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RSRA/X-WING - A STATUS REPORT

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ABSTRACT

The X-Wing is a stoppable rotor aircraft which will provide a low disc loading VTOL capability, similar to a conventional helicopter, combined with high subsonic cruise speed capability. As a result, it will hover with low fuel flow rates, making extended duration hover missions practical, and achieve speeds well in excess of 400 knots.

X-Wing development was initiated in the early 1970's. In 1982, DARPA and NASA in the United States contracted with Sikorsky Aircraft to design and fabricate a full-size X-Wing and perform fight tests on the Rotor Systems Research Aircraft (RSRA). These tests will concentrate on the conversion mode of flight, where the X-Wing is stopped to become a fixed wing and restarted to become a rotary wing.

Design and fabrication of the RSRA/X-Wing has now been completed, with the formal roll out ceremony taking place on August 19, 1986. The flight test phase will begin this fall.

1. INTRODUCTION

The concept of VTOL - developing an airplane to take off and land like a helicopter - has been the desire of aircraft designers since the inception of the helicopter. The first VTOLs flew in the 1950's, some using jets for vertical thrust and others using rotors or propellers. But the dream was elusive, and the penalties in vehicle performance were not overcome to a level sufficient for a practical aircraft. Designs using helicopter-like rotors provided for efficient hover and how speed performance, but could not achieve the high speed aerodynamic efficiencies of conventional fixed wing aircraft. Other designs used deflected jet engine thrust for vertical operation on an otherwise conventional fixed wing aircraft. These aircraft proved more successful, since they required smaller compromises to high speed performance. However, they could not hover with the efficiency of a helicopter and were thus restricted to missions which required only the most minimal duration of hover time.

Some of these designs promised to deliver the desired efficiency in both low and high speed flight, but failed to be developed because of excess aircraft empty weight. If a full helicopter rotor and control system is added to a conventional fixed wing aircraft with its wing and control system, and a rotor stopping and stowing system is added, the aircraft empty-weight to gross-weight ratio is so high as to leave insufficient weight available for payload and fuel.

The X-Wing aircraft concept, shown in Figure 1, promises to finally bring true VTOL performance to reality. With its large diameter rotor it hovers with low downwash velocity, high control capability and low power requirements similar to a conventional helicopter. Yet when the X-Wing is stopped, it becomes an efficient fixed wing, similar to other modern fixed wing aircraft. And because only one lift and control system is used for all modes of flight, X-Wing promises to have a low ratio of empty-weight to gross-weight.

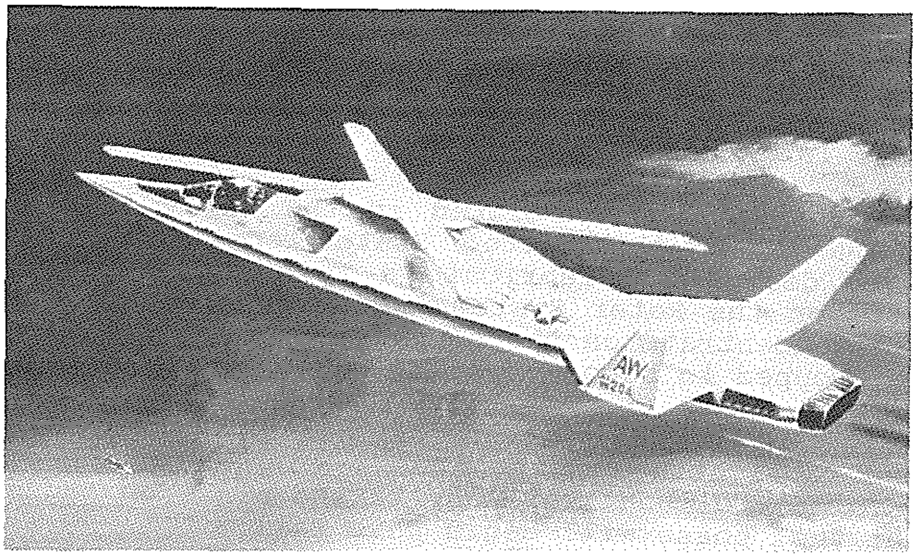

Figure 1 - Aircraft Painting With Convertible Engines

2. THE X-WING CONCEPT

In any VTOL concept which uses a stoppable rotor/wing, chordwise symmetrical airfoils must be used since the airfoils must be capable of developing lift when flying in either direction. This is illustrated in Figure 2. The hover mode of flight is shown in Figure 2A, with the trailing edge of the airfoils illustrated around the rotor disc in conventional helicopter fashion. When the rotor/wing is stopped, as shown in Figure 2C, the airfoils on the left side of the aircraft must fly in the opposite direction.

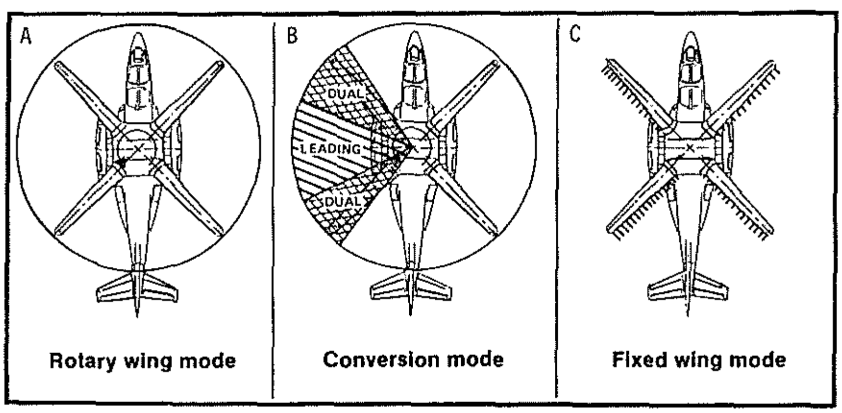

Figure 2 - Dual Blowing Concept

Circulation control airfoils are ideal for this application, since they use the Coanda principal with a jet of pressurized air blown over a rounded airfoil trailing edge. Such an airfoil is shown in Figure 3. This rounded trailing edge becomes a conventional leading edge when no blowing is provided.

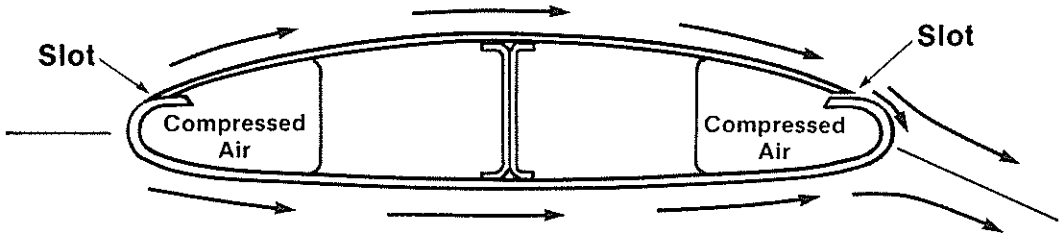

Figure 3 - Airfoil

The most difficult task aerodynamically is the conversion between these two modes of flight. This is shown in Figure 2B. Here the retreating side of the rotor disc, the left side in this illustration, must support its share of the total system lift even through its airflow is reversing direction. This requires blowing over both the leading and trailing edges of the airfoils during certain azimuth positions and blowing out what was the leading edge at other azimuths. As the rotor/wing reduces RPM, the azimuthal segment with "leading edge" blowing grows until its encompasses the entire left side of the disc. The "leading edge" in the helicopter mode of flight, of course, becomes the trailing edge in stopped rotor mode. It is envisioned that the conversion between rotating and stopped modes of flight will occur as the aircraft passes through the 200 knot speed range. The conversion itself will take from 15 to 30 seconds.

It is in this conversion mode of flight that circulation control airfoils are most effectively employed. One of the primary advantages of these airfoils is their ability to generate very high lift coefficients at low Mach numbers. As the rotor/wing is stopped; and the air velocity is reversed over the airfoils on the retreating side of the lifting disc, trimmed lift must be maintained over the disc. This is done by developing high local lift coefficients at the available low local Mach numbers on the retreating side of the disc.

As a result, the X-Wing would not be conceptual feasible without the use of the Coanda effect using circulation control airfoils.

A second necessary technology for the X-Wing is full authority redundant fly-by-wire digital control systems. X-Wing does not use a conventional mechanical control system between the pilots' sticks and the rotor/wing system. The system which provides the air supply to the rotor consists of an air compressor and a valving system feeding rotating ducts which feed the air to the individual blades. The valving system provides the conventional functions of collective and cyclic rotor control, but also provides higher harmonic control with harmonics up to five-per-revolution. A redundant digital fly-by-wire control system controls the compressor and the valving systems, as well as the X-Wing starting and stopping systems. In addition, the control system continuously measures rotor pitch and roll moments and feeds the actual moments being produced back into a feedback loop in the computer to compare them with the commanded values.

This required control technology has only recently been available. On the RSRA, four redundant computers are employed, each using four processors. In addition, backup software is provided in case the primary software exceeds predetermined limits.

The third critical technology required to make an X-Wing practical is in advanced structural materials. Conventional helicopter rotor blades depend upon centrifugal force to provide blade stiffness at reasonable weight. On an X-Wing, this is not feasible since the blade/wing must also operate in the fixed wing, stopped mode of flight. In addition, the X-Wing has two of its wings operating in the 45-degree forward-swept configuration. Thus X-Wing by definition is in the forefront of forward-swept wing technology.

Conventional metallic materials do not provide the required strength and stiffness for these X-Wing requirements with acceptable weight. Only with the advent of advanced high modulus, high strain composites has the X-Wing rotor/wing system become feasible.

These three technologies - circulation control airfoils, digital fly-by-wire electronic/pneumodynamic control systems, and high strength high strain composite materials - have now reached the development maturity to make the X-Wing practical.

3. X-WING DEVELOPMENT HISTORY

The X-Wing concept evolved from the work of Professor Ian Cheeseman of the University of Southampton, England in the 1960s. He experimented with what some call a "Flying Stovepipe" as shown in Figure 4. Dr. Cheeseman employed the Coanda principal to create and then modulate the lift on a cylindrical rotor blade. He believed that such a rotor could be stopped or started in flight if used on a winged vehicle, and employed only for takeoff and landing. The rotor would then be stopped and stowed in flight for cruise efficiency.

Engineers at the U.S. Navy's David W. Taylor Naval Ship Research and Development Center (DTNSRDC) adapted Professor Cheeseman's idea of lift control (circulation control) by blowing tangential over a rounded trailing edge, but substituted a streamlined shape similar to a conventional

Figure 4 - Dr. Cheeseman's Rotor

airfoil. The X-Wing concept was first introduced by Robert M. Williams of DTNSRDC, in 1976.

Early in the development of the X-Wing, an extensive series of conceptual tests were conducted using the Reverse Blowing Circulation Control Rotor (RBCCR) model. This model rotor, built by the U.S. Navy at DTNSRDC, is 80 inches in diameter, has very rigid blades, and employs several simplified control systems to modulate the blowing. The model was tested at reduced tip speeds in the DTNSRDC 8-by 10-foot Wind Tunnel, and at typical full-scale tip speeds on a hover stand. Although no actual dynamic starts or stops were made, conversion between rotary and fixed-wing mode was simulated by slowly varying the rotor rotational speed. These tests were successful, proving the concept worthy of further investigation.

Shortly thereafter, DARPA became interested in the concept and, jointly with the U.S. Navy, awarded a competitive contract for further development to the Lockheed California Company. Lockheed designed, built, and tested a 25-foot diameter X-Wing rotor on a test rig, which simulated a potential vehicle fuselage shape. This model was tested in the NASA Ames Research Center 40-by 80-Foot Wind Tunnel Fig. 5 , and extensive tests were carried out on the Lockheed whirl tower at Rye Canyon, California. Numerous starts and stops were performed up to the wind tunnel maximum speed of 180 knots. These investigations established the feasibility of the concept. DARPA then became interested in carrying the concept into flight demonstration.

Under direction of the Under Secretary of Defense, Research and Engineering, a competitive procurement strategy was adopted. Thus, in 1980, contracts for X-Wing Technology Transfer and Assessment were awarded to Boeing Vertol and Sikorsky Aircraft. Early in 1981, the contracts were completed, with both companies providing favorable assessments and making specific recommendations to reduce technical risks. Follow-on contracts were awarded to both companies to proceed with X-Wing Design Definition. Key elements of these contracts included conceptual design of a flight vehicle of operational size, detail design of a 50-foot diameter rotor system, and various technical verification and concept development activities. These activities provided the contractors with some "hands on" experience with the concept, and placed both contractors in a position to conduct a credible flight vehicle design and test program.

As part of the technical verification activities, a 10-foot-diameter X-Wing model was designed, fabricated, and tested by Boeing Vertol in their V/STOL wind tunnel; see Fig. 6. The model included a representative fuselage, a 10-foot rotor, a representative hub fairing, and a pneumodynamic control valve system.

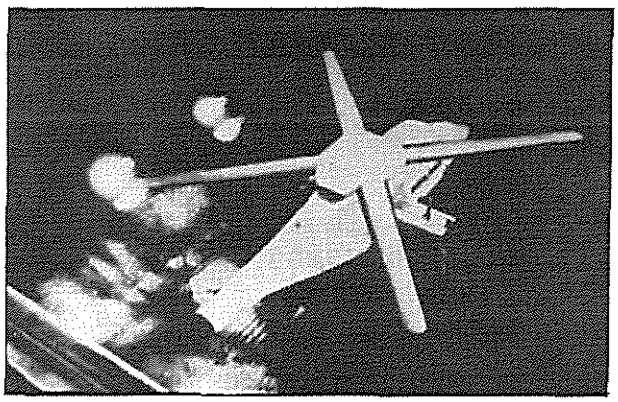

Figure 5 - Lockheed 25' Rotor in Ames Wind Tunnel

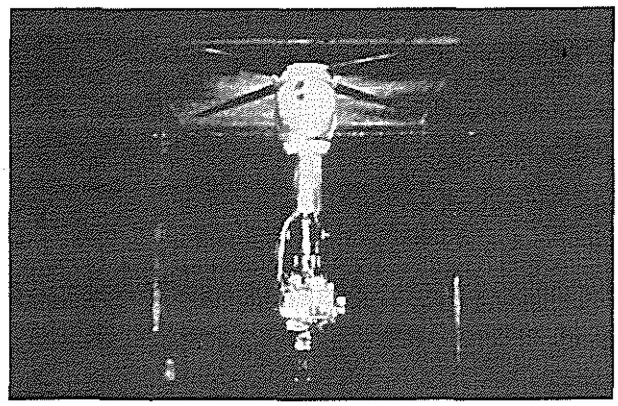

Figure 6 - Boeing Vertol Model

For the next development step, the U.S. Government sought the lowest cost approach which would still retain a rotor of at least 50 feet in diameter and permit systematic assessment of the most critical technical risks associated with the X-Wing concept. This was the basis for selecting the approach to development of an X-Wing rotor to be flown on the Rotor Systems Research Aircraft (RSRA). The RSRA is shown in Figure 7. The inherent capabilities of the RSRA to provide independent control of both lift and drag, together with its unique flight control system, made this aircraft an ideal test bed on which to demonstrate X-Wing technology in flight. The RSRA wing provides the lift necessary to support the aircraft with the X-Wing installed, irrespective of the lift provided by the X-Wing. The auxiliary propulsion fan-jet engines provide the thrust necessary to overcome drag of the aircraft and X-Wing providing high aircraft speeds--again, irrespective of propulsive force and drag induced by the turning or stopped X-Wing. Since the wing and auxiliary engines incorporate load cells, the lift and thrust of these components can be monitored. This, together with the X-Wing load cell system, provides data on head moment and lift and supplies the capability to evaluate the performance of the rotor over its entire range of forces and speeds. Thus, the measured in-flight performance can be compared with the analytical theory to verify or modify predicted analyses.

Figure 7 - RSRA

Unique among the many features of the RSRA, is its crew escape system, which is the only operational escape system currently in use in a rotorcraft. This provides the means to pyrotechnically sever the blades in an indexed manner to avoid impact with the aircraft, to pyrotechnically fracture and jettison the canopy, and to extract the crew members.

4. THE RSRA/X-WING PROGRAM

The DARPA/NASA/SIKORSKY RSRA/X-Wing program Figure 8 has the basic objective of demonstrating the X-Wing starting and stopping conversions of a full-size rotor/wing system in flight. The schedule for this development is shown in Figure 9. The program was initiated in 1983, and at the present time all design and fabrication work is completed. The aircraft rollout ceremony took place on August 19, 1986 and the aircraft was formally turned over to the engineering test personnel at that time. The aircraft is shown in Figure 10.

Figure 8 - RSRA/X-Wing Objectives

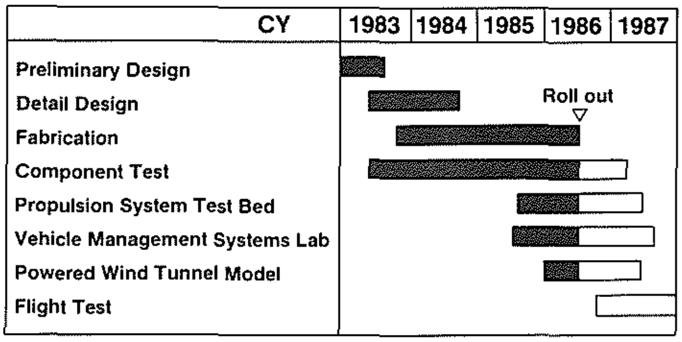

Figure 9 - Schedule

Figure 10 - Completed Aircraft in Roll-Out Configuration

Figure 11 is a side view of the aircraft illustrating the installation of the X-Wing hardware. The upper deck of the original RSRA has been completely rebuilt to accommodate the X-Wing. In addition, the control system has been extensively modified to include the new quad redundant, full authority, digital X-Wing system.

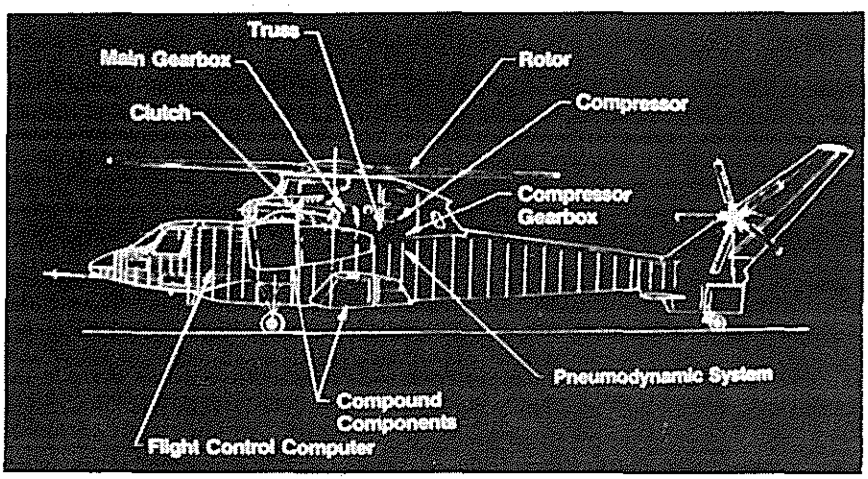

Figure 11 - RSRA Side View Drawing

The X-Wing blade/wing is shown in Figure 12, with a Sikorsky S-76 blade shown for reference. The X-Wing blade/wing has a radius of 27.8 feet and a mean chord of three feet. It is constructed of composite material with metal only being used for the slot lip erosion strip and for fasteners. A flexbeam construction is used to provide mechanical collective pitch change capability without bearings. Figure 13 illustrates the blade/wing components in various stages of manufacture in Sikorsky's Composite Development Center.

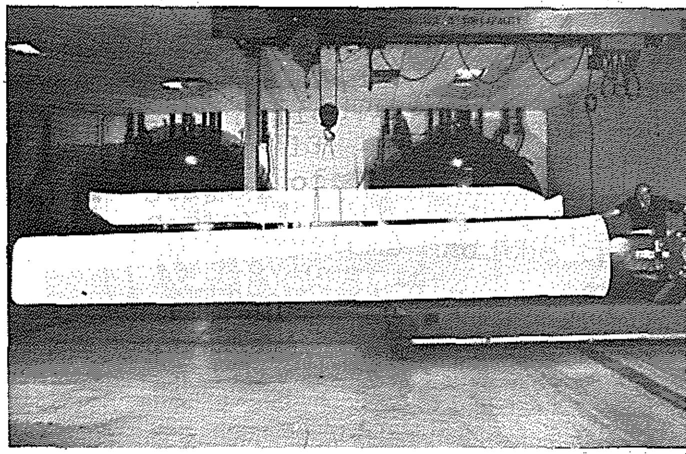

Figure 12 - X-Wing & S-76 Blades

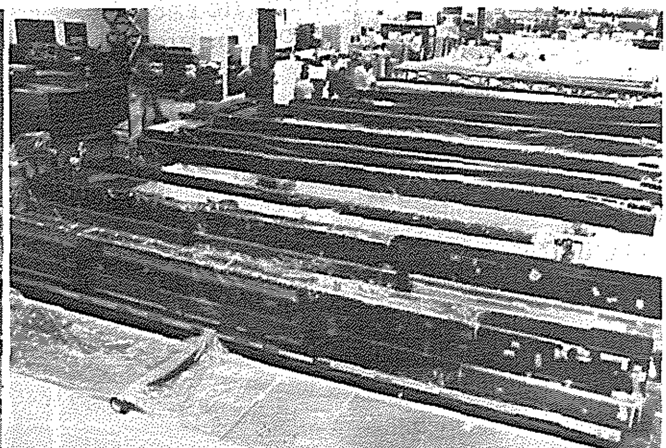

Figure 13 - Blade Components in CDC

The arrangement of the drive and pneumodynamic control systems is illustrated in Figure 14. The forward mounted General Electric T-58 engines and the main gearbox are located similar to the original RSRA and Sikorsky S-61. The main gearbox is extensively modified to include a clutch between the engines and the rotor, and to reduce output speed from 203 to 156 RPM. A high-power through shaft is included to power a second gearbox located to the rear of the main box. This drives the vertically mounted compressor which provides the air for the circulation control system. This through shaft is not declutched when the rotor/wing stops, so that the air supply is available for all modes of flight. The through shaft also powers the electrical and hydraulic systems and the tail rotor.

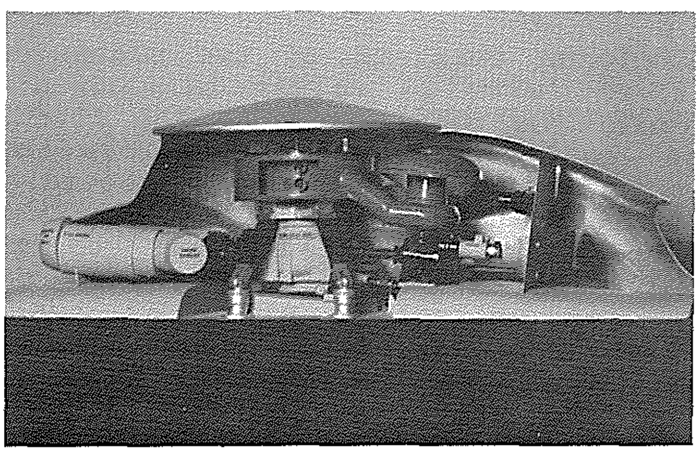

Figure 14 - ¼ Scale Model

The compressor, shown in Figure 15, was developed by the Pratt & Whitney Divisions of United Technologies and is of two-stage axial flow design. A top mounded radial inlet is used. A discharge collector feeds the compressed air to the pneumodynamic control plenum system which is located below the rotor and concentric with it. This plenum is shown schematically in Figure 16. Figure 17 shows the hardware partially assembled.

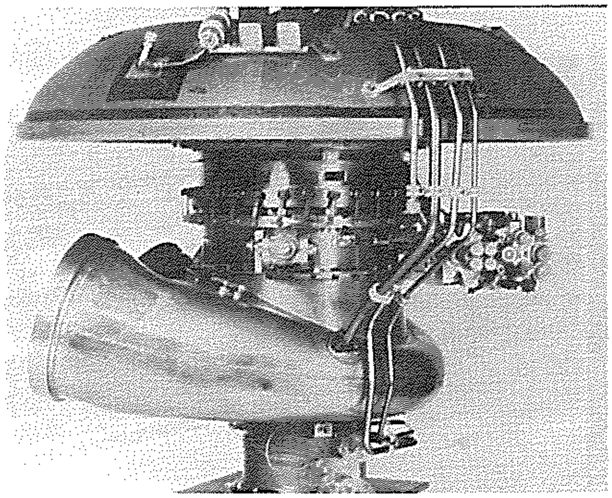

Figure 15 - Compressor

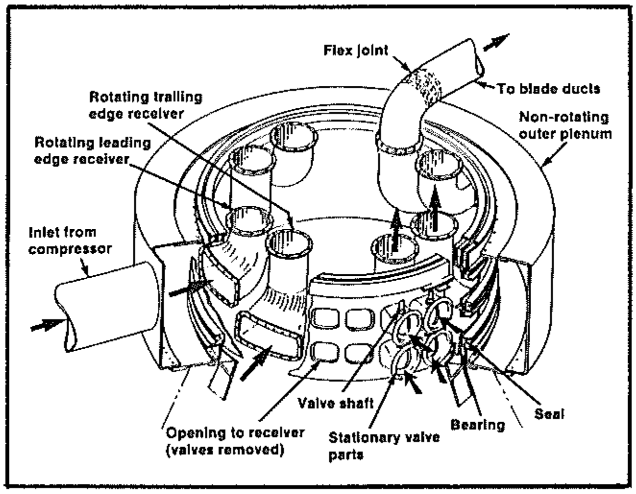

Figure 16 - Plenum Schematic

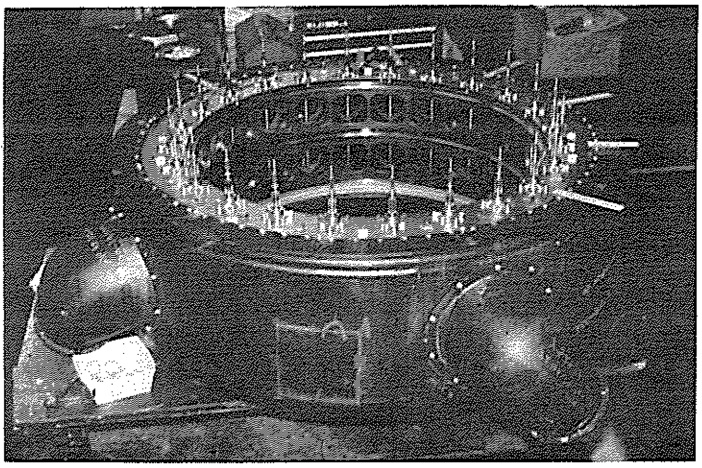

Figure 17 - Plenum

The plenum consists of two planes of pneumodynamic control valves, with 24 valves in each plane. The upper plane controls the air supply to the leading edges of the blade/wings and the lower plane controls the trailing edge. The plenum and its valves do not rotate with the rotor. Receiver ducts rotate inside the plenum collecting the valve-modulated air and feeding it to the blade/wings. Figure 18 is a plan view of the plenum illustrating this operation. For collective pitch all valves are opened equally and the receiver ducts see no variation in airflow as they rotate around the 360-degree azimuth. For conventional cyclic pitch the valve opening positions are varied in a sinusoidal manner around the 360-degree azimuth. Thus, as the receiver ducts traverse the azimuth they see a oneper-rev variation in the airflow. For higher harmonic control the 24 valves around the azimuth are positioned to generate the pneomodynamic wave which is the sum of the desired collective, cyclic and higher harmonic values. One of the advantages of this penumodynamic control system is that this higher harmonic control is provided on the stationary side of the plenum, so that the valves themselves to not have to cycle at the desired higher harmonic frequencies.

The clutch for starting the X-Wing system in flight is shown in Figure 19. It was developed by the Allision Division of General Motors. The brake to stop the system was developed by Dunlop in England.

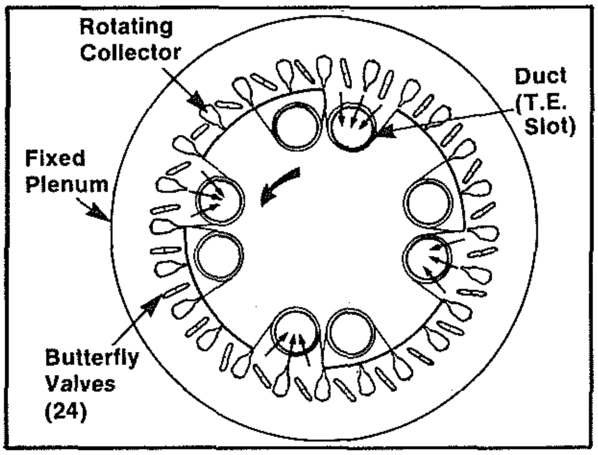

Figure 18 - Plenum Plan View

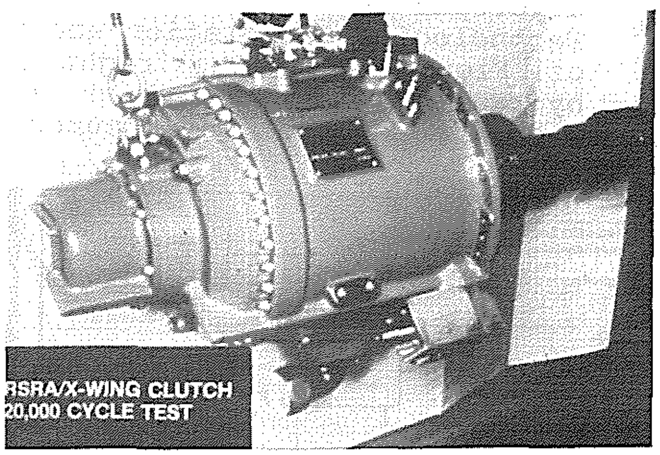

Figure 19 - Clutch

All of this hardware has been fabricated and has been undergoing ground test on a Propulsion System Test Bed at Sikorsky's facility in West Palm Beach, Florida. This is illustrated in Figure 20. Initial tests are using dummy blade/wings which simulate the aerodynamic and penumodynamic load of the real blade/wing. This permits the development of

Figure 20 - PSTB

the pneumodynamic system from the compressor inlet to the blade root, separate from the development of the blade/wing penumodynamic system. After this development is concluded, the actual blade/wings will be installed for full system tests.

The flight control, or Vehicle Management, system is shown in the block diagram of Figure 21. The system controls the pneumodynamic control valves in the plenum as well as the mechanical collective pitch change mechanism and the compressor. In addition, it controls the conversion process by operating the clutch, the brake, and the position indexing system. A full authority, quad redundant, digital fly-by-wire system is used. The flight control computers are being developed by the Hamilton Standard Division of United Technologies Corporation and are shown in the left photograph of Figure 22. The right photo illustrates the electro/hydraulic actuators which are mounted on the top of the plenum to control the pneumodynamic valves.

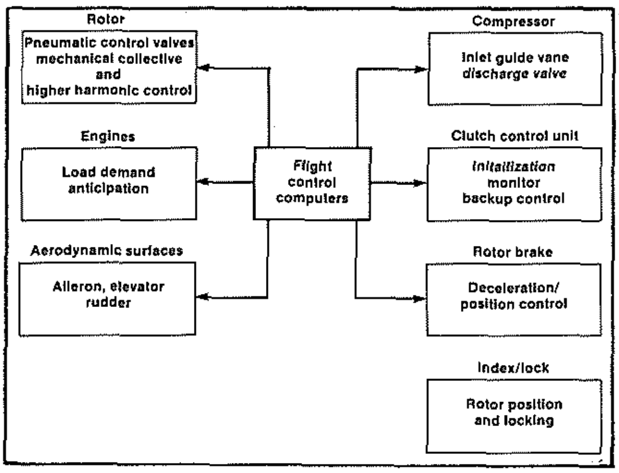

Figure 21 - VMS Block Diagram

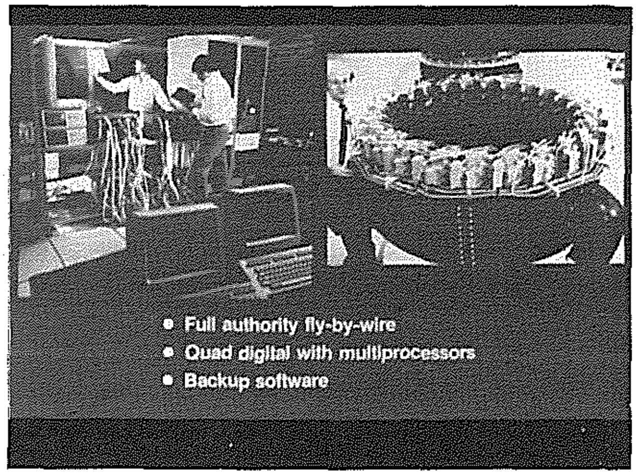

Figure 22 - VMS

This entire Vehicle Management System is being ground developed and tested in a Vehicle Management Systems Laboratory at Sikorsky's Stratford, Connecticut facility. This is shown in Figure 23. The four computers are tied to a full set of the aircraft actuators as well as a fixed-base cockpit. An additional computer facility provides a simulation of the RSRA/X-Wing vehicle. The aircraft instrumentation system is duplicated. This system is being used for software validation and hardware and software testing. Hundreds of operational hours will be accumulated on this system prior to the actual flight test of the system.

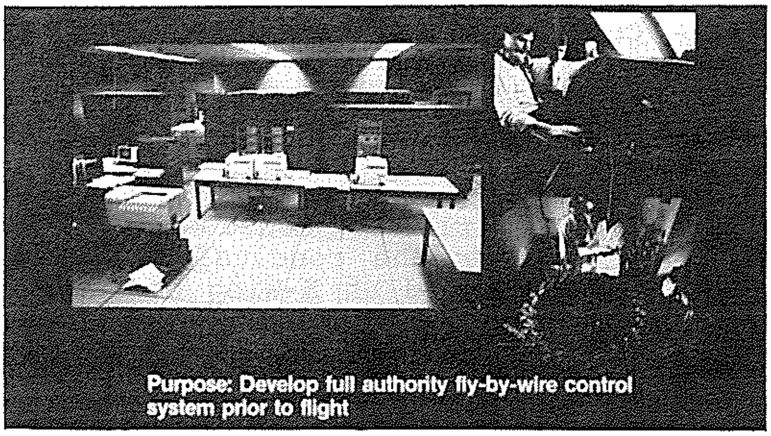

Figure 23 - VMSL

The third major ground test facility being used prior to flight is the powered wind tunnel model, as shown in Figure 24. This is a ten-foot diameter system which accurately simulates the aerodynamic, pneumodynamic, and aeroelastics of the system. The model blade/wings are also made of composite materials and include accurate geometric representations of the air ducting system and the pressure-controlled exit slot. A 48 valve plenum control system is included, as on the full-size hardware. This is shown in Figure 25. Testing with this model began in December, 1985 on the Sikorsky model hover test stand. The model was installed in the United Technologies large-scale wind tunnel in June, 1986 for forward flight tests prior to flight.

Figure 24 - Wind Tunnel Model

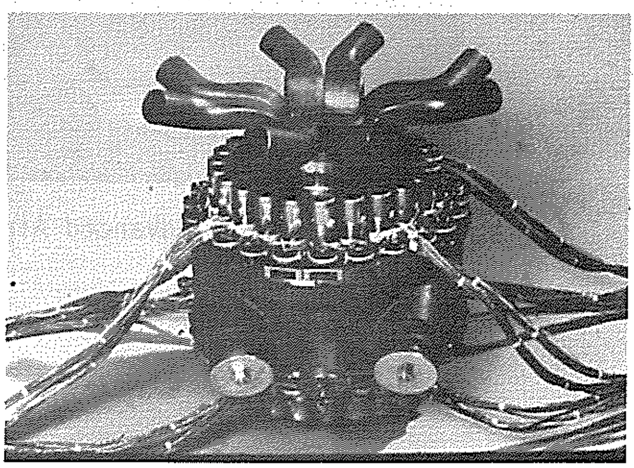

Figure 25 - Wind Tunnel Plenum

All of this subsystem and ground testing is in preparation for the flight test phase which begins this fall. Testing will be conducted at NASA's Dryden Flight Test Center at Edwards Air Force Base in California. The initial phase of testing will be in the stopped mode of flight to develop the flight envelope in this configuration. This will be followed by testing in the rotating mode of flight to develop that envelope. When both ends of the conversion envelope are fully defined, the test of the actual conversion process will be performed. Current schedules show the full envelope testing to be completed by the end of calendar year 1987.

5. THE FUTURE

It is not too early to consider the next step in X-Wing development. After the conclusion of the RSRA test, it would be logical to build an X-Wing concept demonstrator aircraft using a majority of the RSRA-developed hardware. This vehicle might be configured as previously shown in Figure 1 using convertible engines to provide both shaft horsepower and propulsive thrust. Alternatively, it might use conventional turboshaft engines powering the rotor, the compressor and externally mounted prop-fans, as shown in Figure 26. These aircraft would have gross weights of 24,000 pounds and maximum speeds of over 400 knots.

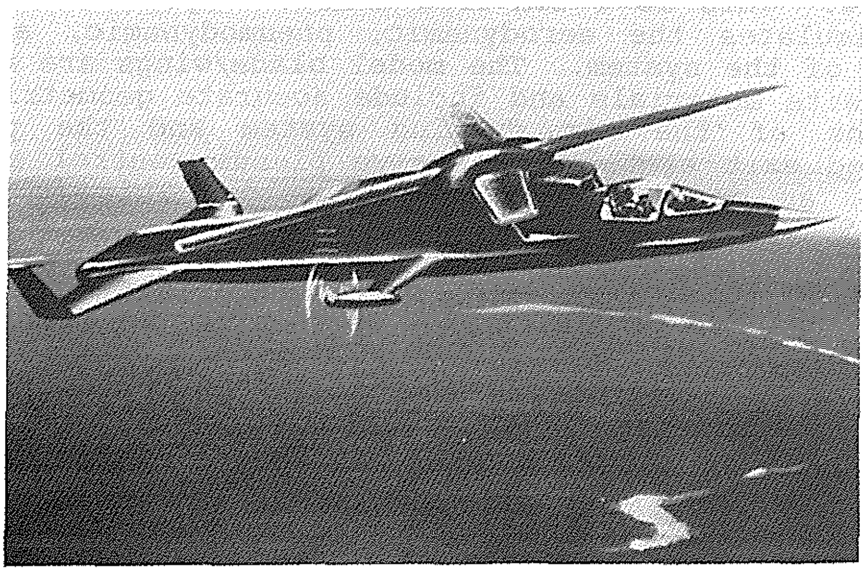

Figure 26 - Advanced Aircraft With Prop Fans