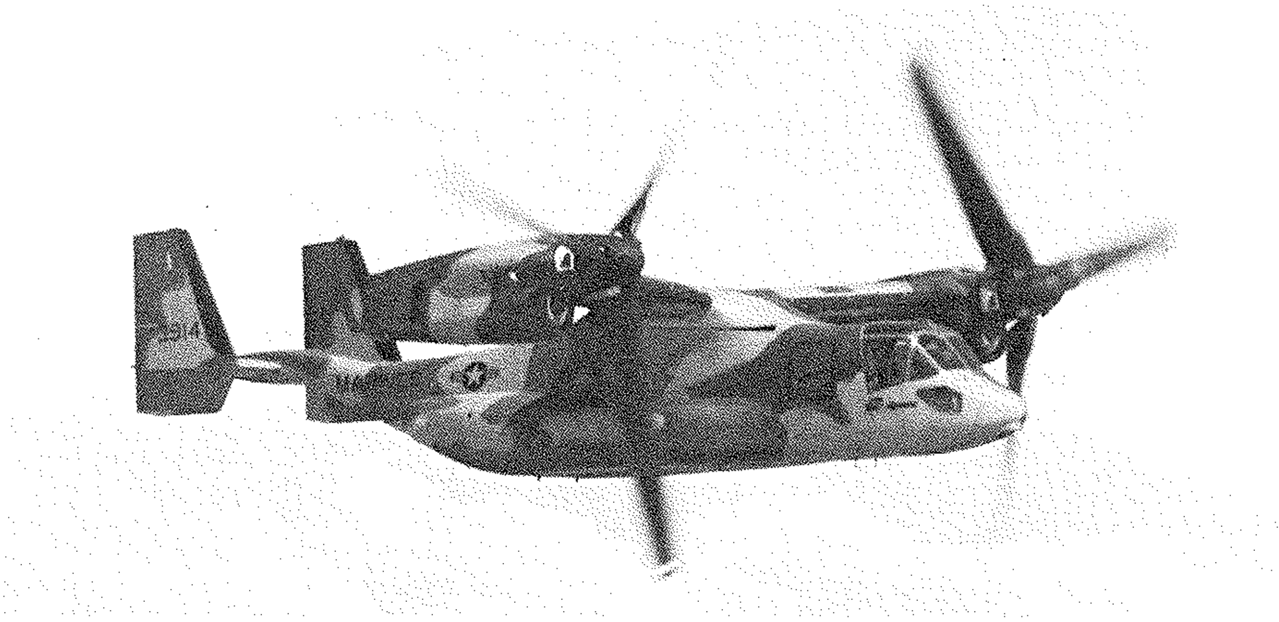
THE V-22 OSPREY – A SIGNIFICANT FLIGHT TEST CHALLENGE

Philip Dunford
and Ken Lunn
Boeing Helicopters
Philadelphia, Pennsylvania – U.S.A.

Ron Magnuson and Roger Marr
Bell Helicopter Textron, Inc.
Fort Worth, Texas – U.S.A.



Abstract

The V-22 Osprey (shown during tethered hover testing in Figure 1) is a V/STOL tiltrotor aircraft being developed by Bell-Boeing for multiservice use and is suitable for a variety of military missions. It provides this capability by combining the novel tiltrotor concept, with mature, proven technology.

Figure 1. Tethered Hover Testing

The V-22 is designed to take off and land like a helicopter and cruise like a turboprop aircraft. It has the capability to reach high speeds, high altitudes and possesses long range capability. Significant increases in payload/range are obtained with a short rolling take-off using partially converted nacelles.

Bell-Boeing has undertaken the challenging task of developing and qualifying the V-22 aircraft and it's advanced technology systems throughout all three flight regimes of the tiltrotor (VTOL / conversion and airplane). Optimized flight test techniques and multidiscipline testing have been incorporated where possible to improve flight test productivity. State of the art data gathering, analysis and simulation methods are being used to produce more data points per flight hour and minimize post flight analysis requirements.

This paper describes the test considerations, test methods, and extra testing required as a result of the V-22's unique multi-mode characteristics.

The paper also discusses some of the significant technical milestones and accomplishments achieved during the envelope expansion and configuration development period, details some of the problems that were encountered, and provides a description of their resolution.

Introduction

Otto Lillienthal was an early German aviator to whom the following quote has been attributed:

"To design a flying machine is nothing;"
"To build it is not much;"
"To test it is everything!"

In his day this was probably true. Design and manufacturing engineers responsible for modern airplanes would undoubtedly challenge the validity of the statement.

However, from the standpoint that flight test is where all the "marvels of technology" created by the design engineers come together, and are required to not only function correctly and in harmony but to meet budget and schedule constraints, it is not difficult to see that the task of testing a multifunction aircraft system, like the V-22, probably is the most significant and challenging aspect of the aircrafts development cycle.

This paper discusses the significant increase in the scope of testing required to qualify the unique multifunction characteristics of the tiltrotor aircraft for multiservice use.

Configuration Description

Figure 2a shows some of the salient design features of the V-22 and Figure 2b the key dimensions of the V-22. Two 38 foot diameter stiff in plane gimbaled rotor systems and engine / transmission nacelles are mounted on each wing tip, and are powered by two 6150 shaft horsepower Allison T406-AD-400 engines (one per nacelle). The aircraft operates as a helicopter when taking off and landing vertically. Once airborne the nacelles are rotated 90 degrees forward which converts the aircraft into a turboprop airplane. The rotors are synchronized by means of an interconnect shaft that runs through the wing between the nacelle mounted transmissions. This shaft also transmits power to both rotors in the event of engine failure. Auxiliary drives from tilt axis and a center wing gearbox provide power for hydraulics, oil cooler and electrical generators. An APU drives through the center gearbox for engine starting.

The aircraft is required to fold compactly for shipboard compatibility. This is accomplished by folding the rotor blades inboard above the wing with the nacelles at 90 degrees (Figure 2c). The nacelles are then rotated to cruise position (0 degrees) and the wing is swiveled over the fuselage.

The V-22 uses an advanced digital fly-by-wire flight control system. In hover, pitch control is provided by longitudinal cyclic pitch of both rotors. Yaw control is obtained with differential longitudinal cyclic and roll control is obtained by differential collective pitch in each rotor. The aircraft is able to maintain a relatively level roll attitude in sidewards flight by programming lateral cyclic pitch (LTM) in the same direction in both rotors in addition to differential collective pitch. In the airplane mode, the V-22 is controlled using conventional aerodynamic surfaces – flaperons for roll control, elevators and rudders on the empennage for pitch, turn coordination and crosswind capability. In the transition mode the helicopter and airplane controls are phased for optimum control response (Figure 2d).

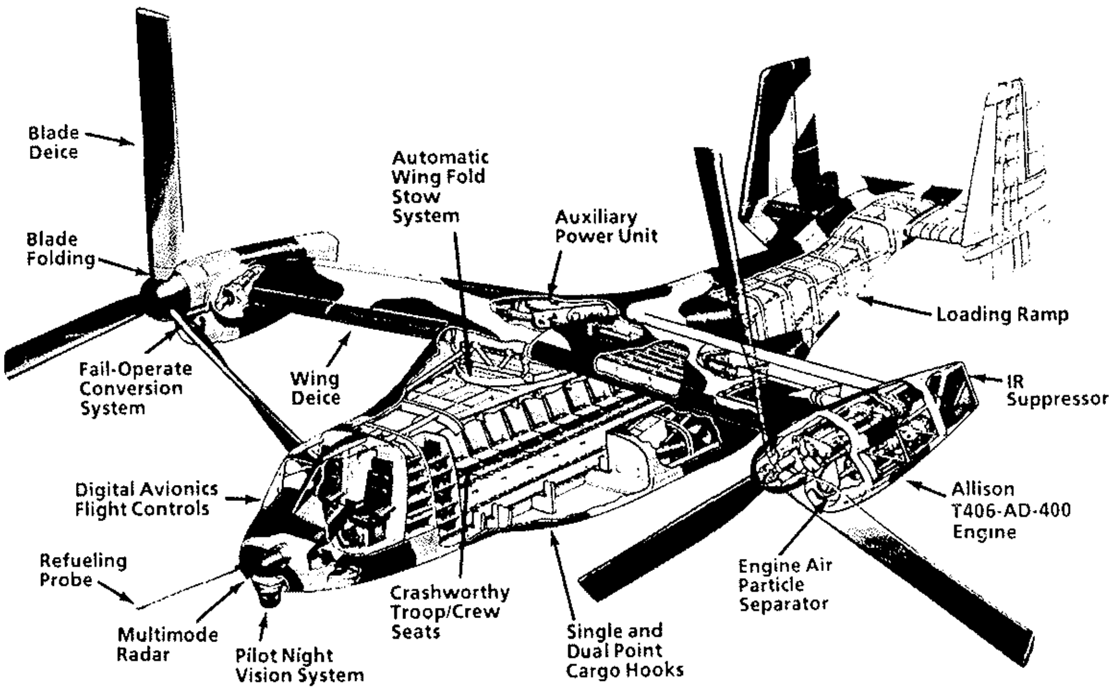


Figure 2a. Salient Design Features

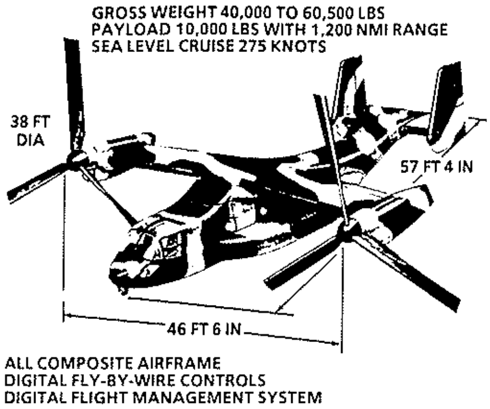


Figure 2b. Key Characteristics

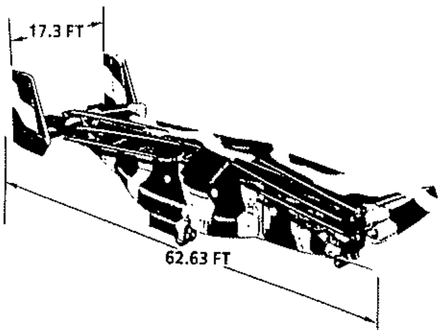


Figure 2c. Carrier – Compatible

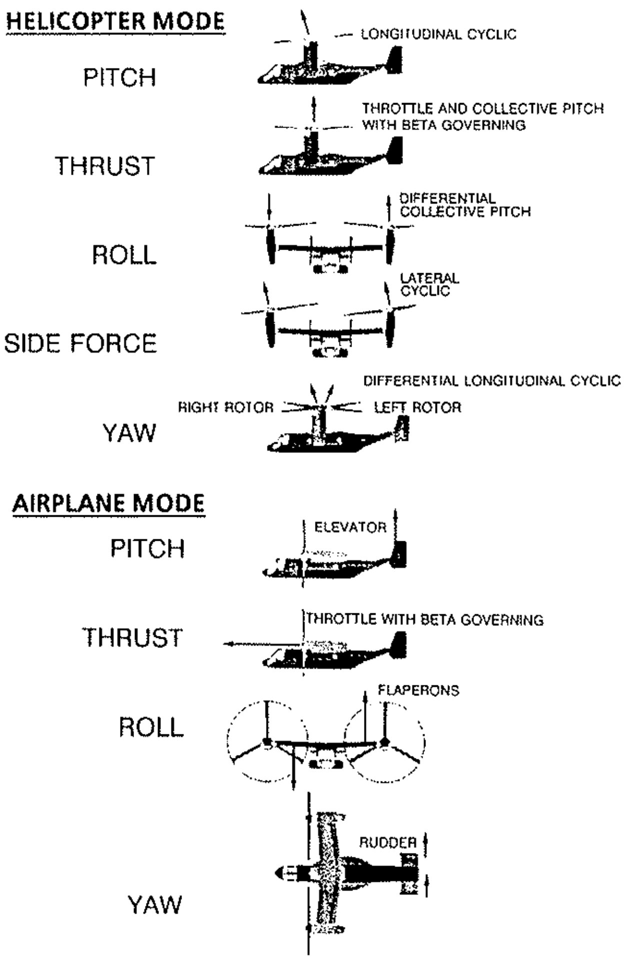


Figure 2d. Control System Characteristics

The V-22 airframe is almost entirely constructed of composite materials and has crashworthy seating for 24 combat troops, two external cargo hooks of 10,000 lb capacity each for carriage of outsized equipment, a rescue hoist, and a cargo winch and pulley system for loading and unloading heavy internal cargo loads through the aft loading ramp which also permits quick egress and exit of troops. The Osprey is capable of all weather instrument flight, day or night, and continuous operation in moderate icing conditions at weights up to 60,500 lb for self deployment.

The Flight Test Challenge

The multi-mode features described above do provide a challenge to the flight tester. An examination of the scope of testing of the V-22 compared to helicopter or airplane testing in general reveals a significant increase in test matrix requirements. First of all, the aircraft has three basic operating modes (Figure 3):

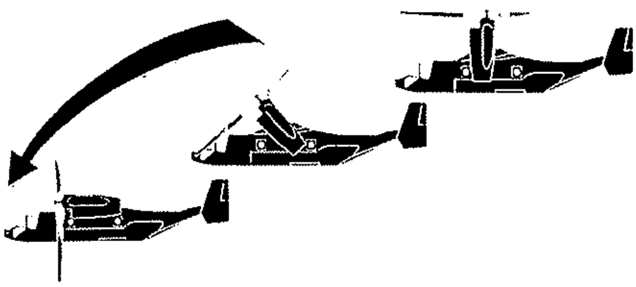


Figure 3. Tiltrotor Conversion

VTOL / (or Helicopter) Mode

- With the wingtip mounted nacelles pointed vertically, the tiltrotor operates like a helicopter with side by side rotors, the rotors providing both lift and control.

Conversion Mode

- As the rotors are tilted, the tiltrotor accelerates with the wing gaining lift as speed increases. Control is provided partly by the rotors and partly by conventional aerodynamic surfaces.

Airplane Mode

- With the nacelles horizontal, the tiltrotor operates as a conventional turboprop aeroplane.

Flight Envelope Testing

When compared to helicopters, the V-22 has a significantly larger airspeed / altitude envelope, which reflects its increased productivity (Figure 4). It can fly almost twice as fast as a modern helicopter cruising at 275 kts with a dash performance of 300 kts.

The V-22 possesses the lift and slow speed versatility of the helicopter up to medium altitudes and the high speed capability of a turboprop aircraft at high altitude.

In addition, the conversion capability of the V-22 not only adds a further primary control axis but provides tiltrotor unique flight characteristics such as rapid acceleration and deceleration, exceptional attitude control for slow speed approach and effective STOL and loiter capability.

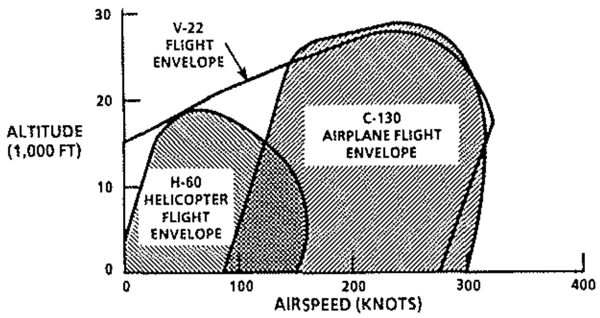


Figure 4. Airspeed / Altitude Envelope

Figure 5 is the V-22 conversion envelope. This diagram shows the sea level airspeed capability of the V-22 at structural design gross weight, for all nacelle angles between 7° aft of vertical and airplane mode. The slow speed boundary defines the aircraft's wing stall limit airspeed (at 40° flap) as a function of nacelle angle. The upper boundary is defined by design limit airspeed (V_L) at each nacelle angle. The figure also shows how this conversion corridor changes as aircraft gross weight is increased. V_{stall} increases and maximum power level flight speed (V_H) decreases, which decreases the conversion corridor at higher gross weights. This effect has been minimized by the incorporation of a conversion protection system (CPS) in the Primary Flight Control System (PFCS). On the upper boundary an active control signal reduces nacelle angle automatically if the aircraft speed is too high for a given nacelle angle. At the lower boundary the CPS modulates the pilot commanded nacelle rate. This allows the pilot to convert to airplane mode as fast as possible without stalling the aircraft. The aircraft maneuver capability within this conversion envelope is shown in Figure 6. At a given gross weight the V-22 possess a V-n diagram for each nacelle angle, the maneuver capability being a direct tradeoff between wing and rotor lift available. This is shown pictorially in Figure 7. One of the benefits of the conversion characteristics of the tiltrotor is that for a constant power, the aircraft possesses a large variable level flight airspeed capability which is particularly advantageous for loiter requirements. In addition in the event of a single engine failure the"bucket" (minimum) airspeed range is considerably wider than that of a helicopter or airplane (see Figure 8). In conversion mode pitch attitude can be adjusted over a wide range at constant airspeed by modulating the nacelle angle. (Figure 9a) This provides the V-22 with unsurpassed external visual cues during approach to hover which has significant advantages operationally, and coupled with LTM, an exceptional slope landing capability (Figure 9b). These characteristics must be fully evaluated during the development flight test program because of the varied flight characteristics at each nacelle angle and significant variation in dynamic system component loads through the conversion envelope. The conversion axis test requirements are analogous to the complexity of testing required for envelope verification at different wing sweeps on swing wing aircraft.

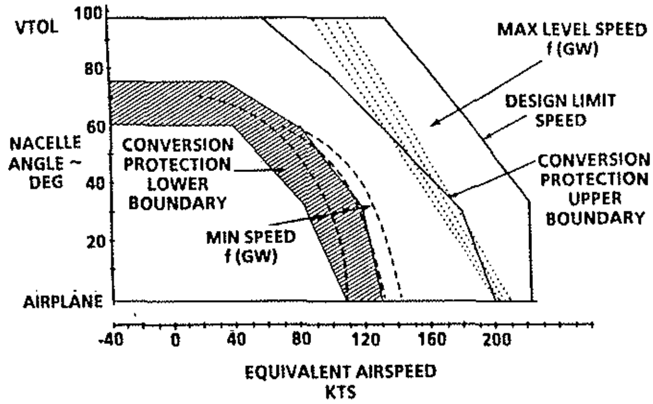


Figure 5. Conversion Corridor

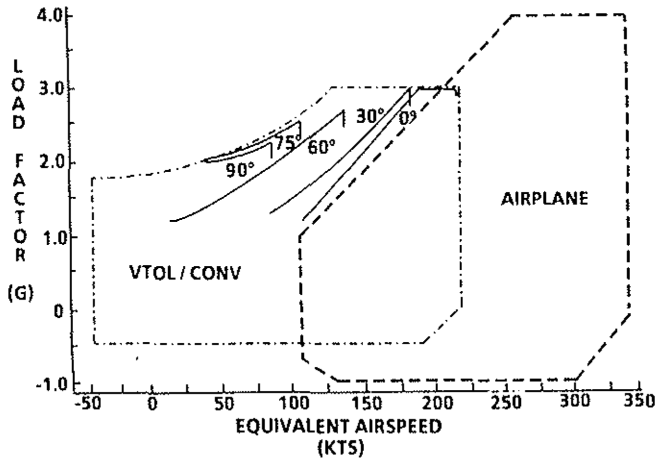


Figure 6. V-n Diagrams For All Three Flight Modes

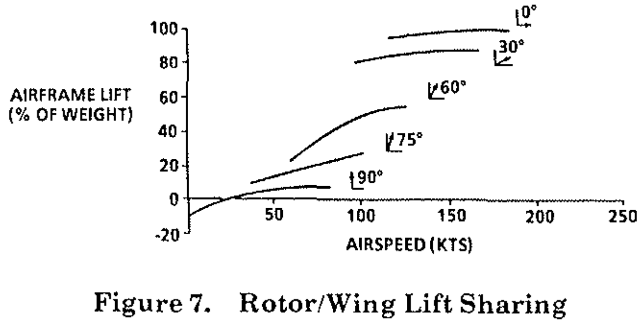


Figure 7. Rotor/Wing Lift Sharing

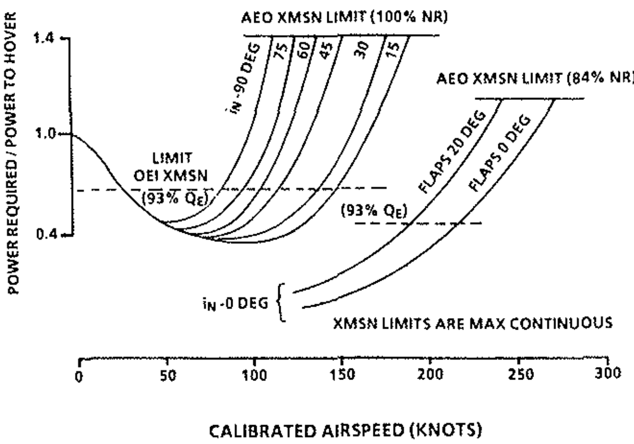


Figure 8. V-22 Power Required For Level Flight

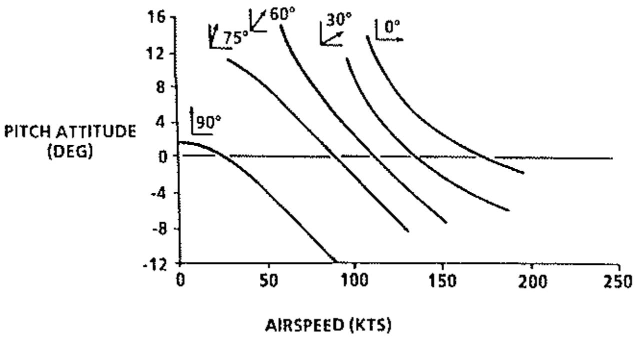


Figure 9a. Pitch Attitude (Angle of Attack) in Level Flight

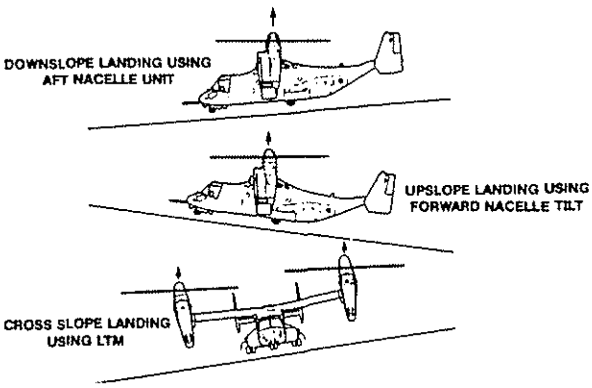


Figure 9b. Attitude Control For Slope Landings

The V-22's multiple flight modes and wide operating flight envelopes generate a very large mission weight and cg range (32,000 to 60,000 lb). (Figure 10 is the GW / longitudinal cg diagram for the aircraft) This requires the aircraft to be tested not only in the vertical takeoff configuration, but in the short takeoff configuration for operation at weights above 47,500 lb. Short takeoffs and landings can be conducted at all nacelle angles between 90° and 60° from the vertical. All of these configurations will be tested because rotor control power varies in all axes as a function of nacelle angle which can result in different handling characteristics at the permitted STOL nacelle angles.

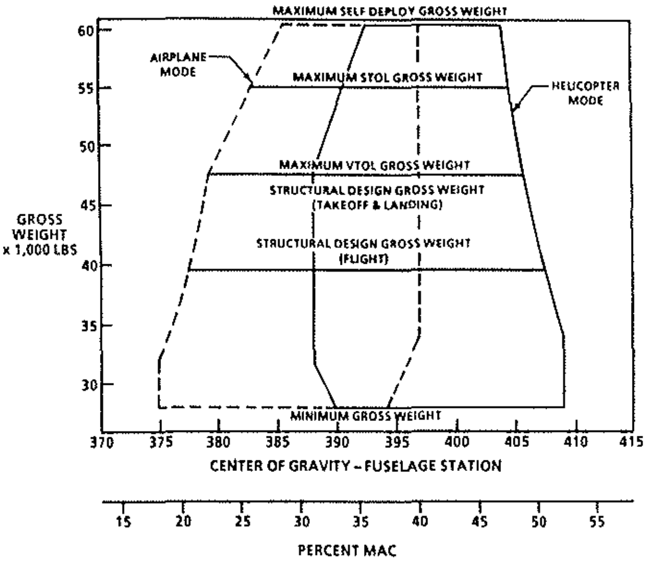


Figure 10. Longitudinal Center of Gravity

Performance

The performance text matrix is magnified by the fact that two operating rotor speeds are used (397 rpm for VTOL and 333 rpm for airplane) to optimize performance and acoustics for the three flight regimes. This wide range of rotor speed and the large gross weight range, coupled with the specification mission ambient temperature and altitude requirements, has generated a significantly larger performance test matrix than normally encountered on other aircraft. For example, Figure 11 shows a comparison of the range of performance testing required on the V-22 compared to that conducted on the CH-47D. These aircraft are approximately the same size vehicle, but the additional rotor speed and gross weight capability of the V-22 increases the performance test matrix requirements by at least a factor of three.

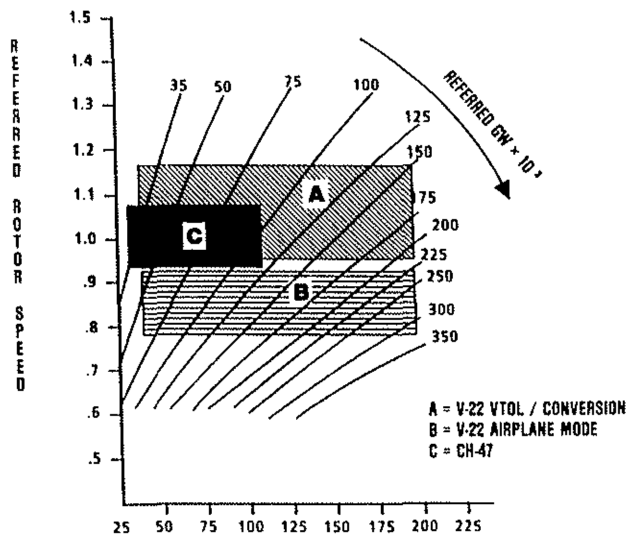


Figure 11. Performance Testing Envelope

Aeroservoelastics / Dynamics

The requirement for two operational rotor speeds presented a significant design and testing challenge in the area of frequency placement during configuration development. The V-22 specification defined aircraft natural frequency avoid band criteria of 10% on either side of the one and three per revolution rotor frequencies for both VTOL / conversion and airplane mode flight. This means that no symmetric or asymmetric wing or fuselage aeroservoelastic modes can be in the 3/rev or 1/rev avoid bands. This requirement is applicable for the full gross weight range of the aircraft. Figure 12 shows the challenge pictorially.

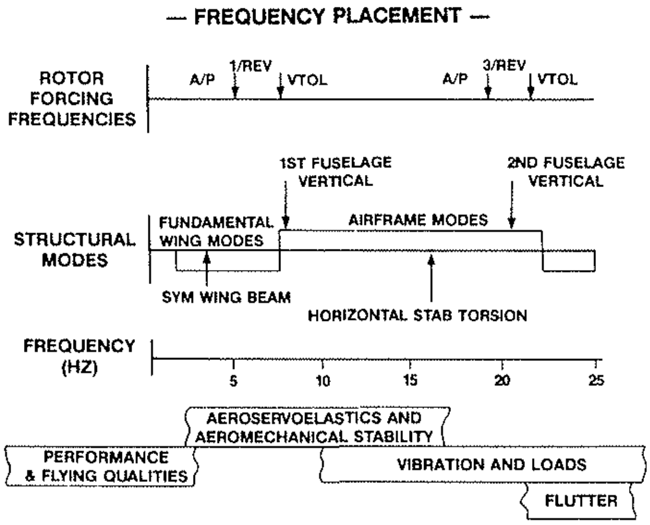


Figure 12. Dynamics Design Challenge

It is evident from Figure 12 that a slight miscalculation in the prediction of any of the wing or airframe frequencies could necessitate a structural or flight control system modification to alleviate any coupling between airframe/rotor and flight control system. A problem of this nature requires retesting a selected spectrum of airspeeds to prove resolution. This has already occurred on the V-22 during configuration development, as will be discussed in some detail later in the paper.

Flight Loads

From a structural standpoint the V-22 is designed to operate to both helicopter and fixed-wing specification requirements; a combination of helicopter (AR-56) and airplane (MIL-8861) specifications with additional unique requirements for the V-22. These V-22 unique criteria are more severe for both strength and fatigue than for current rotorcraft, and mandate the following:

STRENGTH – design to 100% aerodynamic capability

FATIGUE – 10,000 hours fatigue life based on 100% usage at most critical flight and loading condition

The maximum dynamic lift capability of the V-22 is compared to the required design limit load factor at structural design gross weight (SDGW) in Figure 13. It shows that the basic aircraft is able to generate 2.4g more than the design limit load factor at SDGW. The maximum aerodynamic capability for most airplanes is greater than design limit load factor at speeds above the maneuvering speed (V_a), however they are not normally designed structurally for additional maneuvering capability above this speed. This excess lift available in the V-22 does generate increased airframe loads as a result of higher load factor and angle of attack. In addition, in airplane mode, increased oscillatory rotor loads are generated during maneuvers that contain a large rotor pitch rate (i.e., the sum of rotor flapping rate and airframe pitch rate). Basic aerodynamic characteristics of the aircraft at high angles of attack induce an oscillatory pitch response that requires artificial damping to provide desirable handling qualities. In VTOL / Conversion mode, the V-22, like other helicopters encounters increased rotor loads at the onset of rotor stall. In helicopters the rotor design load is limited to the point where the rotor load feedback to the control system becomes excessive. This is not the case in the V-22 where the requirement to design to 100% aerodynamic capability is obtained through the fly-by-wire flight control system in all flight modes.

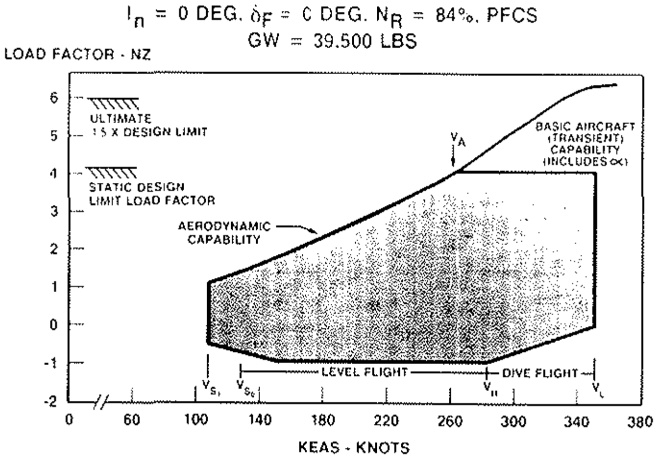


Figure 13. V-n Diagram (Airplane)

A Structural Loads Limiting system (SLL) which limits the maximum load factor and rotor pitch rate in airplane mode and a Rotor Stall Protection System (RSPS) which limits rotor angle of attack in VTOL / Conversion mode have been developed and will be evaluated during envelope expansion.

The SLL has been designed to provide the desired 4g maneuver capability at V_a and provide the desired loads protection for meeting specification requirements. In addition, a significant improvement in pitch response characteristics is achieved as a bi-product (Figure 14).

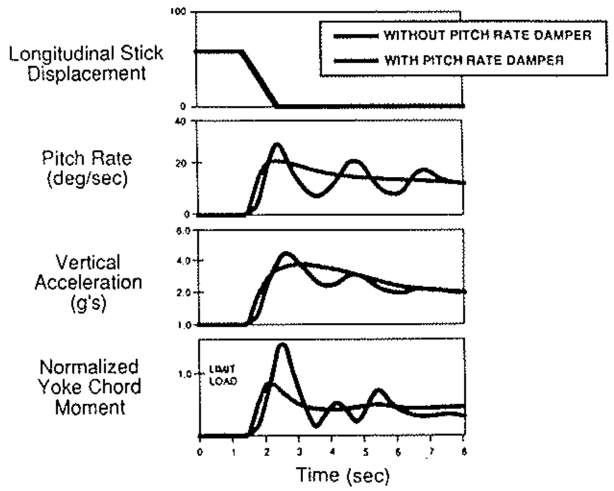


Figure 14. Effect of Pitch Damping on Aircraft Response

These envelope limiting systems as well as the normal AFCS and coupled mode functions in the flight control system all have to be developed prior to demonstrations. A change to the control laws to correct anomalies found in flight test will require in flight regression testing to ensure safety is not compromised and that the system performs to its requirement. This task expands the configuration/development/envelope expansion phase of the flight test program as demonstrations cannot be performed until the configuration is finalized. Simulation and analysis have become a significant part of the V-22 flight test program in order to reduce this task to the testing of significant conditions only. This is discussed in more detail later in the paper.

Avionics

Although not tiltrotor peculiar the evaluation of the "glass cockpit" is an example of how technology advancement has increased test demands. Figure 15 shows the V-22 cockpit. Basically, it consists of four primary displays, 2 control / input displays and several secondary displays. These have not merely been substituted for the traditional HSI and VSI; they are now multifunction displays that allow the crew to select from dozens of displays dependent upon the information required. As well as having the primary HSI / VSI information, the pilot is provided with digital and analog displays for airspeed, rate of climb and descent, torques, temperatures, rotor speed, etc., as well as caution summary pages to inform him of his equipment status.

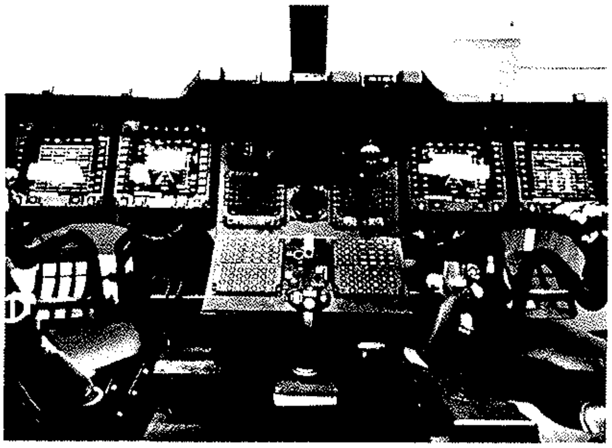


Figure 15. V-22 Cockpit

Those readers involved in the development of avionics systems will know that the testing, debugging and development needed to make these displays work and be "pilot friendly" is in itself a daunting task.

Combine the aircraft unique characteristics and envelope limiting features discussed above, mission peculiar features like blade-fold / wing stow, the advanced technology features such as a digital fly-by-wire flight control system and engine controls which are fully integrated with the avionics and cockpit displays with the fact that new technology graphite epoxy materials have been used for the majority of the structure and you really begin to sense the magnitude of the V-22 testing task compared to the conventional aircraft we are all used to.

The V-22 configuration also requires that all aerodynamic and control characteristics testing be qualified to both helicopter and airplane specifications. So in addition to the normal helicopter testing, classical fixed wing tests are required, e.g. High Angle Of Attack (HAOA), stall and stall departure, short takeoff and landing, and maneuver boundary testing to name a few.

As stated above the versatility of the tiltrotor concept presents the flight test organization with a larger test matrix than that of conventional helicopters or airplanes. The scope of the testing required to fully develop the V-22 is presented pictorially in Figure 16.

Methods Used to Optimize Flight Test Time

Data Processing

The rate at which the V-22 development program can progress is a function of many elements. One of the most important is the ability to process and assimilate the large amounts of data that can be generated in a single day's flying.

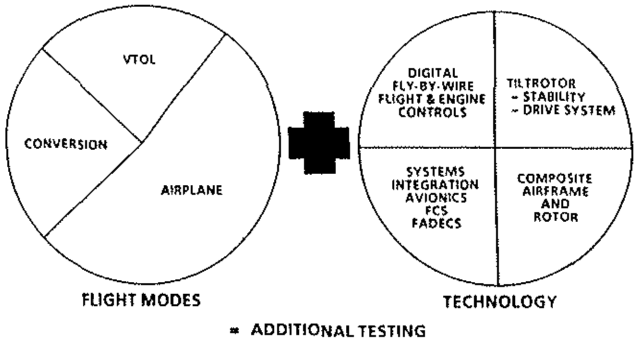


Figure 16. Flight Test Challenge

At Bell-Boeing, we have tried to cope with this plethora of test requirements by conducting 'multiple category testing' on a given aircraft where requirements are compatible. Multiple category testing means providing the capability to record and process data from more than one test discipline at the same time. For example, test conditions for performance and propulsion testing are compatible with Avionics systems development, vibration with flight loads and aeroelastic evaluations, and HAOA testing with the development of the structural load limiting. The challenge is that a large amount of instrumentation is required per aircraft and this can add maintenance schedule delays if requirements are not adequately planned.

During the initial V-22 aircraft testing both aircraft 1 and 2 were flying from the Bell Flight Research Center Arlington, Texas and early developmental problems had to be resolved quickly. It was important to have the capability to rapidly analyze large quantities of multi category time history data. The key to flight test progress is efficient processing of data; "get usable data to the engineers quickly." To this end, the Bell Flight Test Data system (CAFTA) had the capability to quickly provide time history data through a data base network for the purpose of troubleshooting. As the program proceeds through the configuration development stage, this detailed analysis requirement still exists for the aircraft that are expanding the flight envelopes (aircraft 1 and 3) in Arlington.

The use of real time application software is also important, because the nature of the V-22 test schedule is such that there will be little time (as already discussed) to conduct testing in series. The Boeing ATLAS and Bell CAFTA data systems are geared for real time analysis. With careful planning of requirements, this capability produces report quality summary plots at the conclusion of each flight. This capability is already being exercised for initial performance and handling qualities evaluations on aircraft 2 and 4 at Boeing's Wilmington Flight Test Center.

Simulator Support of Flight Test

Improved Simulator Fidelity has allowed the Bell-Boeing team to reduce test requirements. On the V-22, the Generic Tiltrotor flight simulation has been the primary handling qualities development and evaluation tool. During the preliminary design and early full scale development phases of the program the simulator has been demonstrated to be a time and cost efficient tool in the development of the aircraft flight control system control laws.

Subsequent to the design phase, flight and batch simulation have been used extensively in the prediction and evaluation of the aircraft's handling characteristics (by flying the flight card test conditions on the simulator prior to flight test) as well as in the resolution of anomalies encountered during the flight test program.

Excellent correlation with flight data has demonstrated the simulation model fidelity in all flight modes, even in extreme maneuvers such as stalls. Figure 17 compares simulator and aircraft responses for an airplane mode stall. Some minor changes to the math model were implemented, early in the flight test program, to improve aircraft / model correlation. These included:

- Adjustment of rotor wake impingement effects on the horizontal tail
- Wing-on-rotor aerodynamic interference effects
- Rotor power vs. collective pitch relationship
- Wing / pylon / airframe lift / drag characteristics

Flight simulator to aircraft equivalence has been used extensively in the identification of all rigid body aircraft modes (i.e. dutch roll, short period, phugoid, etc.). This method involves driving the simulator math model with flight test control inputs. When the math model's response accurately matches the aircraft's, the model is used to infer relevant aircraft parameters. The use of simulation in this way was largely responsible for the fact that initial PFCS development was completed in less flight hours than planned. In addition, simulator fidelity and systems training was the major factor in completing the flight training of three U.S. Marine pilots in a total of 15 aircraft flight hours, prior to the first Navy evaluation of the aircraft in early 1990. Some advantages realized on the V-22 program by using simulation to support flight testing are listed below.

- Extensive wind tunnel model testing allowed the aircraft's flight characteristics to be modeled and assessed prior to flight testing. Without exception, all pilots (including military evaluation pilots) have undertaken an extensive flight orientation in a V-22 simulator and have commented positively on the excellent correlation with the aircraft's flight characteristics.

- The simulator has allowed multi-pilot participation in problem resolution and high risk test preparation. This has resulted in improved testing efficiency, and flight safety.
- In the area of flight control system configuration development, the simulator has allowed precise control of variables.

  This precise control of variables in the simulator and excellent correlation with flight test data has allowed "intermediate" flight conditions to be omitted from the flight test card, improving flight productivity (data points / flight) by concentrating flight test on the "end points".

All the above combine to provide a significant improvement in flight test productivity and with careful planning and execution, results in considerable savings in flight time, schedule and cost.

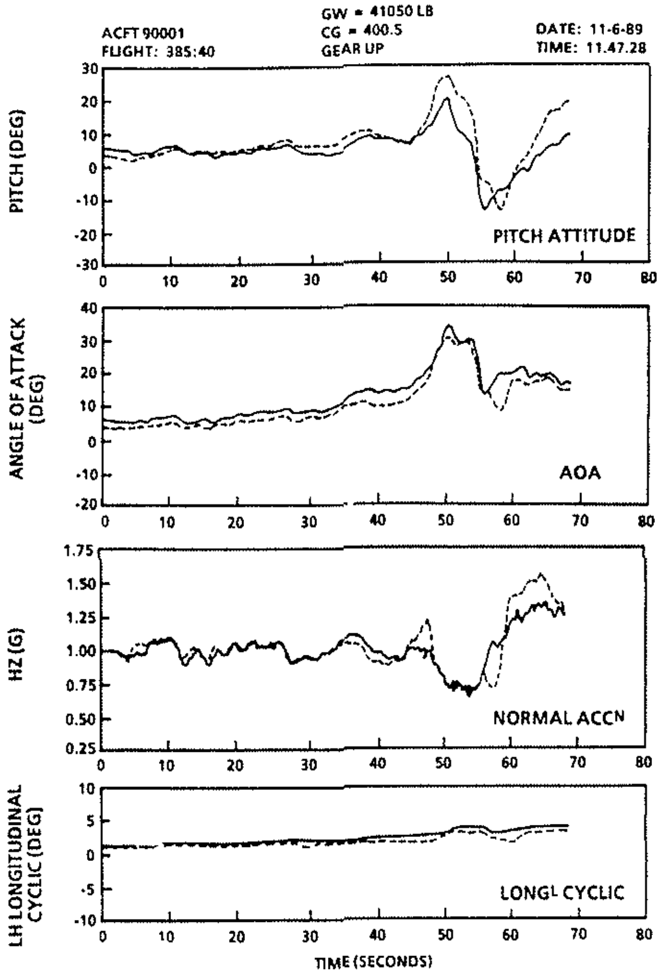


Figure 17. Power Off Stall, 20° Flap, i_n -0°

As envelope expansion continues, simulation is being used extensively to reduce the risk associated with testing such as HAOA, Structural Load Limiting development, Height Velocity, Structural Demonstration, and Autorotative landings.

Flight Test Results

Overview

At the time of writing four V-22 aircraft are on flight status. The specific tasks assigned to each aircraft are shown in Table 1. Initial envelope expansion and primary flight control system development are complete. The aircraft has been evaluated to 350 KTAS, 2.3g and 15,000 ft. (Figure 18 a/b).

Table 1. FSD Aircraft

AIRCRAFT #	PRINCIPAL	ASSIGNMENT
1	Bell	Airspeed Envelope Expansion, Aeroelastics
2	Boeing	Flight Controls, Avionics
3	Bell	Load Factor Expansion, Flight Loads, Vibrations
4	Boeing	Propulsion, Performance Avionics, USAF
5	Boeing	Avionics, E^3, Government Tests
6	Bell	Systems, Government Test

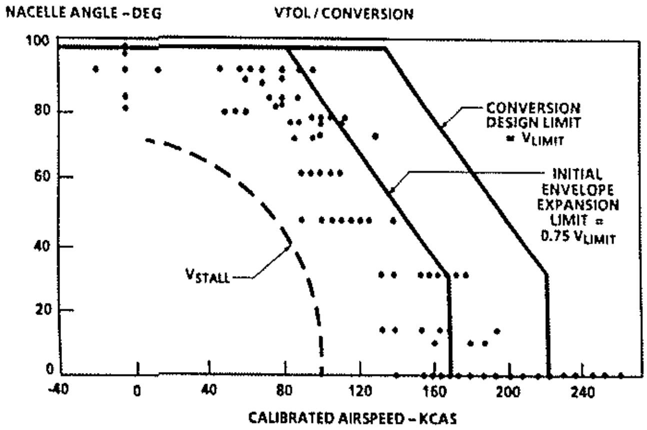


Figure 18a. V-22 Initial Envelope Expansion Status

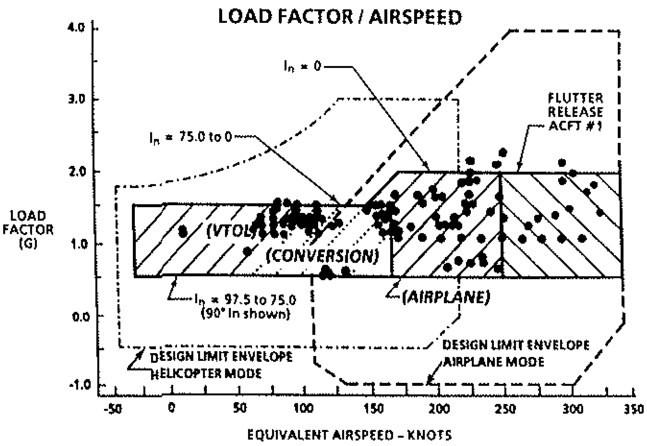


Figure 18b. V-22 Initial Envelope Expansion Status

More than 210 flight hours have been accrued in about the same number of flights, aircraft #2 having flown almost 100 hours. The total operating time on the V-22 rotor and drive system is 750 hours, 250 of which were on the GTA during qualification testing. The flight hour status as of September 1, 1990 is shown in Table 2.

Table 2. Aircraft and GTA Test Status (Sep 1990)

A/C	TOTAL OPERATING HOURS	FLIGHT HOURS
1	240.7	69.3
2	161.7	97.9
3	46.2	10.3
4	70.7	37.1
GTA	249.0	-
TOTAL	768.3	214.6

Although Aircraft 90001 has flown fewer flight hours than Aircraft 90002, its productivity from an envelope expansion standpoint must also be measured by the work accomplished on the 'run stand' in Arlington. The run stand is a tie down capability that allows the V-22 to be operated on the ground at all powers, rotor speeds and conversion angles allowing thorough integrated systems, component and procedure checkouts to be accomplished prior to flight.

This facility has significantly reduced the risk associated with envelope expansion and has provided an early problem identification capability that improves flight safety and increases 'productive' flight time.

All significant initial development problems have been resolved. Notable successes include:

- The reliability and performance of the flight control system and the associated excellent handling qualities of the unaugmented aircraft.
- The reliability and integrity of the drive system which has operated for over 750 hours without a significant problem.
- The airframe – Although the aircraft has only been maneuvered to half of its design limit load factor, strain and loads data suggest that all requirements will be met at the envelope limit.

The engines, proprotor gear boxes and tilt axis gear boxes are a significant source of heat to the nacelle environment and the requirement for efficient nacelle air management in all three modes of flight, particularly in high ambient temperatures, has been a significant technical challenge. After a number of iterations recent design changes to the inlets that regulate the nacelle cooling air flow as a function of nacelle angle have provided sufficient cooling capability to meet the specification requirement for the nacelle environment.

The blade fold wing stow system has been demonstrated on the ground test article (GTA) and will be installed on aircraft 90004 in October 1990 in preparation for shipboard compatibility testing (DTIIB) in December 1990.

Although initial vibration levels of the untreated aircraft were above the specification requirement, a structured approach to vibration reduction proved extremely successful. Further details on this item are provided later in the paper.

The first government evaluation of the aircraft was successfully completed in April, 1990. Three Marine pilots flew the aircraft for a total of 30 flight hours (including training). They gave a very favorable report, summarizing their evaluation with the following quote:

"Within the scope of (DTIIA) the V-22 demonstrated excellent potential for its intended missions".

Fewer deficiencies were noted on the V-22 than for other recently evaluated aircraft and the tiltrotor unique features described earlier in this paper were quoted as "enhancing features".

Aircraft 90004, the performance / propulsion aircraft, has completed initial OGE tethered hover performance evaluations during which an equivalent hover gross weight of 48,000 lb was achieved (aircraft gross weight plus cable tension). Cruise performance testing has been conducted on all four aircraft. Aircraft 90004 will assume the task of 'performance' aircraft as it is closest to the production configuration from an external lines standpoint.

Aircraft 2 was ferried 1,200 nmi from the Bell Flight Test Facility in Arlington, Texas to the Boeing Flight Test Facility in Wilmington, Delaware in May 1990, stopping once on the way. This stop was necessary because of the gross weight (fuel) limitation imposed on the aircraft for the flight. Total enroute time was 5.2 hours.

Although the flight test program has not encountered any major road blocks to continued envelope expansion, the first year of flight testing has not been without its problems. For example three separate anomalies delayed first flight:

- A lateral ground PAO (discussed later)

- A runstand engine failure resulting from the failure of the fuel system negative g valve (solved by modifying the valve).

- An OEI detection logic error in the FCS, which failed to advance the non-failed engine to full power for slow engine failures (solved by modifying the detection logic).

Extensive analysis, lab testing and simulation is conducted on all software or hardware prior to installation into the aircraft. In the case of the FCS, the flight control computers are flown by test pilots with the simulator 'tied in' to the Control System Integration Rig (FCSIR) to exercise the very software that will later be flown in the test aircraft.

However, this flight test program like all others before it has demonstrated that although this procedure uncovers a significant number of problems that would have been encountered first in the air, there is still no substitute for flight test. Two engine control system logic anomolies were encountered first in flight

- An engine speed limiter instability (solved by a simple software mod to the engine control logic in the FADEC.)

- An engine flame out while simulating OEI flight followed by an engine lockup that prevented in flight restart. This was caused by an errant fuel limiting schedule, which has been solved by modifying the schedule.

<u>Aeroservoelastic Anomalies</u>

Two significant control system / airframe coupling anomalies have been efficiently resolved during initial envelope expansion. Analysis, simulation and ground testing were used in a major supporting roll to flight test in this resolution, thereby reducing the in-flight testing requirements.

The first was a pilot augmented oscillation (PAO) which occurred prior to first flight during unrestrained ground runs at 100% rotor speed. Lateral aircraft oscillations at a frequency of approximately 1.5 Hz were induced when the pilot gripped the cyclic control. This oscillation had a damping ratio of -4.0% critical. When the pilots' hand was removed from the stick, the oscillation became positively damped with a damping ratio of +3% (see Figure 19a). This was not a ground resonance problem but the result of exciting the aircraft's upper focus rigid body roll mode through pilot anthropometric coupling. The resulting lateral acceleration at the pilot's seat produced an inertial input, via the pilots arm, to the flight controls which were, at the time, unbalanced laterally.

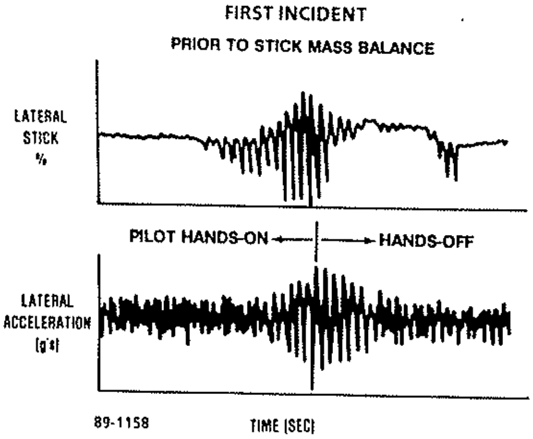


Figure 19a. Ground Pilot Augmented Oscillation

The approach used to analyze and resolve the problem was a combination of aircraft ground shake tests, mechanical control characteristics measurements, simulation, software control law changes and linear modeling of the system.

Various solutions were considered including mass balancing the stick in the lateral axis, altering the lateral stiffness characteristics of the tires and landing gear oleos, desensitizing the coupling by adding a software notch in the lateral control axis and removing forward loop shaping.

Lateral stick mass balancing was chosen as the interim solution to the problem, primarily because simulation predicted that a software notch at 1.5 Hz and / or removal of forward loop shaping degraded handling qualities to unacceptable levels. The landing gear characteristics were shown by analysis not to contribute significantly to the problem.

After incorporating the lateral mass balance, a detailed series of ground shake checks with and without rotors turning were conducted to prove the solution. Figure 19b shows the results of some of the testing. In this case, the 1.5 Hz high focus roll mode was excited by large amplitude pilot inputs and was shown to be well damped (8.5% critical) upon removal of the pilot input. (the pilots hand remaining on the control continuously).

The second flight control system / airframe coupling problem occurred in airplane mode at 250 KCAS. An uncommanded, unstable lateral oscillation at approximately 3 Hz was experienced with a low level lateral viscous damper installed. Data analysis showed that the pilot coupled with the lateral stick dynamics and the asymmetric wing chord bending natural frequency. (See Figure 20a). To resolve the problem aircraft shake tests were conducted to verify the control system natural frequency with the pilot in the control loop and the basic airframe mode frequencies. The simulation batch analysis was updated to include the pilot coupled modes. Flight tests, with an incremental build-up in airspeed and with various lateral stick viscous damper configurations, were conducted to the airspeed at which the instability had previously occurred. Using this test data, the instability was simulated and high speed flight conditions analyzed to quantify the effect of flight variables on the instability.

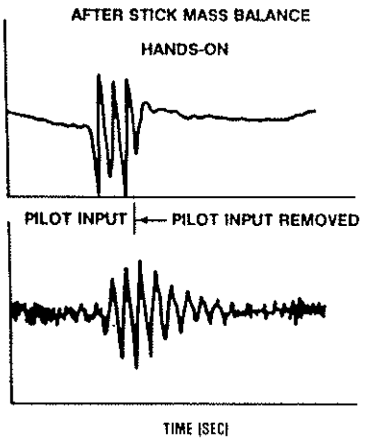


Figure 19b. Ground Pilot Augmented Oscillation

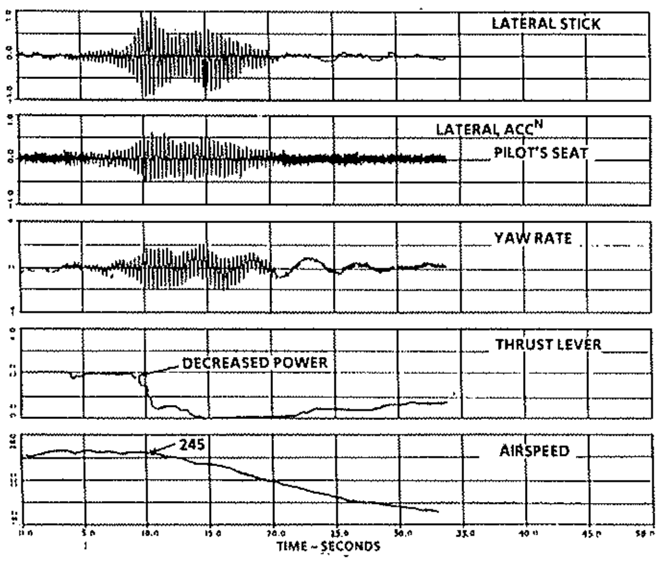


Figure 20a. In Flight Pilot Augmented Oscillation

Once the physics of the problem were understood a notch filter was incorporated in the lateral control axis. Extensive piloted simulations were conducted to confirm that the notch had no significant handling qualities impact in all flight modes. The aeroservoelastic analysis was repeated with the notch installed in the control system and the aircraft was shown, by analysis, to be stable to the envelope limit. The flight control system software was modified, and retested in the flight vehicle. Flight tests to 350 KTAS have shown positive damping, for the asymmetric wing chord mode (see Figure 20b).

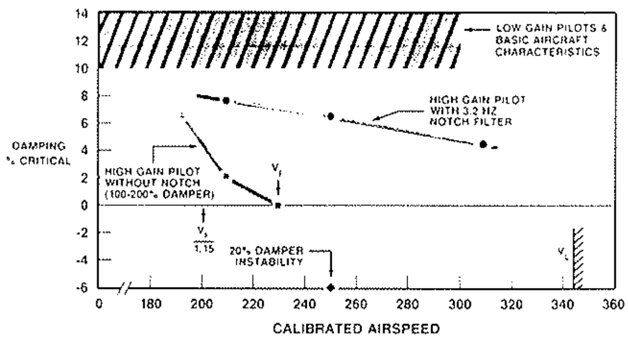


Figure 2b. V-22 Aeroelastic Stability

Flight Characteristics

An assessment of V-22 flying qualities on the aircraft's primary (unaugmented) flight control system (PFCS) has been accomplished, over the full range of nacelle angles and a significant portion of the speed and load factor envelopes. The aircraft has demonstrated good level 2 handling qualities throughout these flight envelopes (Figures 21a, b & c) which are indicative of the soundness of the V-22's aerodynamic and flight control characteristics. Compliance with the applicable military specifications for level 2 flying qualities has been demonstrated.

Flight control system development testing will continue as the flight envelope is expanded in airspeed, load factor, gross weight and cg. Task aggressiveness will be increased as the aircraft load factor capability and maneuver rates are increased and the structural load limiting features of the aircraft are developed.

Testing of the automatic flight control system will commence in the fall and will be available for the initial ship trials in December 1990. Since the handling characteristics of the PFCS have demonstrated excellent agreement with simulation, predictions suggest that the AFCS development goal of level 1 handling qualities will be achieved.

Vibration

All rotorcraft face the problem of vibration. The V-22 tiltrotor is no different. What is different is the way this technical challenge has been managed. From the initial design stage, vibration was anticipated and given top priority.

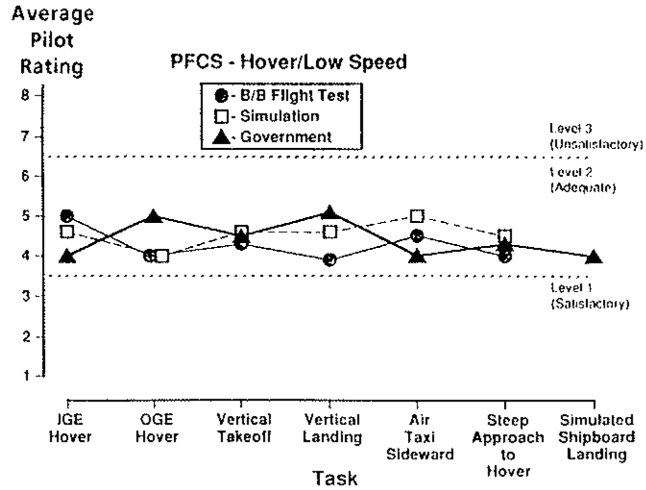


Figure 21a. Cooper-Harper Rating vs Mission Task

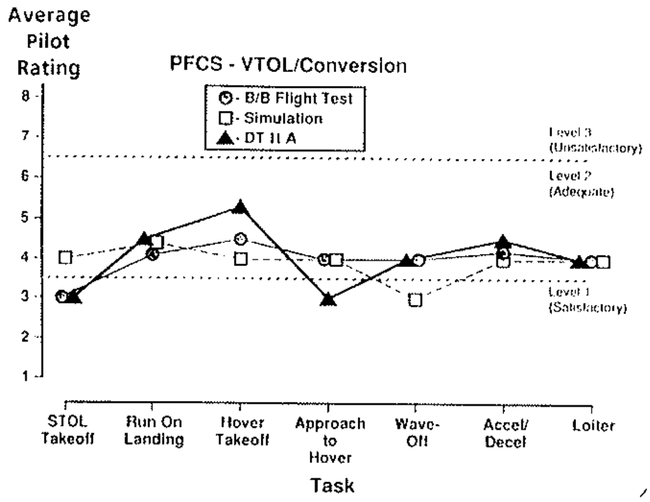


Figure 22b. Cooper-Harper Rating vs Mission Task

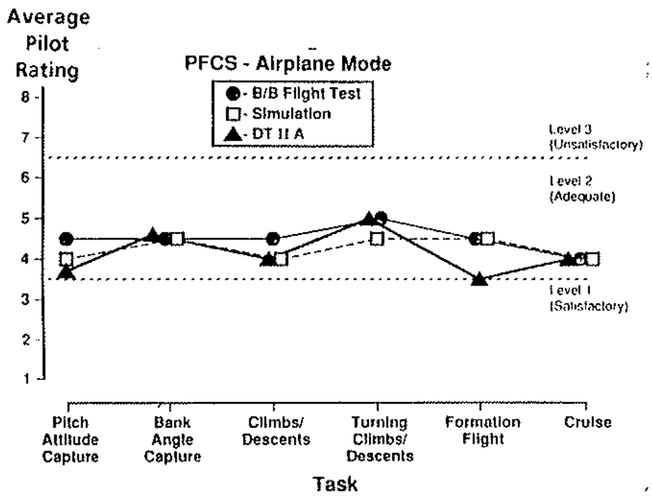


Figure 21c. Cooper-Harper Rating vs Mission Task

More analysis, wind tunnel model testing, simulation and ground testing has been conducted during the V-22 development program than on any other rotorcraft program. This resulting experience and database helped identify several vibration reduction approaches that could be used if the need arose. However, the vibration reduction devices were not installed during the early stages of flight testing so the untreated aircraft vibration environment could be quantified. Once this was completed, the devices were tailored to the measured environment and installed in the aircraft.

Resulting vibration levels are within specification limits for the cockpit and cabin. Figure 22 illustrates the V-22 specification, the baseline untreated vibration levels and the levels after treatment, at 260 KTAS.

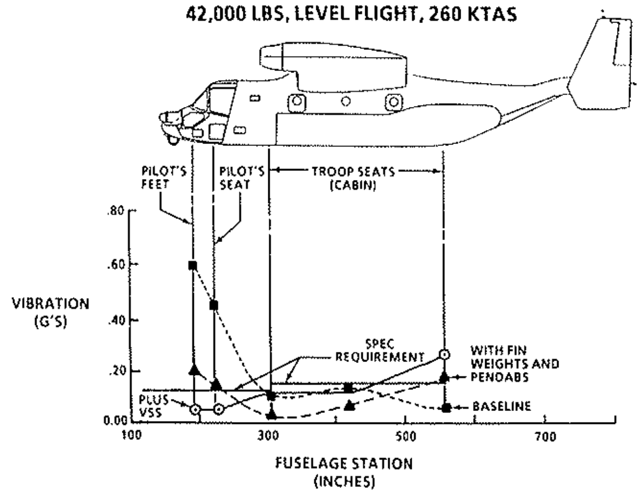


Figure 22. Airplane Mode Vertical Vibration (3 Rev)

Controlling the vibration environment involved the incorporation of a three-stage vibration reduction package:

Stage One: Fin weights were added to the vertical stabilizers to provide the desired frequency placement and prevent fuselage resonance in cruise mode.

Stage Two: Pendulum absorbers were added to the hubs primarily for oscillatory load alleviation in the nacelle. The additional side benefit was a significant reduction in fuselage vibration when flown in conjunction with the fin weights.

Stage Three: This consists of a computer controlled Vibration Suppression System (VSS) which "tunes" the suppressor to critical rotor-forcing frequencies, effectively canceling out most of the vibration. It has worked exceptionally well in flight tests and will be optimized to reduce vibrations further, if required during later stages of testing.

Within the constraints of current testing and with the vibration reduction equipment in place, the Osprey's vibration compares very favorably with other turboprop aircraft and meets all V-22 specification requirements.

XV-15 Contribution

Some benefits gained from the flight testing accomplished on the XV-15 technology demonstrator are summarized in Table 3. Had some of these undesirable tiltrotor characteristics not been identified and resolved in the V-22 design, the V-22 flight test program would undoubtedly have been significantly longer. In addition, the XV-15 test data was used to develop and validate the initial generic tiltrotor math model which has been supplemented with V-22 wind tunnel and flight test data to provide an extremely useful and representative simulation capability.

Table III. XV-15 Lessons Learned

XV-15 CHARACTERISTIC	V-22 SOLUTION
• SLUGGISH ROLL RESPONSE IN HOVER	– INCREASED ACTUATOR RATE PFCS FORWARD LOOP SHAPING
• SLUGGISH VERTICAL RESPONSE IN HOVER	– OPTIMIZE THROTTLE / BLADE PITCH RESPONSE WITH FORWARD LOOP SHAPING – TORQUE COMMAND LIMITING SYSTEM
• HOVER IGE 'INSTABILITY' (LATERAL DARTING)	– ALTITUDE / HOVER HOLD FUNCTIONS TO AFCS
• EXCESSIVE BANK ANGLES IN SIDEWARD FLIGHT	– SYMMETRIC SWASHPLATE TILT, REDUCING BANK ANGLE
• LARGE TORQUE TRANSIENTS IN AIRPLANE MODE MANEUVERS	– DIFFERENTIAL COLLECTIVE PITCH / ROLL RATE COMPENSATION
• MARGINAL DIRECTIONAL CONTROL DURING HIGH SPEED TAXI & RUN ONN LANDINGS WITH FORWARD NACELLE TILT / LOW POWER	– ADD NOSEWHEEL STEERING
• LONGITUDINAL 'CHUGGING' IN AIRPLANE MODE IN TURBULENCE	– ADDED ROTOR GOVERNOR FEED FORWARD
• EMPENNAGE BUFFET IN CONVERSION CAUSED HIGH LOADS AND VIBRATION	– INCORPORATED BUFFET LEVELS INTO DESIGN CRITERIA – WING FENCE TO DEFLECT WING / NACELLE VORTEX
• HIGH 2P ROTOR / PYLON LOADS / VIBRATION DUE TO JOINT WHEN ROTOR FLAPS	– ELIMINATED WITH CONSTANT VELOCITY HUB

Summary

The full envelope expansion / configuration development phase of the flight test program is currently underway with the incorporation of conversion corridor protection, structural load limiting and the automatic flight control system planned for late 1990. These are all software additives to the fly-by-wire flight control system.

At the end of this initial validation phase, while some problems, as discussed previously, have been encountered and solutions identified, no major technical "showstoppers" to continued development exist.

The program is now entering a phase designed to develop and demonstrate the full flight envelope and mission potential of the V-22 Osprey.

The buildup of the flight envelope to maximum airspeed (345 KCAS) combined with increasing load factor has already begun and all four aircraft have been updated to the configuration defined by tests accomplished in the initial validation phase.

Emphasis is being increased on systems testing such as fuel systems, avionics, propulsion, hydraulics and external load operations. Toward the end of 1990, aircraft three and four will commence shipboard operations and early in 1991 aircraft four and five will be operated by a U.S. Marine Test Squadron for an operational evaluation.

The first evaluation by test pilots from the Naval Air Test Center has been accomplished and these pilots are participating in the ongoing contractor testing as cockpit crew. The second flight test aircraft has operated from the three principal test sites in Texas, Delaware and Maryland and validated the common airborne / ground station concept, including the data link between the three sites.

Aircraft two and four have already been operating between the Boeing Flight Test Facility in Delaware and the Naval Air Test Center in Maryland. Aircraft three will also be flown to and operated from NATC in November for initial ship trial preparation so that by year's end, flight testing will become routine at the three principal test sites.

Concluding Remarks

As noted previously, the V-22 requires an extensive test program to develop and demonstrate compliance for three flight regimes. This compliance testing is now accelerating. There is a great deal of testing still to be accomplished, however, the joint Navy-Bell-Boeing test team believe that the major technical challenges have been met. From this stage of development no technical showstoppers' have been uncovered, or are anticipated. The premise that high flight test data productivity combined with selective use of the simulation facilities and proven analysis methods can expedite the test program has, we believe, been proven.

The test team is enthusiastic about being a part of this historic flight test program which we believe heralds a new era in the annuls of aviation – not only is it history in the making, it's hard work, ... and it's fun.

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