

SEVENTEENTH EUROPEAN ROTORCRAFT FORUM

Paper No. 91-25

V-22 PROPULSION SYSTEM DESIGN

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SEPTEMBER 24 - 27, 1991

Berlin, Germany

**Deutsche Gesellschaft für Luft- und Raumfahrt e. V. (DGLR)
Godesberger Allee 70, 5300 Bonn 2, Germany**

OPGENOMEN IN
GEAUTOMATISEERDE
CATALOGUS

N61295

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Abstract

The propulsion system of the V-22 Osprey, comprising the drive system, the power plant installation, and the proprotor, is a unique design driven by the operational requirements of this tiltrotor aircraft.

The drive system, which includes five gearboxes, shafting, and special nonlubricated flexible couplings, is described. The rationale for arrangement and lessons learned is followed by a discussion of the effect of special requirements such as shipboard compatibility and cooling. Lubrication system operation from horizontal to vertical modes, operation over a wide range of engine speeds, and altitudes from sea level to 6000 m are substantial design considerations. The development testing is also described.

The power plant is the Allison T406 two-spool version of the T56 series engine rated at 4550 kW (6100 hp), which is designed to operate from horizontal to vertical positions at each wing tip. The power plant installation, including air induction, engine mounting, fly-by-wire controls, fuel system, and secondary power, is described.

The rotor system design is driven by the wide range collective pitch control required to achieve tiltrotor flight and the need for aeroelastic stability with a mechanically simple system. Rotor system material and construction, component design, blade folding, development problems, and testing are discussed.

Introduction

The V-22 propulsion system represents 40 years of engineering endeavor and encompasses three different models of flying prototype aircraft. The first was the XV-3 in the early 1950s. This aircraft was powered by a piston engine (rated at 336 kW) installed in the fuselage behind the pilot. The drive train incorporated a speed shift mechanism, in order to slow down the rotor speed for high-speed converted flight while maintaining constant engine speed. The aircraft was plagued with insufficient power and rotor pylon dynamic stability, but was successfully converted to airplane flight.

The next generation tiltrotor, the XV-15, truly demonstrated the feasibility of the technology, especially the tilting-engine concept. The free power turbine allowed the rotor system to operate over a wide range of speeds without drive train shift mechanisms. Pylon stability was satisfactory with a three-bladed gimballed rotor attached to a stiff pylon.

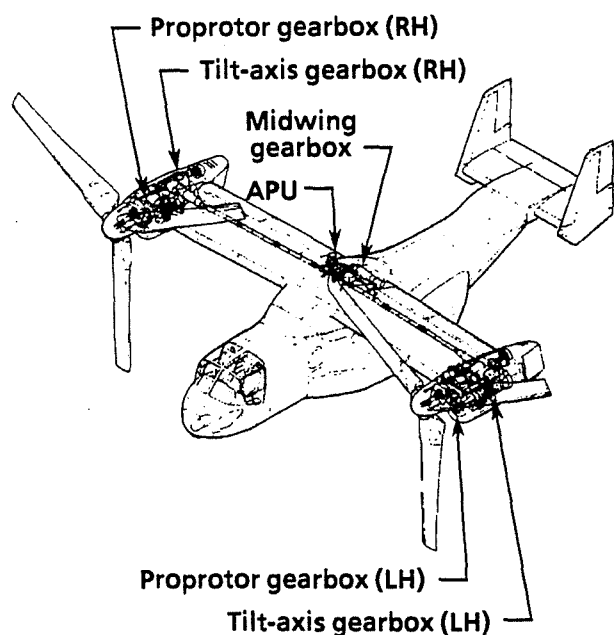
The V-22 propulsion design is the first design to meet operational requirements as outlined in rigid NAVAIR specifications. Fly-by-wire control technology simplifies the mechanical design, and use of composite materials achieves significant weight savings and other operational advantages.

Drive System

Two 11.5-m diameter (38-ft) proprotors are driven in counterrotating directions by a 4550-kW (6100-hp) turbine engine located in tilting nacelles at each wing tip (Fig. 1). The system of five interconnected gearboxes provides distribution of the total power available from the engines on demand from the proprotors and driven accessories. Power splits are allowable between the two engines in any combination. Power differential during maneuvers is accommodated by transfer across the wing shafts. Full one-engine-inoperative (OEI) condition is accommodated in the same manner.

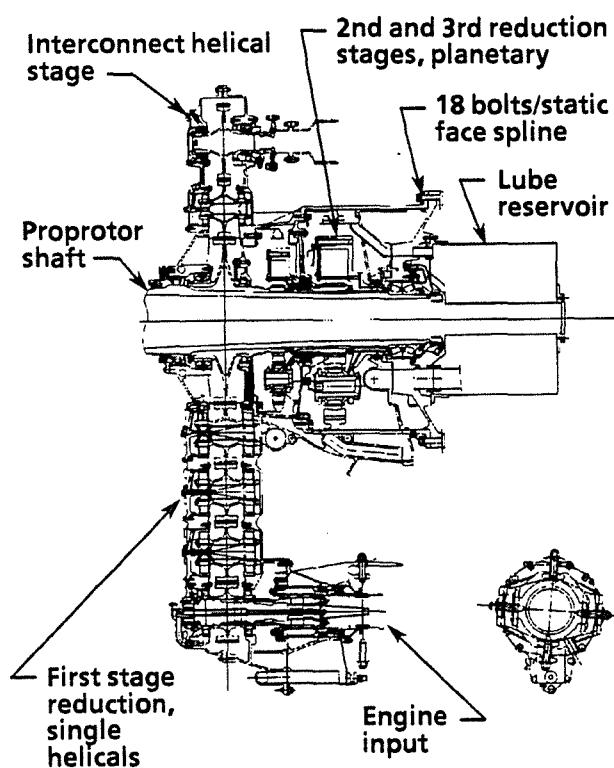
Counterrotation is achieved by deletion of one idler gear from the first stage reduction of the righthand proprotor gearbox (PRGB). On both sides of the aircraft, the first reduction stage of the PRGB is an off-set axis drive allowing the engine and proprotor centerlines to be positioned parallel and 74 cm (29 inches) apart. This offset allows the gearbox to be arranged so that rotor loads are transmitted directly to the tilting structural component while the engine is suspended underneath.

The PRGB is a three-stage speed reduction unit with the principal output being the rotor shaft driven concentrically through each stage (Fig. 2). The need to present a low frontal area in airplane mode dictates a small-diameter gearbox. Epicyclic gear staging fits this need and has the advantage of splitting power to reduce gear mesh loads. Rotor



1-G758

Fig. 1. V-22 drive system.



1-G759

Fig. 2. Cross section of the lefthand proprotor gearbox.

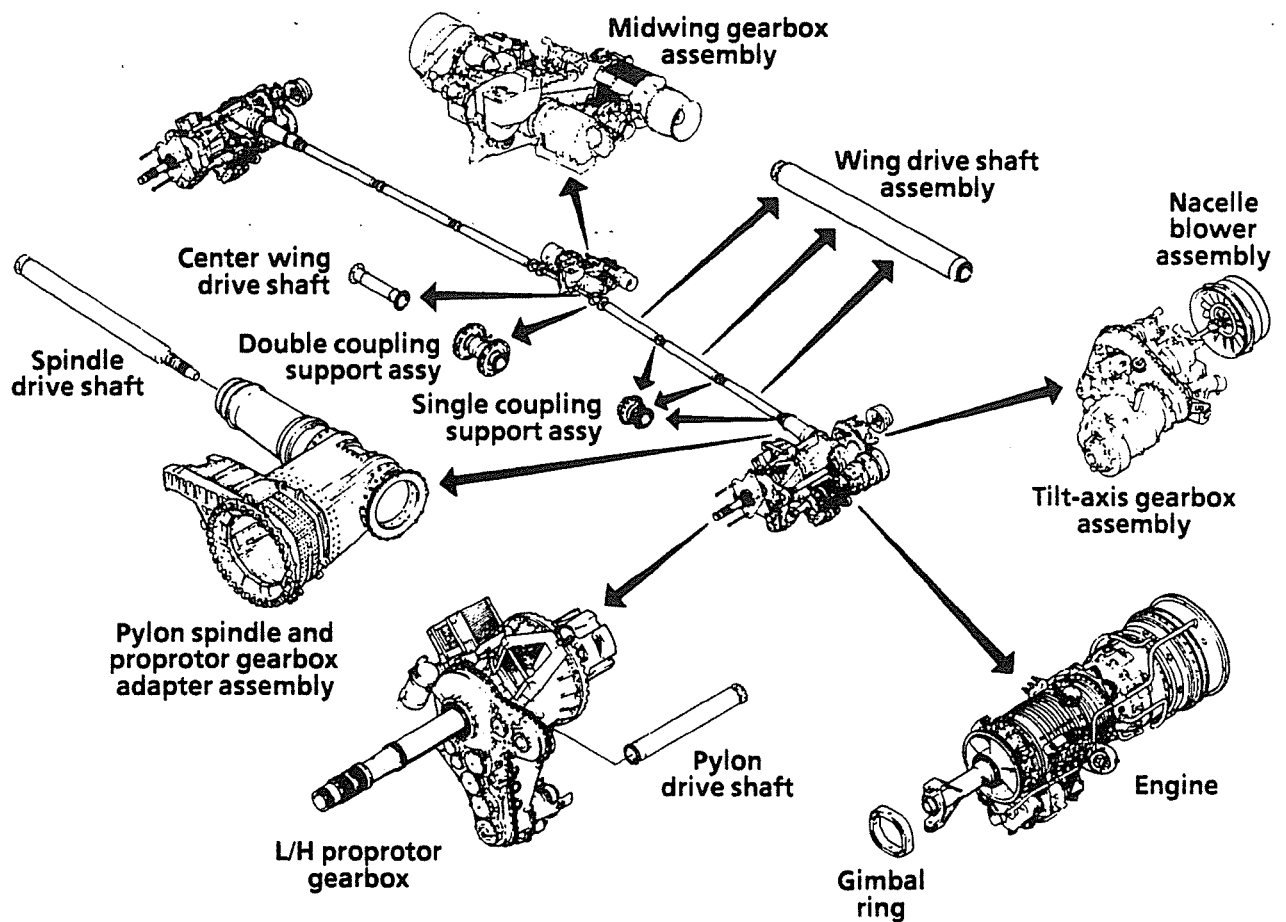
loads are reacted by the gear housing, which is rigidly attached to the tiltable support structure by 18 bolts clamping a static face spline. This type of joint uniformly distributes the rotor torque reaction circumferentially around the structure. The first reduction stage is a single-row helical gear train

spanning the 74-cm (29-in) offset. Another branch of the same helical stage includes the output/input of the PRGB to and from the interconnect drive system. This drive is offset 46 cm (18 in) to the outboard side of the nacelle and lies in the dihedral plane of the wing when the nacelle is in airplane mode. The first bay of interconnect shafting is also parallel to the rotor shaft and clears the pylon support structure; it consists of a drive shaft segment with flexible couplings between the PRGB and the tilt-axis gearbox (TAGB) in such a manner that the gearboxes may be removed and replaced independently. The second and third stages of the PRGB are simple planetary units with the low-speed stage carrier splined to the rotor shaft.

As shown in Fig. 3, the two PRGBs are interconnected by a system of 12 sections of shafting supported by three gearboxes and eight shaft support assemblies that contain dual grease-lubricated ball bearings. The TAGBs contain spiral bevel gear sets which allow the complete nacelles to tilt about the support axis in the wing while maintaining, on demand from either direction, a continuous power flow through the shafts at any nacelle attitude. The two inboard shaft support assemblies and the midwing gearbox (MWGB) have a total of six nonlubricated flexible couplings, each operating continuously at 2.3 deg misalignment to allow the shaft line to accommodate the aircraft wing sweep and dihedral. The total direction change is 13.8 deg. The input/output shaft of the MWGB serves as a simple straight-through support for the shaft segments at the aircraft centerline. Other nonlubricated flexible couplings are located at ten additional locations along the drive line to accommodate structural deflections of the wing and manufacturing tolerance buildup that accrues when components are installed. No special alignment procedures or tools are required.

An overrunning clutch is located at the input to the PRGB in a removable quill which also serves as the forward engine mount. This clutch is a double-row sprag device operating up to the PRGB OEI input rating of 2700 N·m (23,950 lb·in) and 15,000 r/min.

Additionally, the three gearboxes in the interconnect system provide output pads for 13 accessory drives across the wingspan. The aircraft APU is directly connected to the MWGB and can overdrive the system to power a constant-speed generator, an environmental control unit (ECU) compressor, a utility hydraulic pump, and the MWGB oil cooler blower independent of the rest of the system. The APU can be operated when the rotor system is static, with the wing stowed or deployed for flight. The



1-G780

Fig. 3. V-22 drive train components.

mounting system for the MWGB is designed to avoid loads being generated in the housing due to wing structural deflections. The gearbox is also supported by the wing stow ring and thus follows the wing during its 90-deg pivot during folding operations.

Each of the five drive-system gearboxes are independently cooled and lubricated with DOD-L-85734 oil. There are no external pressurized lubrication lines and the heat exchangers are mounted directly to the gear housing, which enhances reliability. Quantitative debris monitors (QDM) are located in the trap of cyclonic debris separators. Filtration is to the 3- μ m level. The pressure and scavenge oil pumps are mounted external to the gearbox and driven by a gear train branching off the first helical stage. In addition, the PRGBs and TAGBs have an emergency lubrication system consisting of oil-misting nozzles fed from continuously replenished reservoirs internal to the gearboxes. Upon gearbox oil pressure loss, these nozzles are activated by compressed air supplied by engine bleed air.

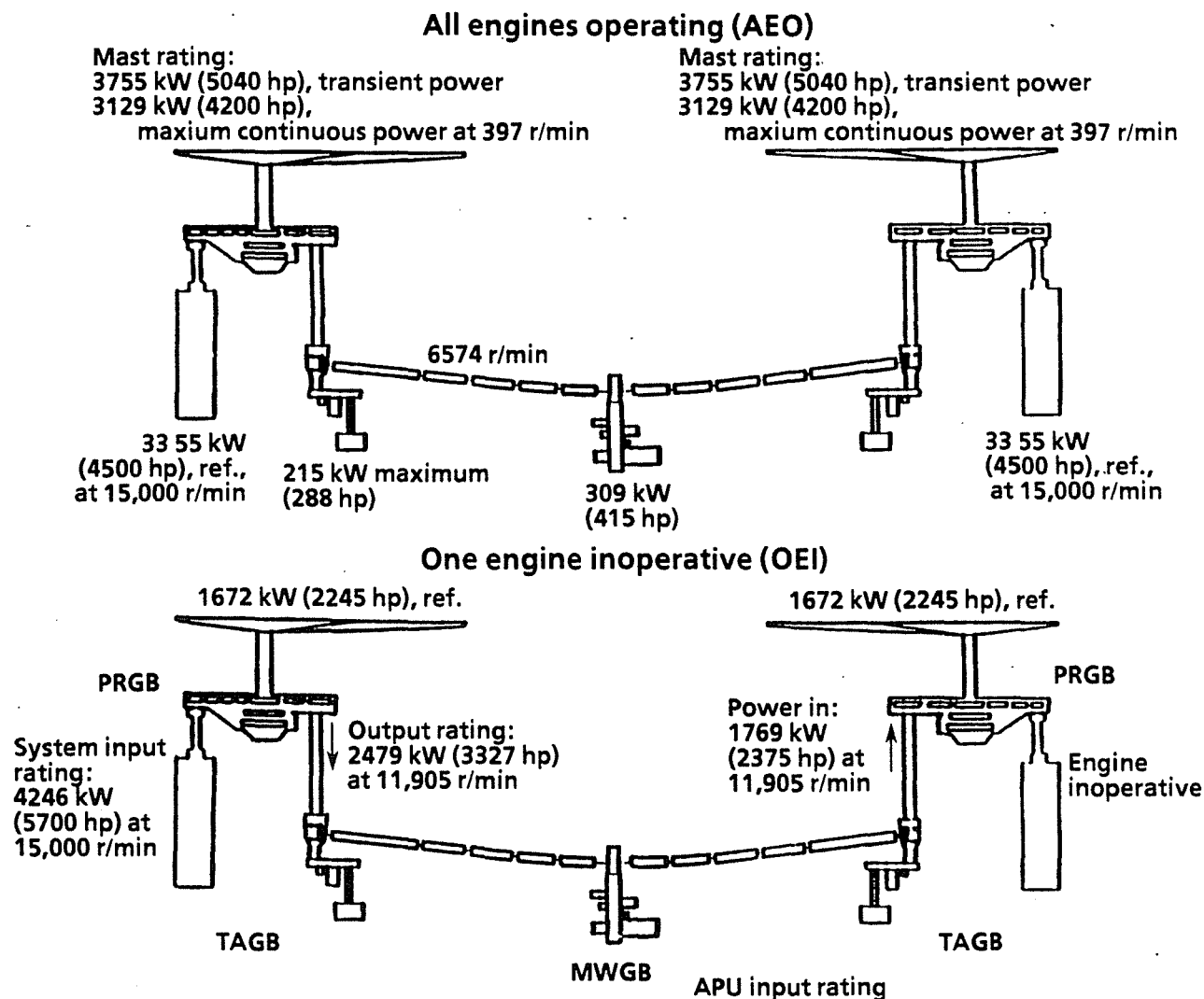
Operation of the proprotors at a 16% reduced r/min for cruise efficiency is accomplished by engine speed

reduction. The drive system has a fixed gear ratio of 37.8 to 1. Drive system ratings are shown in Fig. 4.

Drive system lessons learned during the prototype development of the XV-15 included the following:

- (1) Reduce the complexity of gearbox castings for producibility and separate the functions of tiltable structure from gear housings in order to reduce deflections that affect gear alignments.
- (2) Eliminate the bolted joint at the tilting support structure transition into the spindle and place gearboxes and shafting external to the support structure for maintenance accessibility.
- (3) Provide better management of gearbox seal leak paths to avoid shaft support grease dilution in spindle.
- (4) Mount the engines directly to gearboxes, but avoid generating stresses in the housing by using a gimbaled joint.

Other requirements of the V-22 influenced component configuration, such as the large number of



1-G761

Fig. 4. Drive system ratings.

accessories to be driven. The MWGB on the XV-15 was a one-to-one bevel gear set accommodating the 14-deg shaftline inflection. On the V-22, a series of flexible couplings replaced the function of the bevel gear and the MWGB becomes a lightweight train of spur gears to be accessory drivers.

Shipboard compatibility required ability to brake the rotors and then position the blades for folding and locking the rotors via the drive system against the effects of offset blade weight and surface wind with blades folded. The rotor brake is mounted on an independent gear stage of the MWGB, which reacts directly to the interconnecting shaft line. Both rotors are braked to a stop in 10 s from 40% r/min or in a total of 25 s after engine shutdown. The disk and linings are carbon composite. The disk is 10.5 inches (26.6 cm) in diameter. The rotor positioning unit (RPU) is an externally-mounted hydraulically-powered device mounted on the

MWGB on the same shaft but on the opposite side of the gearbox from the rotor brake. It positions each rotor's nonfolding blade to point inboard from any stopped azimuth, thus allowing the blade folding to proceed.

The wing stow operation on the V-22 is achieved without disconnecting the drive system.

Lubrication of Tilted Gearboxes

Gearboxes for tiltrotor aircraft experience steady-state operation at attitudes from 10 deg aft of vertical to 20 deg below horizontal. In addition, there are transient attitudes which may reach 45 deg nose down or up in airplane mode as well as roll in either airplane or helicopter modes to 90 deg. Another phenomenon associated with tiltrotors is the transient centrifugal force field at the wing tips due to roll rates.

Oil management must carefully consider thermal distributions as they change from hover to high speed. A bearing or gear must avoid excessive flow or being submerged in accumulations of unscavenaged oil, across all attitudes. Oil jet streams must not be distorted by sheets of air or oil spun from gear rims unstripped of oil.

Tiltrotor aircraft are capable of long-distance flight, including over-water routes where a complete lubrication failure must be avoided. For such usage, an emergency lubrication system is essential and the misting system designed into the V-22 is adequate for the purpose.

Oil filling and quantity indicators are oriented to operate in accordance with the position of the tilted gearboxes when maintenance is to be performed. This may occur in helicopter mode, as on a flight line, or in airplane mode, as when the aircraft is stored in a hanger. Functionally, debris monitors are located in the lube flow path as energized by the scavenge pumps.

Oil level and quantities to be added can be determined both statically and dynamically and are displayed remotely, because the nacelle is taller than a man's height and the cowl openings are out of reach.

Testing Facilities

Bench testing and ground-run testing included capability for tilted operation. Oil management development was the principal reason for this. Oil scavenging must be complete for all cavities created at the various rotor tilts and at any position in between. Excessive windage losses consume power and generate heat in local areas. Gear baffles must function and bearings must pass off excessive oil in any tilt position. Loads and deflections generated by the rotor and control system were also included in the testing. These loads varied in amount and direction between helicopter and airplane mode.

The ground-running facilities with tilt capability provided dynamic interaction between the mounting structure and the drive system components. The bench testing facilities were arranged to test individual gearboxes or components. Shown in Fig. 5 is the tiltable bench test stand for the PRGB, which is a balanced frame supporting the test specimen and stand components - a total weight of 158,550 kg (350,000 lb). The stand pivots into a floor pit.

Special Development Problems

Although the arrangement of the drive system is new, the components are conventional state-of-the-

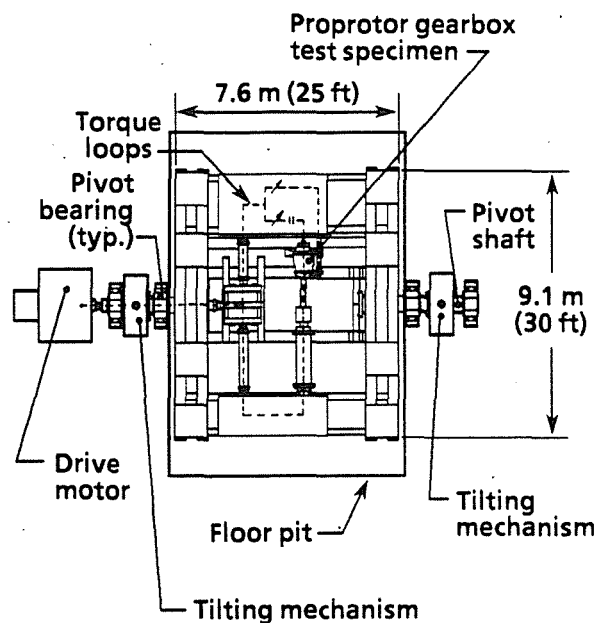
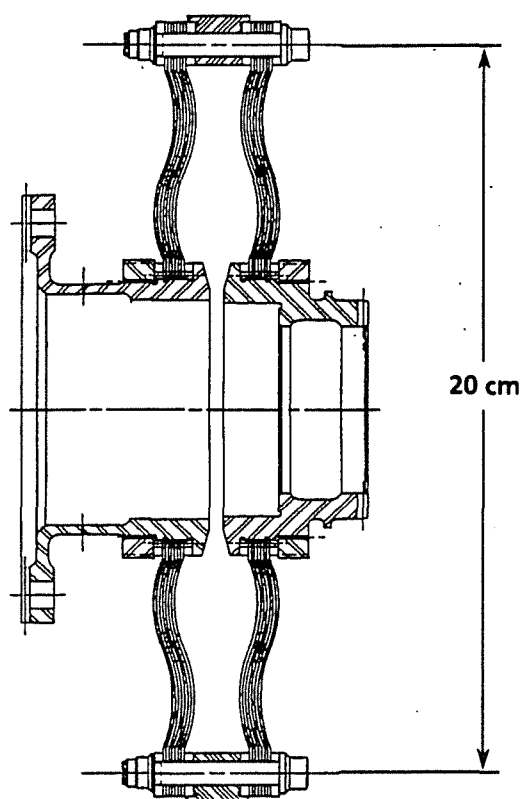


Fig. 5. Proprotor gearbox test stand.

art aerospace-quality gears, bearings, and housings. Two areas of known development risk were accepted going into the program to obtain advantages in weight, cost, and maintainability. Both of these items have been successfully realized.

First, nonlubricated flexible shaft couplings (from Zurn Industries, Inc., Mechanical Drive Division, of Erie, PA) were used at high steady angles, as described above, and required considerable development and rigorous fatigue testing. Zurn's multiple-element convoluted-diaphragm coupling (Fig. 6) was not a new concept, but required extraordinary development effort to obtain reliable operation at up to 3.5 deg misalignment. Stainless steel diaphragms of 0.2159-mm (0.0085-in) thickness, spacing elements, and clamp rings of special proportions were tailored to provide a stress-free assembly. Testing included static and fatigue margin demonstrations. Fatigue testing was conducted at a stress level of 125% of the maximum transient level on four specimens operating simultaneously on a regeneration-type test stand. The couplings proved to have a very benign failure mode. When a diaphragm was forced to fail, a telltale sound was emitted. The edges of the failed diaphragm rub and cause a clicking sound, which is detectable by rolling the coupling through a partial turn; this sound can be heard in an airport flight-line ambient noise background. The couplings also proved to be durable even after diaphragm failures: they were shown to be capable of continued operation for more than 5 hours at maximum torque (OEI) conditions. There have been no failures of the flexible couplings during flight test operation of the prototype aircraft.



1-G763

Fig. 6. Dual multiple-disk convoluted-diaphragm flexible coupling.

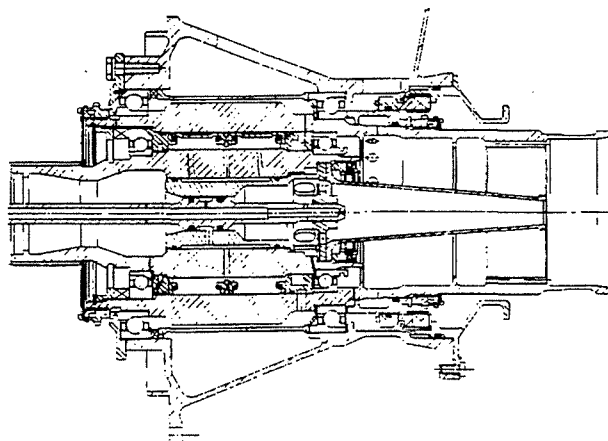
Operating at 6574 r/min, the flexures accumulate 10 million cycles every 25 hours of operation. These stress cycles are mostly sensitive to the shaft misalignment, and nearly independent of the torque transmitted.

Second, engine/drive system overrunning clutches were developed with the Formsprag Product Division of the Dana Corporation. The operation of these clutches was satisfactory for single and twin-engine operations. The overtorquing margins, race/sprag contact surface fatigue, and the retainer cage endurance are good.

Engaging the second engine to an already operating system was problematic at low gearbox oil temperatures, because the cold (high viscosity) oil forced the sprag elements to a position where the usual geometric and spring forces could not operate in the normal manner. An adjustment was made to the sprag retainer that limited the lifting action of the sprag elements, thus preventing the elements from lifting themselves beyond the range of the engaging forces. This modification lowered the temperature at which engagement was possible to an acceptable range. From the required cold-soak temperature of -53.9°C (-65°F), an acceptably short warmup of the oil allows second clutch

engagement. An air restart of an engine can also be made at minimum temperature levels in flight.

Overrunning can be continuous at all r/min splits without race wear. This required extensive alternate oil flows and distribution. The configuration developed includes multiple oil-feed holes and pressure delivery of oil through the bore of the inner races, as shown in Fig. 7.



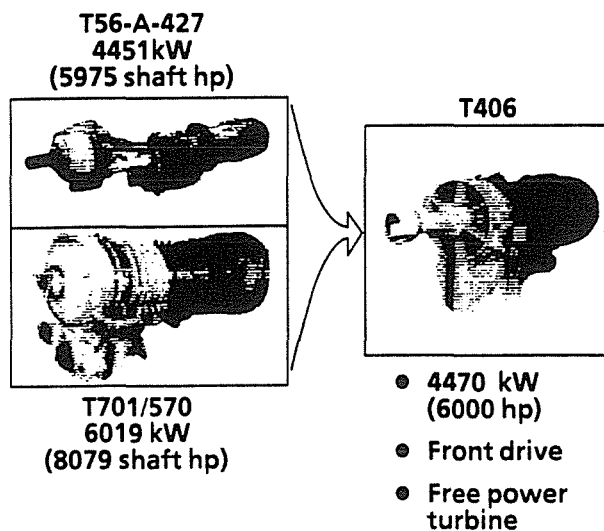
1-G764

Fig. 7. Overrunning clutch assembly.

Positioning of the clutch assembly at the input and operating at high input r/min levels provided the simplest staging, saved weight, and allowed interchangeable field replacement without removal of the gearbox from the aircraft.

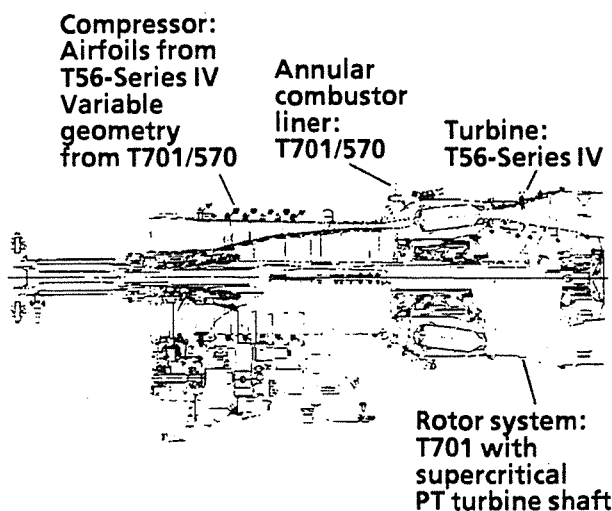
Power Plant

The V-22 is powered by two Allison T406 twin-spool gas turbine engines mounted on each wing tip and attached to the underside of the transmission (Figs. 3, 8, and 9). The T406 engine has a long and successful history in such aircraft as the Lockheed Electra and the C-130. The V-22 aircraft design was well under way before the final engine selection was made by the Department of the Navy, although in the natural order of things the engine development should have preceded the aircraft by about two years. This situation placed Allison under extreme schedule pressure to deliver engines for the ground test article and for the flight vehicle. The engines that were provided for the ground test article were not required to meet the engine model specification, but they served very well for the ground test article. The first flightworthy engines did not meet the model specification weight and fuel economy, but produced predicted power at measured gas temperatures 32.7°C (59°F) above that allowed in the production model specification. With time and development, Allison produced engines that were in full



1-G785

Fig. 8. Derivation of the T406 engine.



1-G786

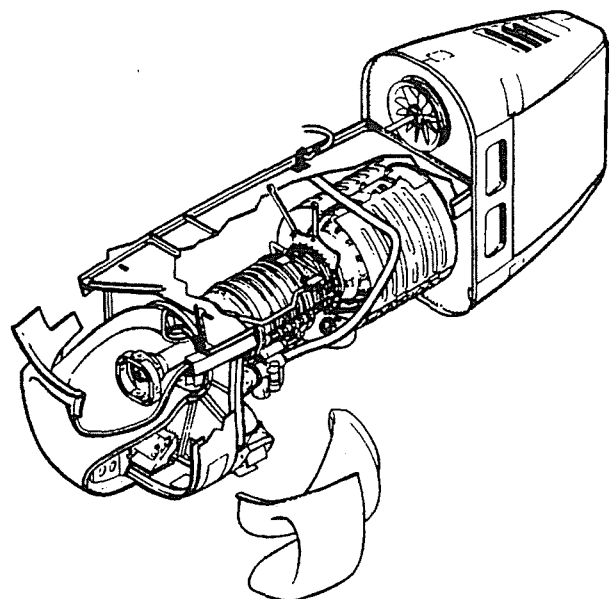
Fig. 9. Cross section of the T406 engine.

compliance with the specifications and to date the engine problems have been relatively minor.

The engines operate in the vertical mode during takeoff to provide some 182 kg (400 lb) of lift each in the form of exhaust thrust. The performance advantage of the exhaust thrust more than compensates for the increased engine weight required in the lubrication system due to tilting. Allison constructed a complete test rig to develop the lubrication system, with the result that the system is working quite well.

Power Plant Installation

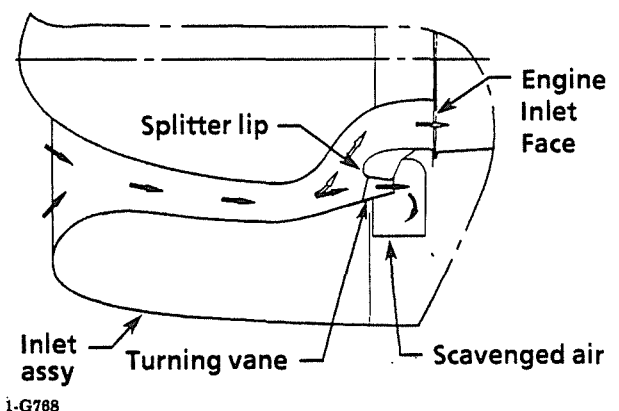
A composite view of the power plant installation is depicted in Figure 10.



1-G787

Fig. 10. Nacelle engine installation.

Air Intake. The view of the engine air inlet (Fig. 11) shows the path of air as it enters the particle separator on its way to the compressor entrance. This particle separator design is a joint effort between Boeing and Bell using technology and internal flow computer codes from Boeing Seattle, wind tunnel model testing at Boeing Philadelphia, and full-scale particle separator test development at Bell Helicopter. The full-scale particle testing was accomplished over a period of about 18 months. The initial design did not meet the NAVAIR model specification requiring separation efficiency of 90% for particles in the 100- to 1000- μ m size; for the 20- to 100- μ m range, the 75% requirement was exceeded. This was unexpected, as more difficulty had been anticipated with the smaller particle size. The results of the development testing yielded changes to the splitter lip location and the outer wall to reduce bounce of the larger particles into the inlet gap. In the fully developed version, pressure drop losses were held to 0.7% or below.



1-G788

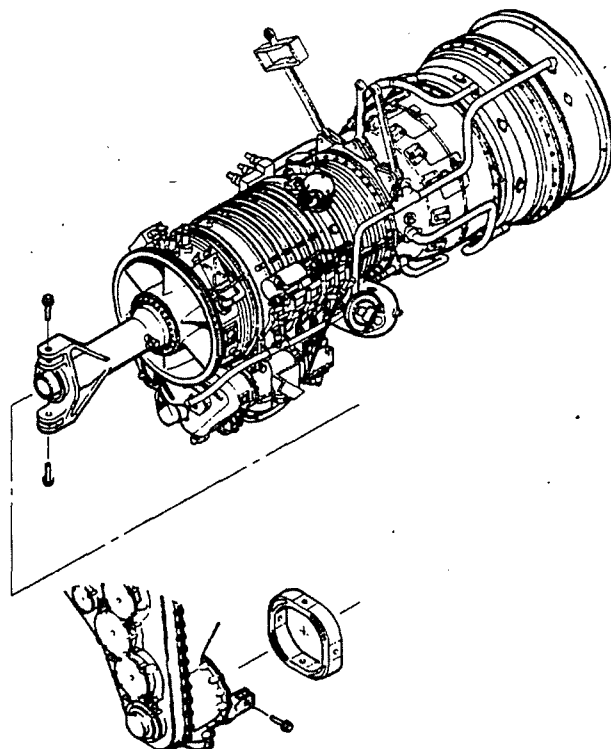
Fig. 11. Inlet air flow

The inlet is protected against atmospheric icing by designing to a heated running wet philosophy. As can be seen on Fig. 10, the forward portion of the inlet is split down the middle, each half being a fiberglass composite assembly electrically heated by means of the Lucas Aerospace Spraymat process. The aft portion of the inlet system is the splitter lip and vane assembly, which is a welded titanium structure mounted directly to the front face of the engine inlet. This unit is heated by engine compressor interstage air. A test article was fabricated and the development and qualification testing has been successfully completed in the NASA Lewis icing tunnel. During these tests, a reduction of the electrical load requirement to about 46% of what had been originally predicted was achieved by applying just enough energy to keep the surface ice free.

To date, inflight aircraft testing has revealed that the inlet is remarkably distortion free when compared to the engine limit (i.e., 36% of the maximum engine limitation).

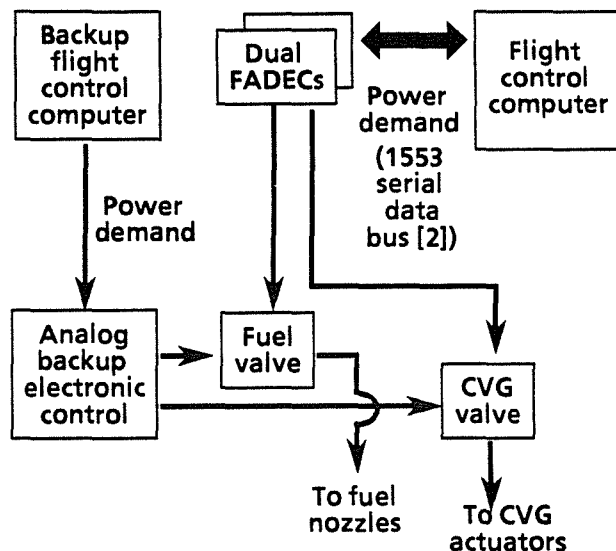
Engine Mount. The engine is attached (Fig. 12) to the prop rotor gearbox at the front or drive end by means of a gimbal that reacts shear loads as well as axial forces. The aft mount comprises three single links that attach to the engine at its midframe and react only lateral shear loads, but no axial forces, thus allowing for thermal growth. Both front and rear mounts react torque, which means that the mount system is torsionally redundant. This occurred because it was determined, after the design was released and hardware was being fabricated, that the front gimbal had negative stress margins for the revised dynamic design loads; the easiest way to correct the mount system was to add a third link at the midframe. It should be noted that the aft inboard mount has a soft "racetrack" section to tailor the stiffness of this link for proper lateral frequency placement. Another change that occurred during flight testing was a stiffness increase for the gimbal ring. The engine vibration levels are well within Allison's specified limits.

Engine Controls. The engine controls for the V-22 are integrated into the flight control system. As can be seen on Fig. 13, the control elements communicate via a 1553 bus. There is no mechanical link between the cockpit and either the analog backup electronic controls (ABEC) or the two full-authority digital electronic controls (FADEC). It was decided to provide the ABEC for full scale development risk reduction in case the FADECs had undetected software errors. To date, there have been several instances where both FADECs failed fixed and the ABEC was selected to keep the engine online and



1-G769

Fig. 12. Engine mount.



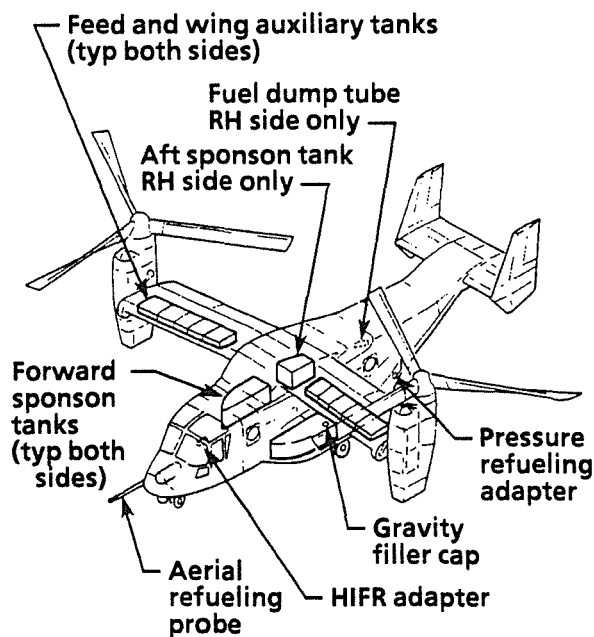
1-G770

Fig. 13. Control architecture.

operating. As might be expected, there have been some data bus communication problems and the engine power turbine overspeed limiter was dynamically unstable when it came into operation. This problem required a compensation network and notch filter to be installed into the FADECs. High-altitude throttle chops produced lean combustor blowouts and the FADECs were once again modified to enrich the deceleration schedule by 25%.

The controls were manufactured in the United Kingdom by Lucas Aerospace. Each engine is provided with its own engine condition lever with off, idle, crank, and fly positions. The pilot sets the engine condition lever to the desired power condition and the aircraft flight controls maintain proper rotor r/min by adjusting the blade pitch as necessary.

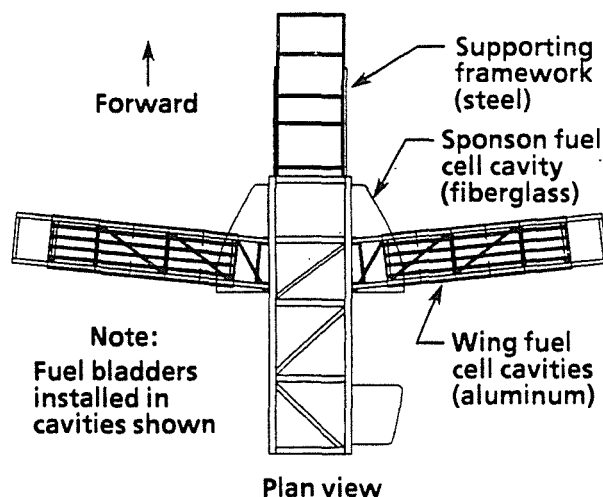
Fuel System. The fuel system (Fig. 14) has provided one of the most significant design challenges in the power plant installation. By contract, the system is required to be in compliance with MIL-STD-1290 for crashworthiness and MIL-F-17874 for design and function. Also, ballistic vulnerability played a significant role in the design because one of the V-22's primary missions is Marine assault, thus exposing the aircraft to hostile ground fire. These design drivers, coupled with an aggressive weight target, produced a complicated and challenging design problem. This situation was recognized up front and a complete replica of the fuel system was built in the form of an "Iron Bird" (Fig. 15). Testing on the Iron Bird preceded aircraft operations, and many (though not all) problems were found and resolved. Without this valuable tool, significant program delays would have occurred.



1-G771

Fig. 14. Fuel system configuration.

The functional concept of the system (Fig. 16) is that each engine has its own dedicated feed tank and that fuel from the rest of the system replenishes the feed tank as fuel is consumed by the engine. The burn sequence which is automatically controlled by the dual redundant fuel management units (FMU) first transfers all fuel out of the wing auxiliary cells.



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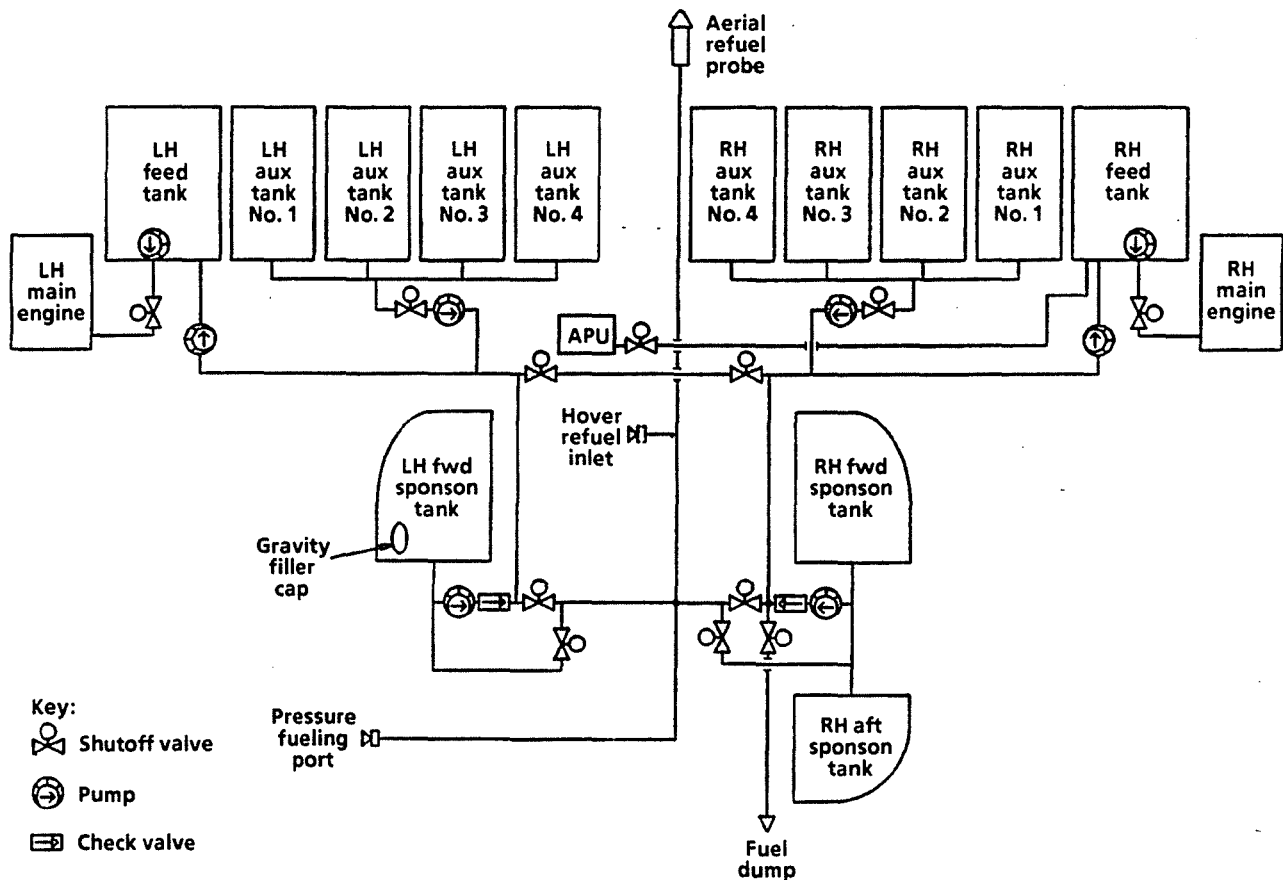
Fig. 15. Fuel system "Iron Bird."

Then the lower sponson fuel is consumed, leaving the feed tank volume for last. Functional control of the system is usually automatic; but the pilot does have some override options such as manual control of the cross transfer valves and the ability to select boosted fuel transfer and feed, fuel dump, and aerial refueling. Normal fuel transfer and feed are in the suction mode (for ballistic vulnerability reduction), which has proven to be a development problem, especially when the tanks are empty and the defuel valves leak air into the transfer system. The level control system in the feed tank has also experienced some unreliability problems resulting in overfills and underfills. The situation was remedied by a redesign, and the final system has the following significant features:

- a. Nitrogen inerting of the ullage
- b. Pressure refueling
- c. Gravity refueling
- d. Suction defueling
- e. Fuel dump
- f. Aerial refueling
- g. Selective loading during refueling
- h. Breakaway valves at critical connections

An additional feature is the monitoring capability of the system: the operational status is stored in the FMU and is available to the pilot in flight as well as to the ground crew for trouble shooting and servicing. The operational availability of the system has now reached a very satisfactory level.

Engine Exhaust/Nacelle Cooling. The engine exhaust system for the V-22 is a variable-area, plume-mixing device whose thermodynamic performance is classified. In addition to providing the previously mentioned functions, it serves as an ejector to pull cooling air through the engine bay.



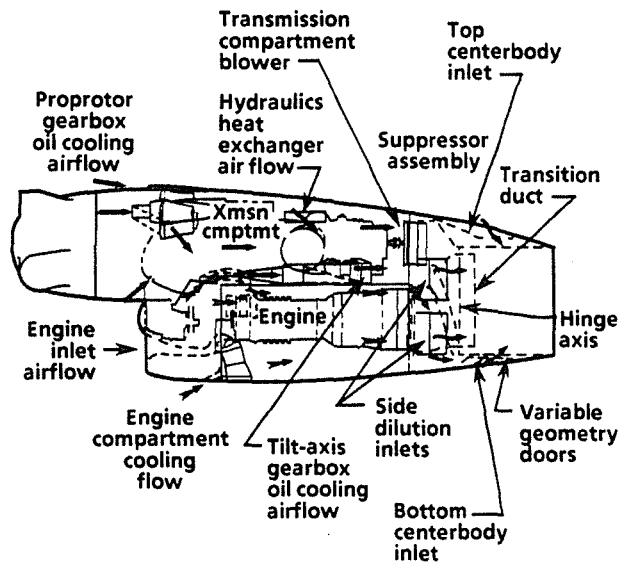
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Fig. 16. Schematic of the fuel system.

As can be noted on Fig. 17, the exhaust air from the transmission compartment blower is mixed internally, thus providing plume cooling.

Development testing has shown that it will be necessary to deflect the exhaust stream outboard away from the fuselage to prevent hot air from entering the various avionics and environmental control inlets under the wing. The performance aspects of the variable exhaust area are still being debated as a drag reduction feature. The entire unit has been designed and fabricated by Airesearch Los Angeles.

Engine compartment cooling, exhaust suppression and exhaust plume dilution, and reduction of skin temperatures are a part of military vulnerability reduction measures. The engine bay cooling air is induced through the forward three inlets by ejector action in the suppressor. As shown in Fig. 17, a transmission compartment blower is mounted on the centerline of the nacelle and is shaft driven from the TAGB accessory gearbox section. Cooling air is thus induced to flow through the gearbox and hydraulic system radiators in the upper nacelle and into the engine exhaust to join the aft portion of the exhaust suppressor. During airplane mode flight and in the event of blower failure, gearbox cooling is

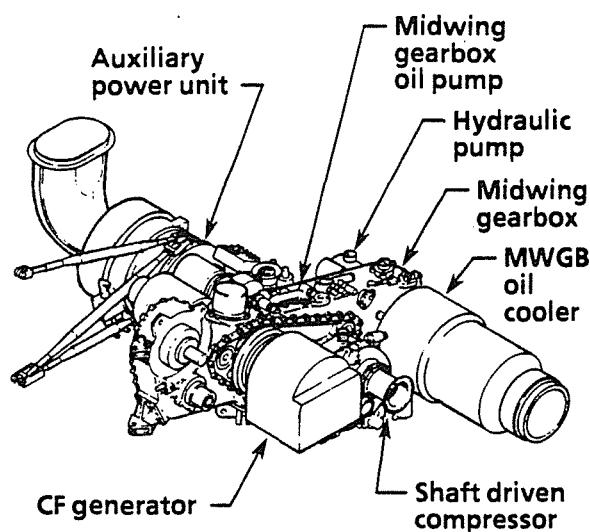


1-G775

Fig. 17. Nacelle air management.

by ram air through scoops and openings in the forward portion of the nacelle.

APU. An aircraft the size and complexity of the Osprey requires an APU (Fig. 18). This need is supplied by a flat-rated 186-kW (250-hp) single-spool gas turbine that drives into the midwing gearbox.



1-G776

Fig. 18. APU / midwing gearbox.

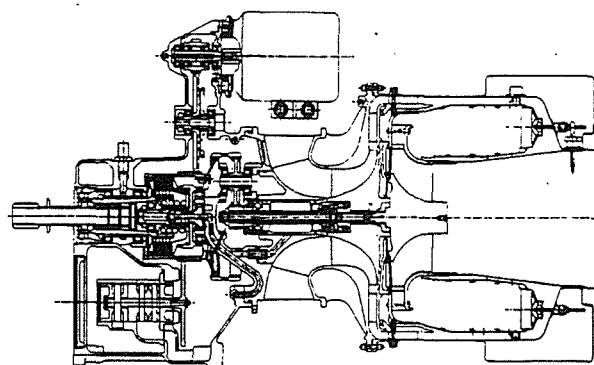
The APU is electrically started by the aircraft battery or a ground power unit and once it becomes operational, the 34,470-kPa (5000-psi) hydraulic pump activates the hydraulic engine starter (on command). The hydraulic engine starter is a lightweight unit specially designed for this application by Airesearch Fluid Systems. In the event the APU does not start, there is a provision for ground power hydraulic start of the main engine.

When the flight engines are inoperative, the APU drives the following:

1. Hydraulic pump (34,470 kPa/5000 psi).
2. Load compressor for environmental control system.
3. Constant frequency alternator.
4. Oil cooler fan for gearbox.
5. Gearbox oil pump.

In this mode, the midwing gearbox is isolated from the drive train by means of an overrunning clutch. Conversely, when the flight engines are operative the APU is isolated by an overrunning clutch and the above accessories are part of the main drive system. The APU is intended for ground operation only and thus is not entirely surrounded by firewalls. The power unit was designed and manufactured by Sundstrand Turbomach in accordance with the Bell-Boeing specification.

Figure 19 shows a cutaway section which reveals the turbomachinery, reduction gear, and multidisk clutch. Since the unit is a custom design with aggressive weight targets, Turbomach was forced to use a number of unproven components and accessories which led to numerous reliability problems. New lightweight electrical and ignition harnesses, igniter plugs and the clutch servo system



1-G802

Fig. 19. Sundstrand Turbomach APU.

were the major contributors to the high failure rates. An APU test stand was constructed to expedite repair and rework on site instead of returning units to the manufacturer in San Diego. Integrating the software and clutch operation with the drive train operation has also been a significant challenge, but most of these problems are now past, and APU operation is now reliable.

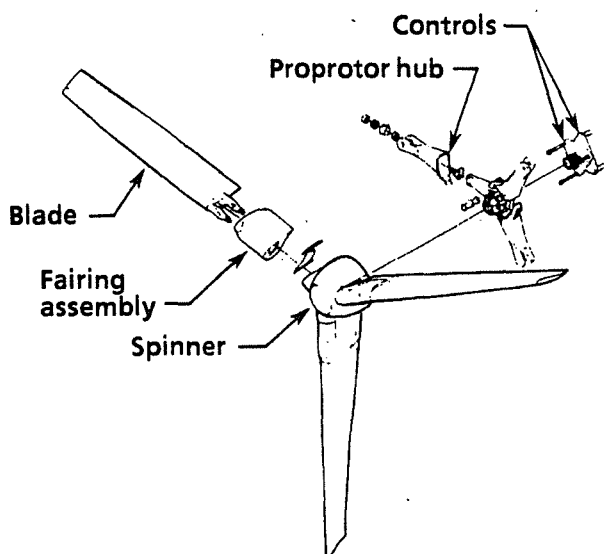
Rotor System

The proprotor assemblies of the V-22 tiltrotor employ helicopter rotor technology, rather than that of airplane propellers. The rotors have cyclic and collective pitch control and attach to the mast by a constant-speed drive coupling that allows flapping freedom. Each rotor has three blades, which are rigidly joined to a central hub; the first inplane natural frequency of the blade is above the rotational frequency. Thus the rotor is of the free-flapping, stiff-in-plane type, so that lead-lag bearings and dampers are not used, and the rotor system is not subject to the ground resonance type of mechanical instability. Figure 20 depicts the right-hand proprotor assembly.

Cyclic and collective pitch are introduced into the rotor by a swashplate. The cyclic travel range is equivalent to that of typical helicopters; but the collective travel range is much greater, to accommodate the pitch needed during high-speed flight in the airplane mode.

Although the materials and construction techniques were derived from helicopter technology, the proportions of the elements and the selection of the 3-bladed rotor are not typical of recent multibladed helicopter designs from Bell Helicopter Textron, Inc. or other manufacturers. The structural arrangement is driven by the requirements of the tiltrotor aircraft.

The stiff-in-plane rotor, tuned above resonance with respect to the fundamental rotational frequency, is



1-G842

Fig. 20. Proprotor system.

selected to simplify the overall aeroelastic design of the aircraft; it avoids the ground resonance possibilities of an articulated or soft-in-plane rotor, and results in a mechanically simple hub without lag bearings, flexures, or dampers. This arrangement avoids Coriolis loading, but still results in relatively large blade-root bending moments.

The flapping freedom enabled by the constant speed drive coupling provides good aircraft control. Ability to make rapid turns in hover or at lower flight speeds, which is a substantial control advantage of the tiltrotor aircraft over other types of convertiplanes, is provided by differential cyclic pitch that tilts the thrust vector of the rotors. Here the flapping motion is important (i.e., the thrust vector tilt, rather than rotor hub moment) for control power.

Three blades, rather than four or more, are used to achieve a minimal amount of delta-3 (pitch-flap) coupling, without resorting to a complex control system.

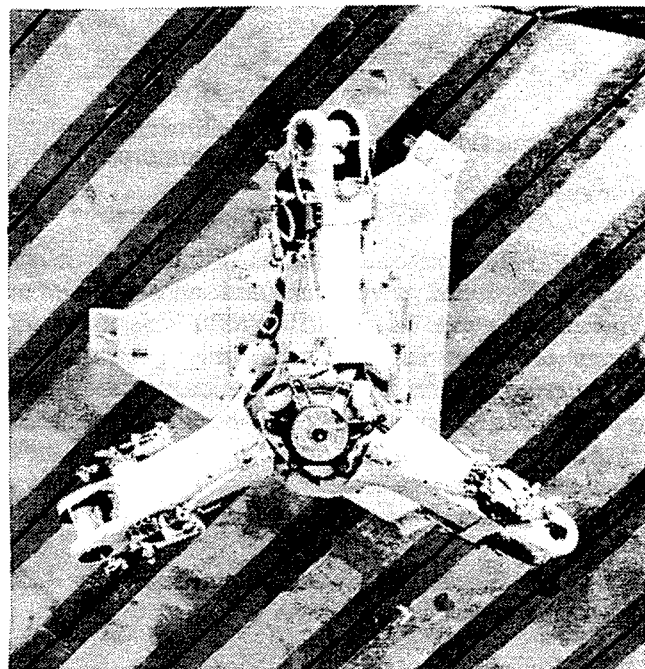
Materials and Construction

The blade and hub are composed primarily of carbon-fiber- and glass-fiber-reinforced epoxy, with attachment fittings of corrosion-resistant titanium alloy and stainless steels. Aluminum is used for some secondary attachments such as blade root fairings and in the folding mechanisms. Blade pitch change motion and centrifugal force reactions are accommodated by elastomeric bearings; other bearings in the rotating controls and folding mechanism are lined with Teflon® fabric. The rotor hub has no lubrication requirements, and the rotating controls

require lubrication only on the swashplate rotation bearing.

Rotor Hub Assembly

The hub assembly (Fig. 21) consists primarily of the constant speed drive coupling; the fiberglass/epoxy yoke; pitch change bearings, which provide for blade pitch angle change and react blade bending and centrifugal forces into the yoke; the carbon fiber/epoxy grip; and the blade folding mechanism.



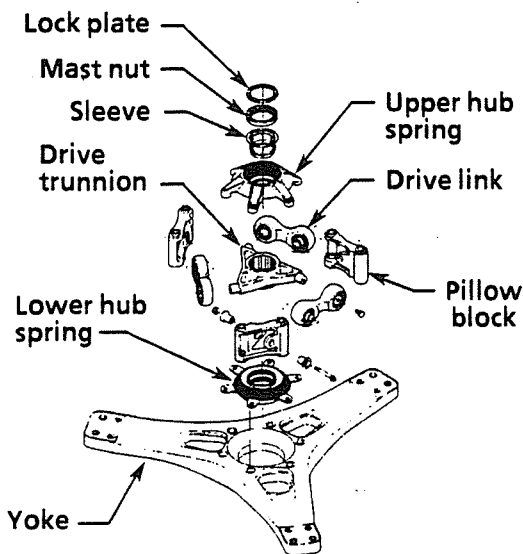
1-G843

Fig. 21. V-22 hub assembly.

Constant Speed Drive Coupling. The constant drive speed coupling (Fig. 22) transmits drive torque to the rotor and allows hub flapping up to the stop travel limit of 10.5 deg. The coupling comprises spherical elastomeric upper and lower hub springs, which act as centering bearings and also react rotor thrust, and a three-link constant speed drive mechanism that transmits torque.

A number of concepts were considered in search of a reliable, long-life, constant-speed rotor drive coupling, and several designs were evaluated by sub-scale tests. One other type of coupling was subjected to some full-scale testing also.

The three-link drive finally selected for the V-22 was conceived and developed by Lord Corporation (Erie, PA); Barry Controls (Boston, MA) also is licensed to manufacture the links. The links are arranged as three sides of a hexagon. One end is driven by a spider splined to the rotor mast and the other end attaches to a pillow block bolted to the yoke. Elastomeric bearings of a carefully chosen

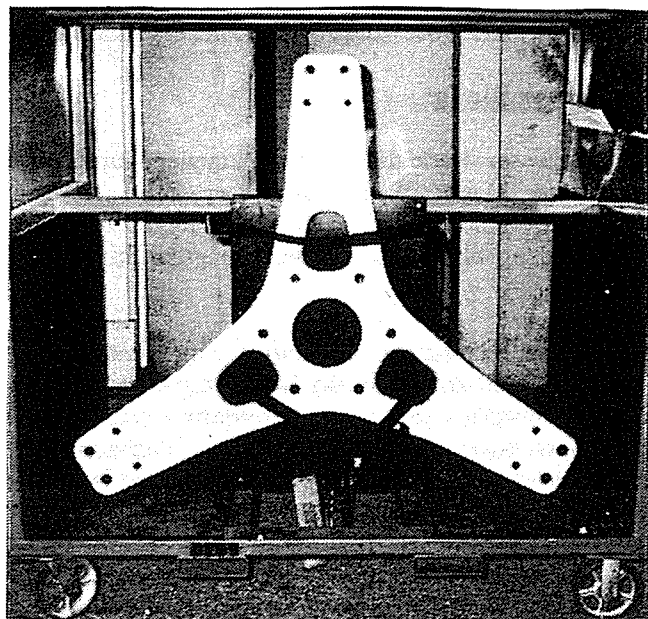


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Fig. 22. Drive coupling.

radial stiffness are installed in the link ends to attach them to the supporting structures. In operation, the constant speed of the drive is achieved by oscillating deflections along the axis of the links. Careful measurements have shown a very nearly constant speed output from the coupling.

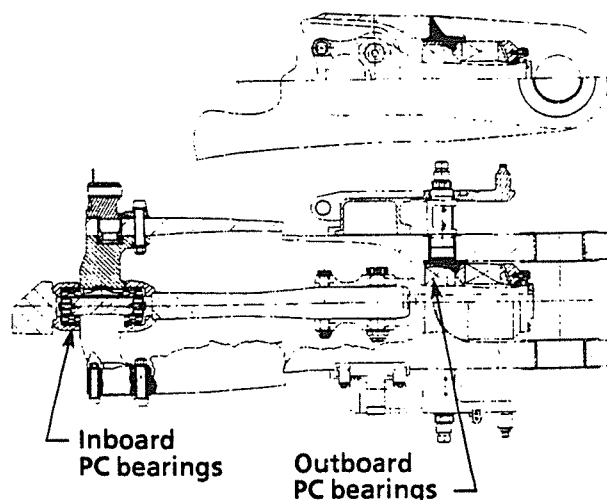
The Yoke. The yoke (Fig. 23) is made of S-2 fiberglass/epoxy molded to finished shape in a closed cavity matched die mold. Only minor machining, including boring of attachment holes and the central clearance hole for the mast, is required after molding. Finishing consists of nondestructive inspection, installation of antifretting coatings and bushings in the attachment areas, and painting.



1-G845

Fig. 23. V-22 yoke.

Pitch Change Bearings. The elastomeric pitch change bearings attach between the yoke and the grip. Figure 24 shows a section through the hub with the bearings installed. The inboard bearing set mounts in a shaped hole machined into the yoke and consists of a three-bearing set. The journal bearings attach a small shaft to the yoke, and a spherical bearing mounted between the journals attaches the shaft to the inboard bearing beam which, in turn, attaches to the grip. This arrangement minimizes the overall diameter of the bearing package, helping to minimize the frontal area presented by the hub in airplane flight mode.



1-G846

Fig. 24. Prop rotor hub.

The outboard bearings, consisting of a radial bearing and an axial bearing to carry blade centrifugal force, attach to a spindle bolted to the outboard end of the yoke and are housed directly in the grip.

The Grip. The grip is constructed of carbon fiber-epoxy. Its basic function is to attach the blade to the rotor yoke and controls. The blade attachment to the grip includes the blade folding mechanism.

The grip is constructed by filament-winding of nine tubular layers, with insertion of precut plies and preformed filament-wound belts between each wound layer. After winding, the grip is cured in a closed-cavity mold, laminating pressure being supplied by an internal bladder. The molded grip is finished in a manner similar to the yoke. The grip is a massive composite laminate, reaching a maximum wall thickness of approximately 50 mm (2.0 inches). In addition to carrying the blade root bending loads, it is subjected to high shear loading because of the relatively short spacing of the blade attachment and the pitch change bearings.

Centrifugal force is transmitted from the blade through the main attachment lugs on the outboard end of the grip. These lugs consist of eight filament-wound belts, laminated into the grip between the ± 45 -deg grip barrel windings. The centrifugal force shears out of the belts into the barrel, and then is transmitted into the fitting housing of the elastomeric retention bearing.

The main attachment lugs transmit blade chordwise bending moment directly into the grip, and, in conjunction with the fold latches, the beamwise bending moments. The bending moments are then reacted into the radial pitch change bearings.

The pitch horn, a fitting for connection of the controls to the grip, is bolted to a flat surface on the inboard end of the grip. The grip laminate is primarily 0-deg and ± 45 -deg carbon fiber epoxy in this area.

Blade Fold System. The blade fold system is a part of the aircraft folding system, which reduces the space required for shipboard storage. The entire aircraft fold system comprises the rotor positioning unit (RPU), nacelle tilting, and wing fold systems, in addition to the blade fold mechanism.

The blade fold system is electrically powered by a motor for each blade housed within the hollow main blade bolt. The motors connect through lead cables and a slip ring to a nonrotating power source. The sequencing of blade folding is as follows:

1. The rotors are indexed with a "master blade" aligned with the wing by the RPU.
2. The blade collective pitch is raised to the maximum travel by the hydraulic flight control actuators.
3. The motors on all three blades of both rotors are energized simultaneously to (1) unlock the blades from flight position, (2) engage the pitch locks to prevent blade droop loads from reacting into the controls during folding, and (3) open the appropriate blade root fairing doors.
4. When the pitch locks are engaged and the blade latches disengaged, the master blade motor shuts off; this blade does not fold.
5. Continued motor operation of the remaining blade motors drive these blades to the folded position.

Unfolding is the reverse of the above sequence.

Fold Drive Mechanism. As mentioned above, the blade fold motors are housed within the main blade pins. Each motor drives two differential planetary reduction gears, attaching to the blade root and reacting into the fold latches mounted on the grip. A manual drive device is available so that the blade can be folded or deployed if a motor or electric system failure occurs.

Fold Latch Mechanism. The fold latch fittings attach to each side of the grip, by means of clamping bars, to form a collar encircling the grip. Shear loading from the latches is transmitted into the grip by a pin engaging a bored hole in each side of the grip. This arrangement avoids a multiplicity of highly loaded fasteners in the grip barrel.

A linkage driven by the output of the fold gearing moves the blade latch pin, the pitch lock, and the fairing door hinges. When these elements reach their travel stops, the gearing torque causes rotation of the blade relative to the grip. A sequencing bellcrank, mounted on the fold latch housing, senses the relative position of the gearing, and controls the latching and folding motions.

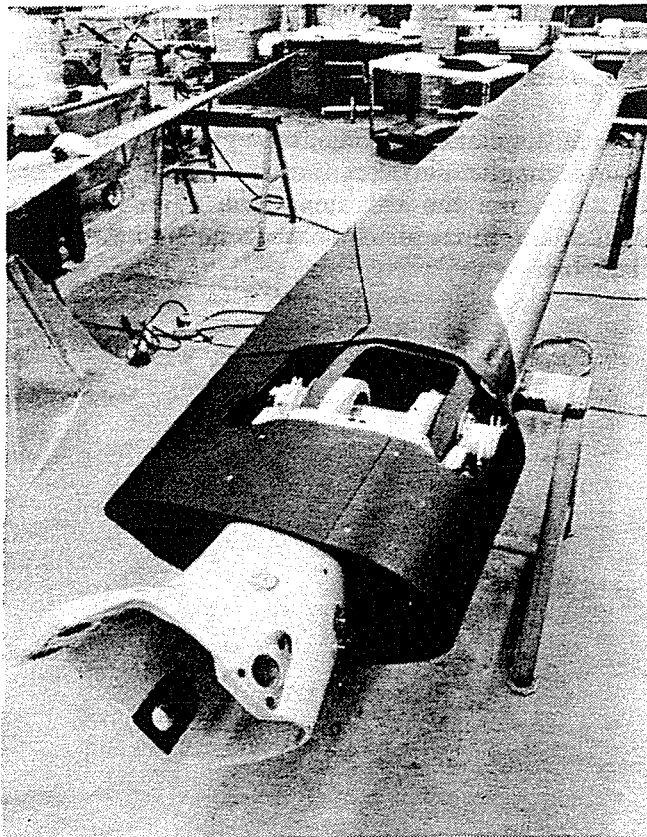
Proximity switches, as a more reliable alternative to limit switches, are used to stop the motor after the proper time, and to signify completion of the folding function.

The primary latch mechanism consists of a fixed stop machined into the latch fitting body, and a sliding pin housed in the fitting body. The latch mechanism maintains uniform loading on the laminated-composite blade root tangs by its inherent features.

Proprotor Blade

The proprotor blade differs from a typical composite helicopter blade in its geometry, and in the construction of the blade root, which forms a part of the low-drag blade-fold system. Figure 25 depicts the blade.

The blade has linear chordwise taper, nonlinear beamwise thickness taper, and approximately 45 deg of theoretical overall aerodynamic twist. The chordwise taper and high twist are to achieve high cruise efficiency in the airplane flight mode. The large amount of beamwise thickness taper is to retain high bending stiffness in the plane of rotor rotation in the airplane mode, where, because of the high twist, the beamwise direction of the blade is oriented very nearly in the rotational plane. In-plane frequency placement remains well above 1/rev under all blade pitch angles.



1-G847

Fig. 25. V-22 rotor blade.

The principal elements of the blade are a nose cap assembly, spar, and afterbody.

Nose Cap Assembly. This assembly comprises the erosion protective strips and the deicing heater element. The erosion protective strips include a hot-formed titanium strip extending from 25.0% span to the blade tips and a nickel cap extending from 75.0% span to the tip. The deice heat element is of woven wire. The elements of the nose cap assembly are bonded together in a special manufacturing tool.

Spar Assembly

The spar assembly forms the main structural element of the blade. The spar contains eight full-length filament-wound belts, four of which encircle the main retention bolt and four which extend in-board to form the fold latch extension tangs. Webs of ± 35 -deg carbon fiber epoxy carry shear loading in the tangs; torsion wraps of ± 45 -deg fiberglass, inside and outside the belts, carry shear and torsion in the spar, and form the box structure. A lead nose weight is bonded into the spar at the blade tip for section balance to preclude aerodynamic flutter.

Afterbody. The blade afterbody consists of a 0.5mm (0.021-inch) outer skin supported by Nomex® honeycomb core. The skins are multiple plies of

fiberglass tape and include a woven outerply to protect the tape fiber and to aid in avoiding water penetration into the core. The aft edge of the skins are reinforced by a trailing edge strip of fiberglass, with spanwise-oriented fibers.

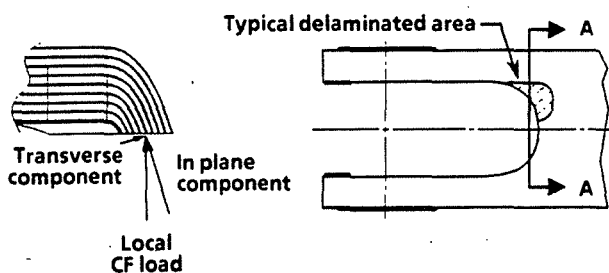
Special Developmental Problems. In the design of any new rotor system some developmental problems can be expected. These may be anticipated when technology is known to be breaking new ground and are often addressed early in the design program by means of design support tests; or they may be unanticipated, being revealed only by full-scale testing. Both types of developmental problems were encountered on the V-22 rotor system.

The contracts prior to full-scale development of the V-22 included considerable design support testing for the rotor: Material screening, tests of design elements, half-scale structural model tests of the composite yoke, and grips and model tests of several couplings were conducted. These tests supplied design data for full-scale design and confidence to proceed with the highly original composite construction of the yoke and the grip. However, in spite of the relatively extensive subscale testing, subtleties of laminate behavior led to problems in the actual grip and in the blade root tangs, which required unusual and extensive development to correct.

Blade Grip Development

The grip is constructed primarily of carbon fiber epoxy. Full-scale tests have revealed several early delamination failure modes; most of these were solved by simply increasing the local wall thickness with additional bias-reinforcing plies between the main filament windings.

An exception was a very puzzling delamination around the area where the centrifugal force fitting contacts the grip (Fig. 26). This delamination occurred at varying load levels of different specimens; some occurred with application of less than 25% centrifugal force, some beyond limit load. Because of the seemingly random load levels, these delaminations were first attributed to variations in laminate quality and fit between the centrifugal force fitting and the grip. However, considerable study revealed a transverse tensile loading in the throat of the grip where the fitting contact occurs, arising from the oval shape of the part in this area. This geometry can only be seen on a diagonally cut section of the grip and was not detected during the design or structural analyses. However, once observed on laboratory post failure analyses, the transverse stresses were demonstrated by a test grip which had an array of strain gages located in the throat area.



Section A - A

1-G848

Fig. 26. Throat delamination.

The fix for this delamination was to incorporate a preloaded clamp ring to each end of the centrifugal force fitting to react the transverse load. This device was demonstrated by tests of the strain-gaged specimen to eliminate most of the transverse tensile stresses.

The grips continue to be inspected at specified intervals of operation on all full-scale development aircraft due to continued concerns for potential growth of delaminations.

Blade Root Tangs

The blade root tangs are clamped between the fixed and movable stops and the fold latch to react the beamwise blade bending loads. The composite tangs are protected from fretting with the latches by metal "shoes" fastened to the blade root.

The original design of the blade fold latch had a swinging latch block that attached in a bored hole in the grip at one end and was supported by the latch fitting at the other. When loaded by the blade root tang, deflection of the latch housing caused uneven loading of the blade roots and delaminations in the root tangs. The latch block itself had inadequate fatigue strength.

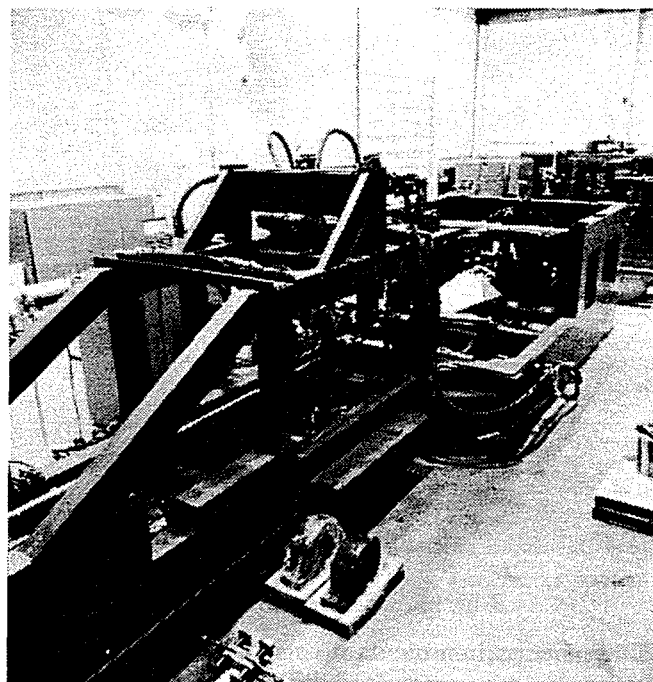
This problem was solved by changing the blade root shoes to a one-piece, thermal-fitted box in lieu of the original two-piece bonded shoes, and redesigning the latch to increase its strength and to incorporate self-aligning mating surfaces that ensured uniform loading across the contact surfaces on the blade.

Full-Scale Structural Testing

Full-scale structural testing consists of laboratory static and fatigue testing of the rotor's major subassemblies and endurance testing of the elastomeric bearings. Each elastomeric bearing has two sources

of supply, Lord Corporation and Barry Controls, and each supplier has completed an endurance test of at least one sample of each bearing.

Each of the major components required special test setup for application of static and fatigue loads. Figure 27 shows the test apparatus (approximately 12 m in length) required for the rotor hub grip and blade root.



1-G849

Fig. 27. Rotor hub grip and blade root test apparatus.

Actual flightworthy, full-scale hardware was used for tests. The blade specimens are prepared by cutting off actual bonded blade assemblies to the required length and bonding loading doublers to one or both ends for attachment to the test machine.

Test loads are applied by computer-controlled hydraulic cylinders and monitored by strain gages bonded to the test specimen. The input loads on the rotor component include centrifugal force and distribution of bending moments achieved by application of both couples and shear loads.

Concluding Remarks

Drive System

The V-22 drive system consists of simple and independent components which have state-of-the-art features such as minimal number of joints and reduction stages, bearing and gear steels of

high cleanliness and hot hardness, run-dry capability and emergency lubrication systems, rate-sensitive debris-monitoring, and capability of on-condition extended operational periods. This system was designed and developed with all the considerations of long service life, reliability, maintainability, and producibility appropriate to a vehicle destined for operational use.

Power Plant

The T406 engine demonstrates that is possible to modify and update the technology of a proven turboprop engine into a very good tiltrotor power plant. The features of the engine installation for the tiltrotor aircraft require some unique design

solutions suitable for operation in both as helicopter and turboprop modes.

Rotor System

The V-22 proprotors represent a major advancement in rotor system development. The achievement of a failsafe structure by extensive use of composite structural elements and elastomeric bearings, combined with the constant speed drive and automatic blade folding system, have required extensive design, manufacturing development, tooling, and testing. The failsafe nature of the composite component offers the potential of long service life in future commercial applications through on-condition certification.