V-22 FLIGHT TEST UPDATE

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<u>Abstract</u>

The Bell-Boeing V-22 Osprey Tiltrotor is a unique aircraft capable of landing vertically like a helicopter, flying at speeds in excess of 300 KTAS (Knots, True Air Speed) like a turboprop, with the added feature of folding the rotor and wing for deployment from shipboard for U.S. Navy, Marines, and SOF operations. During the development of the V-22 and the 1000 hours of flight testing, many technology and design development problems were encountered and overcome. This paper presents an overview of many of these challenges. It also reviews the integrated approach to testing now being used for the flight test program, and describes the changes that have been implemented to improve flight test productivity in the next phase of the test program.

Introduction

The V-22 tiltrotor is a unique aircraft that can efficiently hover like a conventional helicopter,

and cruise at speeds up to 300 KTAS with the efficiency and comfort of a turboprop airplane. Designed by the Bell-Boeing team for the U.S. Marines, Navy, and Air Force, the V-22 is currently in the Engineering and Manufacturing Development (EMD) stage, during which four production, representative airframes will undergo development and qualification testing. While one Full Scale Development (FSD) aircraft is completing risk reduction flight testing and pilot training at Patuxent River, Maryland, the first EMD aircraft is in preparation for first flight, having completed point load calibrations and ground vibration testing in Fort Worth, Texas, and is scheduled to fly in late 1996. After initial envelope development, each aircraft will ferry to Patuxent River for development and demonstration testing which culminates in an Operational Evaluation (OPEVAL) in 1999. The program plan for the overall development program is shown in Figure 1.

The V-22 obtains its unique capabilities through its engine and rotor nacelle motion, specially designed high twist rotors (47.5 degrees twist),

Flight Test Overview



Figure 1.

and reconfigurable fly-by-wire (FBW) flight control system (Figure 2). In the Vertical Take Off and Landing (VTOL) mode, the tiltrotor is controlled much like a helicopter, using rotor cyclic and collective forces for longitudinal and lateral control. In airplane mode, rotor controls are phased out except for use as trim devices, and standard airplane control surfaces are used to control the aircraft. In transition or Short Take Off and Landing (STOL) mode (between VTOL and airplane modes), a combination of rotor and airframe forces are used to provide control. Some of the notable design features of the V-22 are shown below.

38-foot diameter rotors.

- 6150 SHP engines installed in nacelles on each wing tip.
- Nacelle tilt from 95 to 0 degrees.
- Sized primarily by requirements for shipboard compatibility and spotting on the flight and hanger decks of a LPH, LHA or LHD.

- A triply redundant FBW flight control system which facilitates the phasing and scheduling of the flight controls and allows for complex control law scheduling as a function of a variety of parameters including nacelle angle and airspeed.
- Seating for 24 combat troops.
- External cargo up to 15,000 pounds.
- Loading/unloading internal cargo through an aft ramp.
- Folding of the rotor blades and wing for stowage aboard ship.
- Adverse weather instrument flight capability, day or night.
- Continuous operation in moderate icing conditions.
- Self-deployment capability.
- Structure of a combination of machined aluminum, fiber placed graphite, and titanium.



The FSD aircraft have completed over 1100 flight-hours during the politically troubled life of the program. The FSD test program has resulted in the collection of a significant amount of data on aircraft characteristics. References 1 through 13 describe the early flight test findings, and since 1992, the principal focus of flight testing has been to support the EMD effort by testing areas that significantly impact the EMD design

The Flight Test Program

Background

The Tiltrotor program has its genesis in the highly successful XV-15 Tiltrotor program conducted by Bell Helicopter, NASA, and the Army beginning in the 1970's. A series of studies conducted between 1981 and 1983, confirmed the feasibility of a full scale tiltrotor aircraft for a number of military missions, as well as the potential for civil applications. A Joint Services Vertical Lift Aircraft program was established for a notional JVX aircraft, which was eventually redesignated as the V-22 Osprey. Preliminary Design contracts were issued to Bell-Boeing beginning in 1983, leading up to the FSD contract, which was awarded to Bell-Boeing in 1986.

First flight of Aircraft 1 was on March 19, 1989, and over the ensuing three years, Aircraft 2, 3, 4, and 5 were introduced to the program. A total of 757 flight-hours were completed for envelope, systems and aircraft development. Although six aircraft were manufactured, final assembly and wing mating was suspended on Aircraft 6 due to program requirements, cost and schedule. On June 11, 1991, Aircraft 5 crashed on its maiden flight at Wilmington, Delaware; although the crew escaped without serious injury, the aircraft was destroyed. The cause-- miswiring of redundant roll rate sensors--was not considered to be a tiltrotorunique factor.

On July 20, 1992, Aircraft 4 crashed into the Potomac River in the vicinity of Marine Corps Base Quantico, Virginia, its intended destination, at the end of a ferry flight from Eglin Air Force Base, Florida. Tragically, the crew was lost and, the aircraft destroyed.

Extensive investigations indicated there were no cause factors attributable to the fundamentals of tiltrotor design. The investigations did, however, lead to safety enhancements which were incorporated in the remaining FSD aircraft (Aircraft 2 and 3) and the EMD design, as well as the Integrated Test Team (ITT) operating procedures. The analysis that led to the design enhancements had application beyond the mishap area in that the safety enhancements were incorporated in the wing and midwing as well as in the nacelles. In October, 1992, the FSD contract was terminated and a new EMD program was structured for two phases: the risk reduction phase using FSD Aircraft 2 and 3, and the EMD flight test phase which will use four new EMD aircraft. The EMD aircraft incorporate numerous design improvements for reliability, weight reduction, and reduced cost, as well as from the lessons learned in FSD and EMD risk reduction testing.

A V-22 EMD/LRIP (Long Range Initial Production) Program Schedule is shown in Figure 3).



Figure 3. V-22 EMD/LRIP Program Schedule

The Current Program

Signing the EMD contract marked the beginning of the current program phase and a new approach to V-22 flight test development. Prior to EMD, envelope expansion had been conducted at Arlington, Texas, with Aircraft 1 and 3, while Aircraft 2 and 4 were based primarily at Wilmington, Delaware. At various times, testing for Electro Magnetic Variations (EMV), Flight Control System (FCS), Downwash, Sea Trials, Propulsion, and government Demonstration Testing (DT) were conducted at the Naval Air Warfare Center-Aircraft Division (NAWCAD), Patuxent River, Maryland, and at the Climatic Lab, Eglin Air Force Base, Florida. The EMD flight test contract specified:

- Formation of an Integrated Test Team (ITT) of Bell-Boeing-NAWCAD-Naval Air Systems Command (NAVAIR);
- Working together at a single principal test site at NAWCAD, Patuxent River;
- Risk Reduction testing of two FSD aircraft and demonstration testing of four new EMD configured V-22's.

Significant Flight Test Issues

Risk Reduction

The risk reduction phase included investigative flight tests such as flight loads, envelope expansion, aeroservoelastics, high angle-ofattack, icing, high altitude hover performance, FCS and avionics development.

Since 1993, the V-22 has been in a "risk reduction" flight test phase that directly supports ongoing design efforts for the EMD contract. Two of the FSD aircraft have completed an additional 343 flight-hours in this flight test phase. Aircraft 2 was used for Primary Flight Control System (PFCS) and Automatic Flight Control System (AFCS) optimization, IPS development, Operational Test (OT) assessments, hover performance testing, and demonstration flights. Aircraft 3 was primarily used for envelope expansion, aeroservoelastics tests, high-angle-ofattack investigations, external loads testing, downwash evaluation, and preliminary autorotation characterization.

Integrated Testing

The V-22 Integrated Test Team was a new concept. It integrates contractor and government test activities in order to reap the benefits of greater efficiencies in cost and schedule. This concept provides an early and continuous government evaluation of the aircraft and aircraft systems, as related to specification and mission performance requirements. Integrated testing has demonstrated financial, schedule, and performance benefits by reducing the requirement for dedicated government testing. Traditionally, flight testing consisted of a detailed contractor development program before it was turned over to the Navy testers, who have historically gathered much of the same data at their own facility with a view toward validating the contractor's data and providing a flight release for operational testing. The goal of the ITT was to avoid this duplication by defining joint test requirements and conducting both development and demonstration testing as an integrated team.

Since the commencement of EMD, all flight testing on the V-22 has been based at the Navy's flight test facility at Patuxent River, Maryland. The contractor and the government have merged their flight test personnel into one team which plans and conducts the flight testing as a single entity. The government's ITT representatives include pilots, aircrew, engineers, and test specialists from the Navy, Marine Corps, Air Force, NAVAIR and OT pilots. While testing and maintenance on the aircraft is still a contractor's responsibility, developmental testing is supported by a mixed crew of government and contractor personnel. Only operational flight tests are flown by an all military aircrew.

Envelope Expansion

Envelope expansion for a military transport tiltrotor aircraft is a protracted affair for several reasons. First, beyond the normal altitude, gross weight and Center of Gravity (CG) variables, there are three fundamental configurations to explore; VTOL, conversion, and airplane modes. Within conversion and VTOL modes, there are a number of nacelle angle configurations to evaluate. The airplane and rotorcraft specification requirements of MIL-8800 series and AR-56 collectively add to the range of required testing. The novelty of the design, in propulsion and rotor systems, structure, and unusual inertial characteristics of the mass distribution, all combine to considerably open the scope of testing.

The complexity of the V-22, while providing its unique versatility, results in a high degree of interaction between areas often treated more independently when testing other types of aircraft.

The following are some of the key envelope expansion points reached to date:

- 349 KTAS (308 KCAS) max speed dive; 294 KTAS (240 KCAS) -level flight (VH) at 18,000 ft
- +3.4 g at 290 KCAS
- 21,500 ft max altitude
- 51,500 lbs gross weight
- CG's from 390 to 406 in
- 4,000 lbs external load out to 175 KTAS

During FSD and risk reduction flight testing, several developmental issues were encountered and resolved. Resolution of many resulted in enhancements to the overall characteristics of the aircraft. Each, however, had unique challenges to the design test team. The following addresses some of these and the techniques used to evaluate them in flight test.

Handling Qualities The multiple control surfaces of the V-22 enable the handling qualities of the aircraft to be tailored for its many flight regimes. The pilot interfaces with the control system through a conventional center stick with pedals and a thrust control lever (TCL). In helicopter mode, control moments are generated by fore/aft longitudinal cyclic pitch (longitudinal stick), a combination of lateral cyclic pitch and differential collective pitch (lateral stick), differential longitudinal cyclic (pedals), and collective pitch (TCL). In airplane mode, control forces are generated by elevator (longitudinal stick), flaperons (lateral stick), rudders (pedals), and power (TCL).

The Primary Flight Control System (PFCS) provides the flight critical functionality of the unaugmented control system. The AFCS enhances the Handling Qualities through forward loop control shaping, increased damping, and automatic hold features. In airplane mode, an angle-ofattack command system will be provided. Unlike a conventional helicopter, the V-22 pilot commands engine power, not collective pitch and the rotor speed governor modulates collective pitch to maintain RPM.

Substantial progress has been made in the past four years in achieving the Detail Specification requirement of Level 1 Handling Qualities throughout the envelope with the AFCS augmented Flight Control System, and for at least Level 2 handling qualities in degraded modes with only the PFCS operating. Incremental introduction of the AFCS to all areas of the flight envelope, which was initially restricted until protection against hardovers and other failure modes was confirmed, has appreciably improved overall pilot opinion of the V-22 (Figure 4). In general, the V-22 is reported to be a well-behaved aircraft and a pleasure to fly throughout the flight envelope.

VTOL Mode Of the three flight modes, VTOL is the most dramatically improved, particularly in the precision hover task in-ground-effect and its related vertical takeoff and landing tasks. Desired performance of these essential, fundamental tasks are critical to the Marine Corps mission which requires the aircraft to land and launch from a ship, hook up to external loads, and effectively work in confined landing zones. Although it has been consistently assessed by most

V-22 pilots as easy to hover at and above 30 ft., early FCS software was characterized by high workload, particularly in the lateral, and vertical axes.

During the early stages of FCS development, lateral control was implemented essentially through differential thrust between the rotors, and was highly susceptible to PIO and resultant overtorque of the proprotor gearboxes. Lateral control laws for Lateral Swashplate Gearing (LSG) which combines cyclic flapping with



differential thrust, and some additional enhancement of forward loop shaping was incorporated. This has greatly reduced lateral PIO tendencies, as well as noticeably improving lateral precision.

The vertical axis improvements were achieved by augmenting vertical damping using control law vertical velocity feedback, commonly referred to as "h-dot" damping. The net effect in low hover (30 ft. and below) has been to noticeably reduce the previously incessant and often times out-ofphase TCL corrections needed to hold hover height. Efforts in TCL were sometimes preoccupying to the point of neglecting desired control in pitch and roll. Another benefit was improved touchdown predictability in vertical landings - pilots no longer have to concentrate on "feeling for the deck" all the way to touchdown, and can apportion appropriate attention to pitch and roll control, and get noticeably better touchdown dispersions as a result.

One of the more significant improvements in handling qualities was due to the addition of Torque Command Limiting System (TCLS). This feature was added to the flight control system primarily to limit rotor torque and to improve TCL sensitivity. In addition to providing these capabilities, TCLS also improved Handling Qualities by allowing large rapid control inputs to be made without inducing significant over torques. Improved Handling Qualities Ratings (HQR) were achieved during hover height control in that the pilot workload was decreased by removing concern over monitoring rotor torque and rpm. It also brought the pilots scan "out of the cockpit" by removing the requirement to monitor cockpit gauges.

Conversion Mode Clearly the signature capability of the Osprey lies in the simplicity of the conversion maneuver to airplane mode and the reconversion maneuver back to VTOL or helicopter mode. Conversion represents an added control axis compared to conventional helicopters or fixed wing aircraft. The convention for referencing rotor and engine nacelle angle defines various flight mode configurations. Zero degrees is at the horizontal, or airplane mode. Above zero, through 75 degrees, is considered Conversion Mode, through which varying ratios of rotor and wing lift support flight. From 76 degrees through the vertical at 90 degrees to the aft limit at 97.5 degrees is referred to as VTOL or helicopter mode where essential lift is provided by the rotor.

Vertical takeoffs and landings in VTOL mode can be accomplished up to gross weights of approximately 50,000 lbs (limited to 47,500 lbs for typical flight test sorties) with the option for higher gross weight short (rolling) takeoffs, or STO's, in conversion mode with nacelles at 60 degrees. Landings at high gross weights can be accomplished in VTOL mode with nacelles at 85 degrees or higher.

Task tolerances and derivative workloads during conversions are largely affected by two factors: first, the conversion or reconversion rate which is modulated by the pilot at anywhere from zero to 8°/sec, and secondly, whether these maneuvers are as constant altitude tasks, in a climb (the typical conversion case), or a descent (the typical reconversion case). The exercise in thrust lever, nacelle beep, and pitch axis coordination is considerably more relaxed in the latter cases. The introduction of the AFCS autoflaps feature, described below, has helped make this an easier task.

Airplane Mode Handling qualities in airplane mode cruise flight have been evaluated extensively during a number of long range ferry flights to and from remote test sites as well as in both classical and derived dedicated handling qualities assessment flights. The autoflaps feature which is so desirable in conversion mode initially degraded airplane mode handling qualities. The autoflaps control laws are activated as a function of airspeed. This feature was found to degrade trimablilty and to a lesser degree, airspeed control. In this configuration, the aircraft exhibits slightly negative static longitudinal stability. This condition is not present with 10 degrees fixed flaps. Optimization of the autoflaps airspeed schedule is expected to retain desirable longitudinal handling qualities for the EMD aircraft, while providing the "select and forget" benefit intended for autoflaps that is extremely helpful when transitioning to and from airplane mode.

Level 1 Handling Qualities were achieved when flying behind the KC-135 icing tanker. Pilots were able to hold precise position in close proximity to the tanker for long periods of time (20 to 30 min intervals) which were needed to precisely apply icing spray to selected parts of the airframe and rotors. Handling qualities here, and similar experiences with the KC-130, bode well for successful aerial refueling operations in the future with both types of tankers, and for the overall operational potential of the V-22.

Aeroservoelastics_Because of the size and unusual mass distribution of the V-22, (i.e., engine and transmission located in nacelles at the wing tips) airframe flexibility played a key role in development of the overall Handling Qualities. This drove the initial requirement for numerous notch and low-pass filters throughout the flight control system. The filters were carefully designed to attenuate undesirable coupling without imposing degrading phase delays in the pilot or feedback control paths. Pilot models were developed through ground shake test and in-flight Pilot Assisted Oscillations (PAO). The result has been a successful demonstration of required phase and gain margins throughout the flight envelope.

Some significant control system airframe coupling issues were identified early in the initial envelope expansion flight testing. All occurrences involved a destabilizing pilot/control stick feedback loop, which was the principal cause of the oscillation.

One flight control system airframe coupling occurred during airplane mode envelope expansion

at 250 KCAS. An uncommanded, unstable lateral oscillation at approximately 3.0 Hz occurred due to the pilot coupling with the asymmetric wing chord bending natural frequency through the lateral stick. It was found that the lateral motion caused from the vertical fin was the source of the excitation. Once the physics of the oscillation were understood, a notch filter was incorporated in the lateral control axis to reduce the pilots' gain at that frequency.

Another involved pilot bio-mechanical couplingagain in airplane mode with the symmetrical wing chord (SWC) mode. In this instance, pilot coupling occurred through Thrust Control Lever (TCL) motion due to fore and aft acceleration of the cockpit resulting in a significant destabilizing trend above 250 KCAS. A notch filter was added to correct the coupling.

Structural Loads Limiting The rotor of the V-22 represents a compromise between hover performance requirements, cruise efficiency, and shipboard compatibility needs. The fuselage and empennage structure is designed by stiffness and strength margins to eliminate unnecessary weight while providing required strength for a 4g flight envelope and hard shipboard landings. To minimize design loads in the rotor, drive system and the fuselage, structural loads limiting functionality were designed into the flight control system. The following are some of the SLL features:

Rotor Loads Limiting. Airplane Mode The rotors of the V-22 are susceptible to high in-plane loads during aggressive longitudinal or wind-up-turn maneuvers with high pitch rates. The SLL control laws minimize these loads by making commanded rates and accelerations discretely accessible while still providing adequate control power for 4g maneuvers. This system is implemented in a "passive" manner using feed forward limiting and existing feedback paths optimized for loads limiting functions while maintaining Level 1 handling qualities. Risk reduction Flight testing of the SLL system has demonstrated the improvement.

Rotor Loads Limiting, Helicopter Mode During maneuvering in helicopter and conversion modes, large rotor flapping excursions can result in reduced life of rotor elastomeric bearings. To extend the life of these components, a Longitudinal Flapping Limiter (LFL) was designed using the elevator to "re-trim" the aircraft during maneuvers. The control laws reduce rotor flapping by rotating the fuselage relative to the rotor using the moments generated by the elevator and increase rotor component life over a large nacelle/airspeed maneuver envelope.

Drive Shaft Loads Limiting, Airplane Mode

The two rotors are connected via an interconnect drive shaft (ICDS) so that in the event of an engine loss, both rotors receive power from the remaining engine.

In airplane mode with both engines operating, torque differences between the two rotors in maneuvers causes high oscillatory loads within the ICDS, reducing component life. The control laws were designed to balance the torque in the rotors using differential collective pitch (DCP). Roll rate capability was greatly enhanced by this segment of the control laws and also provided enhanced turn coordination.

Drive Shaft Loads Limiting, Helicopter Mode

Torque splits in helicopter mode, generated by DCP, inputs also generate ICDS loading. DCP however, forms the primary roll control force, posing a challenging resolution. To minimize ICDS loading while improving the lateral axis Handling Qualities- which are influenced by the large roll inertia of the V-22- Lateral Swashplate Gearing (LSG) was added to the control laws. LSG uses differential lateral cyclic from the rotors which provides both a rolling moment and a direct sideforce. The addition of LSG, allowed DCP to be reduced to the degree required to maintain control sensitivity. Pilot opinion of the hybrid lateral control scheme was overwhelmingly positive. Precision lateral control, especially in very low speed flight, was enhanced by the direct sideforce generated by LSG. ICDS loads, which result from large lateral inputs, were reduced as the LSG input does not produce a loading through the cross shaft.

Conversion Protection Pilots typically convert manually through the center of the conversion corridor by maintaining a level fuselage attitude. However, in the event of an inadvertent conversion outside the "normal" corridor, a conversion protection system is programmed into the Primary Flight Control System (PFCS) to regulate nacelle movement which is dependent on the desired conversion direction. The conversion protection feature allows maximum conversion, or reconversion rate, without concern for stalling or reaching loads or control limits (Fig 5).



The high speed conversion corridor is essentially a loads boundary for the nacelle conversion actuators, nacelle-wing interface and proprotor dynamic components. The low speed conversion boundary was established to avoid wing stall while accelerating during conversions. This corridor provides a broad airspeed band for each nacelle setting so there are no special requirements associated with staying within these bounds. During conversion acceleration, FCS software prevents the nacelles from converting below the low speed boundary and automatically positions the nacelles forward when incursion into the high speed boundary occurs. During re-conversion, the software also prevents nacelle rotation from airplane mode until below 200 KCAS.

Risk Reduction Testing

The decision to conduct risk reduction testing on Aircraft 2 and 3 as the EMD aircraft design progressed, proved beneficial to cost and risk. As risk reduction testing progressed a number of significant technical and design anomalies were encountered which have all been resolved for the EMD design.

The objectives of the risk reduction test program were five fold:

- 1) To complete an evaluation of as much of the full EMD design envelope as possible, within the constraints of the FSD configuration.
- 2) To validate the V-22 simulation math model in support of the EMD flight test program.
- 3) To identify critical test conditions for EMD qualification.

- Where possible, to conduct development testing to offset test program requirements for the EMD aircraft.
- 5) To reduce EMD schedule and technical risk.

Table 1 describes some of the most significant risk reduction lessons learned and corrections made for EMD. Four significant risk reduction lessons learned have been selected for a more detailed discussion: empennage buffet, hover performance, icing, and downwash evaluations.

EMD Resolution
 Redesigned landing gear to
increase distance between
forward and aft landing
gear
 Install dual direction
hydraulic powered
actuators
 Increased load carrying
capability of EMD
actuators
 Incorporate Torque
Command Limiting system
 Improved AFCS damping
and control power
characteristics
 Added Fuselage Strake
 Added OLC, extended
flaps to 75°, closed IRS exit
to 750 in², removed aileron
motion in hover
 Procedure definition
 Improved IPS
performance

Table 1. - FSD Lessons Learned

Empennage Buffet

During envelope expansion testing in FSD, large oscillatory loads were observed on the H-tail and aft fuselage. The high loads were generated in wind-up turns at moderate speeds (Mach No. = 0.32). Tail buffet occurred at angles of attack significantly lower than predicted stall angles. The definition, analysis, design, and testing of a fix for this problem was a classic example of the need for risk reduction testing on the FSD aircraft. Without it, this significant problem would have been found in EMD envelope expansion, causing significant scheduling miseries. The integrated approach to solving the problem established between the ITT, the integrated product teams from both companies , and the technical experts from NAVAIR was instrumental in finding a solution which was both cost and weight efficient. A series of flight tests, water tunnel tests, and wind tunnel tests was conducted to determine the source of the problem. The subsonic wind tunnel

test showed the source of the buffet to be wing stall, emanating from the inboard wing section and the overwing fairing.

Having found the source of the buffet, the focus of testing shifted to finding an aerodynamic solution to eliminate, reduce, or delay buffet onset. Various aerodynamic modifications were attempted including:

- Gurney flaps on the wing
- Symmetric differential inboard/outboard flaps
- Wing root trailing edge extensions
- Conical Sponson Strakes
- Forebody Strakes



Figure 6.

The wind tunnel tests showed the forebody strake configuration (Fig 6) to be the most promising in generating a vortex which added energy to the flow over the mid-wing fairing area, thus keeping it attached. The strake delayed buffet threshold onset by about 5 degrees in angle-of-attack. No effect on drag was noted except at the stall boundary where overall drag decreased. The strake also produced improvement in the sideslip effects on buffet.

Having identified a potential solution, the next step was to test the strake on the risk-reduction aircraft. Initial flight test results at low Mach number were very positive with a 6-8 degree increase in the angle-of-attack associated with high buffet loads, (Figure 7). Subsequent testing at higher Mach numbers indicated a less dramatic improvement in buffet angle-of-attack. Further investigation found that the wing leading edge deice boot was malfunctioning, resulting in poor aerodynamic performance of the wing. With the leading edge "smoothed" (de-ice boots operating normally), adequate angles of attack were obtained providing the required maneuverability without incurring buffet loads. Flight control system control laws have been modified to incorporate angle-of-attack limiting algorithms which provide additional protection against inadvertent encounters with tail buffet.



Hover Performance

In order to meet the wide variety of intended missions, the V-22 requires adequate hover performance margins. As a result, a large effort was devoted to understanding and optimizing the contributing factors to hover performance.

Solidity ratio, rotor blade airfoil design, rotor radius, and number of blades are some of the design parameters that influence hover performance for conventional helicopters. In addition to these, rotor wake download and jet thrust are significant contributors to the hover performance of tiltrotors.

Early analysis and testing showed that rotor wake impingement on the wing caused a large download (Figure 8). In addition to the normal download on



the wing, a portion of the impinging downwash travels spanwise inboard until it meets the flow from the opposite rotor. The flow rises up in a fountain motion and is reingested by the rotors. This phenomenon, known as the "fountain effect," is responsible for reducing rotor thrust. The V-22 experiences a 10.1% loss of lifting capability due to download. Since a percentage point reduction in download results in a corresponding, 500 pound increase in lift, a thorough understanding of download was essential to meeting the hover performance requirements. Tilting of the rotors inboard-referred to as "opposed lateral cyclic" (OLC) was one approach used to reduce download. This reduced the thrust loss associated with the fountain affect and provided an increase in lift capability.

Initial hover performance testing was accomplished at sea level at Boeing Helicopter's Flight Research Center in Wilmington, Delaware with the V-22 tethered and in free air . Tethering allowed for testing at higher coefficient thrusts (CT) than was attainable in free air hover. Objectives included evaluating the effects of OLC, flaperon position, infrafed suppressor (IRS) exhaust area, and rotor speed on hover performance. OLC was varied from 0 to 5 degrees, flaperon position from 40 to 64 degrees, IRS exhaust area from 1,000 to 750 square-feet, and rotor speed from 100 to 103.8%. OLC improved hover performance by 450 pounds. The other items combined to give an additional improvement of 50 pounds.

Although the initial Hover Performance testing validated the devices used to improve hover performance, the referred rotor horsepower, necessary to meet the various Marine Corps missions was not achievable at Wilmington due to its low density altitude. Therefore, a subsequent Hover Performance test was conducted in Hot Springs, Virginia during August, 1994, to cover the full range of mission requirements.



Figure 9.

The primary objective of this test was to evaluate the effect of OLC and high referred horsepower's at high density altitude. At the lower referred horsepower's, the data collected at Hot Springs closely matched the data obtained earlier at Wilmington and at Pax River. The Hot Springs data showed that as the referred rotor horsepower increased, the beneficial effect of OLC on hover performance decreased, (Fig 9). However, the performance requirements for the various Marine Corps missions was still achieved. In EMD, OLC will be set at 4 degrees.

Icing Evaluation

The initial Icing Survey flight test program, conducted on the FSD aircraft, was the first step in developing an all weather capability for the V-22. This testing began in the winter of 1993-94, and will continue during the latter part of EMD flight tests on the EMD aircraft in the winter of 1998-99.

Prerequisite ground tests on the engine, engine inlet, proprotor blade, and wind tunnel device tests at NASA Lewis were completed in 1989. Initial lightning and electromagnetic environmental effects testing were completed on the aircraft in Wilmington in 1992. In-flight artificial IPS development testing was completed behind a KC-135 tanker for airplane mode at Patuxent River, Maryland and behind a CH-47D Helicopter Icing Spray System (HISS) for conversion mode at Duluth, Minnesota.

Artificial icing behind the KC-135 concentrated on the left engine inlet for liquid water contents of .25 and .75 gm/m³ at -5° C and -10°C, but also included some testing on cloud centerline to evaluate airspeed angle-of-attack sensor and windshield de-icing and anti-icing performance. The centerline position for windscreen and pitot static air data system cloud immersion was a higher gain task, especially in pitch, than the offset, position which was used for left engine immersion; however, the aircraft was well behaved in all axes behind the KC-135.

Similar comments apply to station keeping behind the HISS, a task flown at 60 degree nacelle and 110 KCAS. The HISS tests concentrated on left proprotor and nacelle immersion for liquid water contents of 0.25 and 0.60 gm/m³ at -5° C and -10° C. Although ambient conditions did not allow testing at the colder temperatures of -15° C and -20° C behind either platform, the IPS generally performed well, although some design changes will be made for EMD and significant progress was made during this testing in its optimization.

For EMD, Instrument Meteorological Conditions (IMC) development will be completed prior to natural icing flight tests. Simulated IMC evaluation will be completed in the Naval Air Warfare Center's Manned Flight Simulator to evaluate the existing cockpit management system (CMS) and to develop V-22 specific IMC procedures. Airborne validation of these procedures will be flown as a prerequisite to natural icing.

Other Flight Testing

Downwash

Downwash, or rotorwash, is a natural by-product of all rotorcraft. The V-22's size and aerodynamic characteristics have been optimized to carry the required mission payloads while providing efficient operation in both hover and high-speed forward flight.

The V-22 disc loading does induce a significant downwash at low hover altitudes, but unlike other heavy helicopters, it is very directional and has allowed procedures to be developed that provide an operationally effective working environment around the aircraft and for insertions and extraction's.

In the sea trials aboard the USS Wasp in 1990, the ship's flight deck crew reported that the downwash from a V-22 was similar to that of helicopters they routinely operated and did not impose any particular problem in carrying out their duties.

Close proximity landing tests were conducted by the Multi-service Operational Test Team (MOTT) to determine the capability of the V-22 to takeoff and land in the vicinity of parked aircraft. The data collected in that test showed that the downwash velocity of the V-22 posed no unusual hazards to nearby equipment or personnel.

In a series of flights dedicated to assessing the effect of downwash on ground support personnel involved in external load hookups, 21 approaches and hook-ups were conducted with a HMMWV utilizing different sling configurations and various approach and hook-up techniques. These tests utilized a fleet Helicopter Support Team under the aircraft for load handling and for aircraft altitude and position directions. The tests confirmed that the V-22 downwash characteristics do not restrict external loads operations and that the support team could safelv and effectively perform their duties under the V-22.

The effect of the V-22's rotor downwash on various rescue and special operations personnel were also evaluated e.g., personnel hoisting, fast rope, over water, and rappelling operations. The tests were conducted using experienced military personnel and results showed that although the V-22's downwash had an effect which was different from that produced by helicopters with which test personnel were more familiar, no conditions were encountered which precluded these operations, particularly if procedures were used that optimized aircraft and ground operations.

Operational Testing

Two operational evaluations were conducted during Risk Reduction testing by the MOTT - OT IIA and OT IIB. A total of almost 30 flight- hours were flown in the two assessments.

The following were demonstrated in OTIIA:

Shipboard operations Confined area landings Simulated in-flight refueling (KC-130) Night operations Over water operations Formation flight

As a result of OTIIA, the V-22 was reported potentially operationally effective and potentially operationally suitable.

OTIIB addressed the following operations:

External loads pick up Fast rope (ramp and cabin doors) Rappelling Rescue hoist Rope ladder SPIE Close proximity to other aircraft

The aircraft was once again reported to be potentially operationally effective and suitable.

Paris Air Show

Although not a part of the formal flight test program, but still a part of providing valuable qualitative data, the V-22 and the XV-15 were demonstrated to the public at last summer's Paris Air Show. Both aircraft functioned flawlessly for six consecutive show days, meeting every scheduled demonstration and static display time. That venue demonstrated the tiltrotor technology and capability to the world and allowed Bell-Boeing to determine the potential international military market and show the tiltrotor for commercial applications. The key to success for this effort:--plan, plan, plan, plan! Detailed, upfront planning was absolutely essential, particularly as the decision to take the aircraft to Paris was not finalized until about four months prior to opening day.

The V-22 operated from no less than five sites during its round trip, each of which required an extensive site survey to U.S. Defense Logistics Agency (DLA) requirements. In addition to taking the aircraft to France, a support team and a full spares package were also transported which had to be positioned strategically at each of the above locations to ensure success.

EMD Flight Test

The EMD flight test program initiates with first flight in December, 1996. A total of 99 flight test months are planned on four test aircraft, distributed as shown in Table 2. As indicated,

EMD Aircraft	Test Purpose	Test Months
7	Envelope Expansion / Aeroelastics / Flight Loads & Vibration Survey / Structural Demonstration	24
8	Vehicle Management Systems (VMS) Development / Flying Qualities / Natural Icing	22
9	Propulsion Demonstration & Survey / System Demonstration	13
10	Avionics Demonstration / Sea Trails	14

* Does not include OT, TECHEVAL and OPEVAL testing. Table 2. - EMD Flight Test

this is an aggressive test program. Without the up-front, FSD/Risk Reduction flight testing and the Integrated Test Team, this schedule would be impossible. To accomplish this schedule, considerable emphasis has been given to pre-test flight planning. The EMD planning effort includes completion of all test plans six months prior to first flight and establishment of a test condition database to aid in test planning and test tracking. Out of the 47 flight test plans and 71 operating procedures completed, 14,000 test conditions have been defined. The test condition database is being used by the Aircraft Flight Test Directors to complete planning for the primary, concurrent, and back-up test activity of each aircraft prior to first flight. With increased aircraft reliability and increased productivity, items incorporated by the ITT during Risk Reduction, flight rate is planned at triple that obtained during all of FSD testing. This is the next challenge for the flight test team.

Concluding Remarks

In summary, over 1,100 hours of flight testing to date have demonstrated the validity of the V-22's design and has also provided invaluable data to V-22 Integrated Product Teams for their EMD configuration design efforts. As of this writing, the ITT is continuing to fly the FSD V-22 to gather more data and to offset risk from the EMD test program. Extensive analytical modeling and analyses completed prior to flight testing, ground vibration tests, and developmental flight tests allowed timely resolution of the technical challenges that are inherent in the tiltrotor design. The more that is known about the "prototype", the smoother EMD testing will go. In addition to the continuing flight program, the ITT is involved with preparations for the start of the EMD flight tests later this year, with test planning, and with training a new cadre of flight test crews. As the ITT continues to refine its processes and procedures, the team remains dedicated to conducting a safe and efficient V-22 flight test program.

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Nomenclature

AFCS.....Automatic Flight Control System CT.....Coefficient Thrust DCP......Differential Collective Pitch EMD......Engineering Manufacturing Development EMV......Electro Magnetic Variation FBWFly-by-Wire FCS......Flight Control System FFSForce Feel System FSD......Full Scale Development HQR......Handling Qualities Rating ICDS.....Interconnect Drive Shaft IMC..... Instrument Meterological Conditions IRS.....Infrared Suppressor ITT.....Integrated Test Team KCAS.....Calibrated Air-speed, Knots KTAS..... True Air-speed, Knots LFL Longitudinal Flapping Limiter LSG......Lateral Swashplate Gearing OLCOpposed Lateral Cyclic PAO......Pilot Augmented Oscillation PFCS.....Primary Flight Control System RPM......Rotor Speed, Revolutions per Minute SHP Shaft Horse Power SLLStructural Loads Limiting SWC Symmetric Wing Chord TCL......Thrust Control lever VMS......Vehicle Management Systems VTOL..... Vertical Takeoff and Landing