects of pitch up with sideslip is to pedal turn early in the approach (40-50 kts) for port winds. Adjust heading as required, not necessarily parallel to the ship nor aligned with the 45 degree lineup line. For starboard winds, the technique is to pedal turn crossing the deck at the lowest airspeed practical.

Approach Tolerances
Table C-4

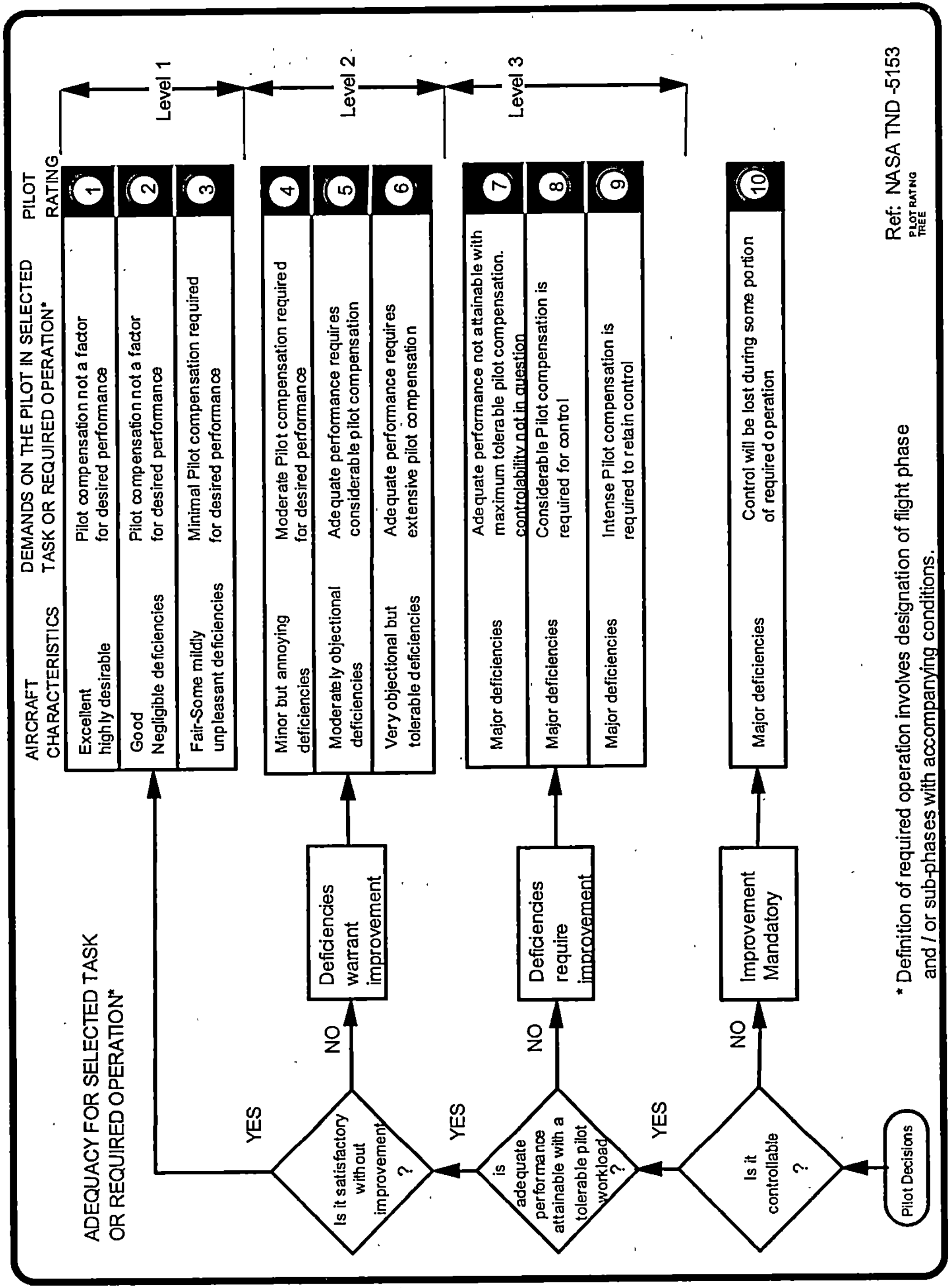
Parameter	Desired tolerances	Adequate tolerances
4° glide slope	± 1 deg	± 2 deg
45° Bearing	± 5 deg	± 10 deg
pitch attitude	$0^\circ \le \theta \le 7^\circ$	$0^\circ \le \theta \le 10^\circ$

Ship Landing (Recovery)

- From a 15 ft hover (not necessarily steady) over the spot, perform a vertical descent and land using the below tolerances.

Landing Tolerances
Table C-5

Parameter	Desired tolerances	Adequate tolerances
pitch attitude	$0° \leq \theta \leq 5°$	$0° \leq \theta \leq 8°$
x position (over the spot)	± 3 ft	± 4 ft
y position (over the spot)	± 2 ft	± 3 ft



Cooper Harper Rating Scale
Figure C-1

Procedure for Data Recording

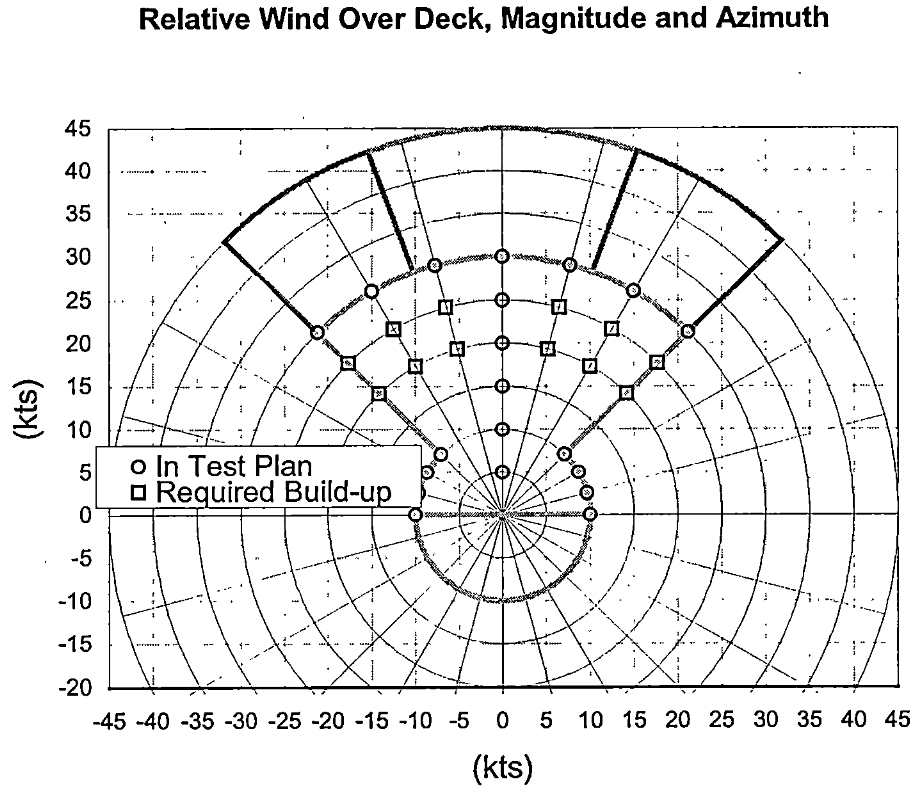
Launch/Recoveries

- One continuous record for the approach and landing is requested. The record is to start approximately when the aircraft is no slower than 60 KCAS.
    - While on the deck after each recovery, it is request the pilots provide a recovery PRS, approach HQR, landing HQR, and comments.
    - Prime data recording should be started prior to power application for takeoff, run continuously through the hover and ending when established on the climbout.
    - While on the downwind leg of the landing pattern, it is request the pilots provide a launch PRS, takeoff HQR, departure HQR, and comments. (Not to interfere with flight duties)

Priority 1 Data Points, Supplement to Test Plan

Description of Points

Conditions listed in the Test Plan are intended to be points that bound the launch and recovery envelope. However, the first sea trials period highlighted a "trouble area" with respect to the "Pitch Up with Sideslip" phenomenon. This area needs to be investigated using more specific build-up than that described in the test plan. Instead of holding RWOD speed constant and progressing out in azimuth (i.e. 0° → 15° → 30° → 45° azimuth) progressing from lower to higher RWOD speed at a given azimuth is the preferred order of build-up. See Figure C-2.



PUWSS Relative WOD Build-Up
Figure C-2

Waveoff Criteria

In addition to all other waveoff calls associated shipboard Dynamic Interface testing, the pilot shall waveoff for any of the following conditions during the landing phase of a recovery:

1) Within 1 cycle of recognizing divergent control inputs and/or noticeable phase shift between control inputs and aircraft response (i.e. divergent PIO).
2) On the longitudinal or lateral stick control stop.
3) TM calls "Knock It Off".
    - a) divergent control inputs and/or aircraft response
    - b) on the lateral or longitudinal control stop
    - c) sustained moderate amplitude lateral stick and/or roll oscillations (i.e. 3-4 cycles of a neutrally stable oscillation)

d) bank angle greater than ±10 deg.

e) roll rate greater than ±20 deg/sec

f) engineering judgment based on monitoring of other FCS parameters
Note: The TM "Knock It Off" criteria may be modified during sea trails as required.

VITA

Christopher C. Seymour was born in Houston, Texas on August 11 1964. He grew up in Lafayette Louisiana and graduated from Lafayette High School in 1982. In 1988 he received a Bachelor of Science degree in Mechanical Engineering from the University of Louisiana and was commissioned as a Second Lieutenant in the United States Marine Corps. After completing The Basic School in Quantico VA he entered Naval flight training in Pensacola Florida. He was designated an Unrestricted Naval Aviator in December 1990 and began training in the CH-46E Sea Knight in Tustin California. Major Seymour was assigned to HMM-164 "Knightriders" and deployed with the 11th and 15th Marine Expeditionary Units to the western pacific in Desert Storm and Operation Restore Hope Somalia. He has held billets in operations as the Weapons Tactics Instructor and various maintenance officer positions.

Major Seymour graduated from the United States Navy Test Pilot School in 1996 and was assigned to the MV-22 Integrated Test Team. He has participated in various projects while serving as a test pilot including the JPATS T-6 trainer, V-22 Sea Trials and Performance and Flying qualities. Major Seymour was awarded the Naval "Test Pilot of the Year" in 1999 for work on the V-22 program.

Major Seymour is currently assigned as an Operational Test Director for HMX-1 on the CV-22 test team at Edwards Air Force Base CA. He has over 3200 flight hours in over 45 different aircraft, including the XV-15, MV-22 and CV-22.