EIGHTEENTH EUROPEAN ROTORCRAFT FORUM

C - 11

Paper No. 106

MERGING THE TWO ENDS OF THE VTOL SPECTRUM

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September 15-18 1992

AVIGNON, FRANCE

ASSOCIATION AERONAUTIQUE ET ASTRONAUTIQUE DE FRANCE

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ABSTRACT

This paper reviews the problems associated with developing a vertical takeoff and landing (VTOL) aircraft that has desirable helicopter-like attributes in hover and low speed operation but is capable of efficient high subsonic cruise speed. A number of different configurations that have been proposed are reviewed and an assessment is made of the relative probabilities of future success. Factors considered to be important discriminators include speed potential, disk loading, empty weight fraction, the need for supplementary propulsion systems or convertible engines, and technical risk. The tiltrotor configuration has considerable merit but will not achieve the highest speeds that might be desired. It is concluded that incorporation of variable geometry, in the form of a variable diameter rotor system, has the best chance of providing the "ideal" VTOL. The variable diameter tiltrotor adds considerably to the speed potential of the tiltrotor, reduces disk loading, and provides numerous other benefits as well. For highest speeds, the variable-diameter single stowed rotor configuration has the desired combination of attributes.

INTRODUCTION

Many VTOL aircraft with speed capabilities greater than that of the helicopter have been proposed, studied, tested in wind tunnels, and flown in experimental versions. Quite a few have been built as production prototypes. As of this date, however, the helicopter is still the only VTOL in production, with the sole exception of the Harrier direct-lift turbofan. The V-22 Osprey tiltrotor aircraft will be the second exception if it, in fact, goes into production. The price for speed in addition to VTOL capability has usually been too high in the past, and there have also been serious compromises relative to the desirable attributes of the helicopter.

The challenge is this: when can we develop an aircraft as fast as the Harrier (or at least moderately high subsonic) that still retains the more desirable low-speed attributes of the helicopter? In other words, is it possible to merge the two ends of the VTOL spectrum (Figure 1) in a reasonably efficient manner?

The trend to date is that the disk loading of the lifting system increases steadily with increasing design speed (Figure 2). Low disk loading is desired in hover because of the relatively low power required, lower fuel consumption, lower downwash velocities, lower noise, autorotational capability in case of engine failure, and better control power that a relatively large-diameter rotor system provides.

Another trend is that the useful load fraction available for payload and fuel decreases with increasing design speed (Figure 3). This factor is responsible for the fact that many high speed concepts in the past failed to pass the test of economic viability, particularly in civil applications.

There is no question that modern composite structural materials and improved propulsion system technology can improve useful loads compared to what could be achieved 20 to 30 or more years ago, when most of the "advanced concepts" were investigated. But can they improve useful load to the point that the economic "Fail" becomes a "Pass"? And even if the economics look good on paper, do the various configurations satisfy the other objectives mentioned - speed and low disk loading?

CONCEPTS THAT HAVE FLOWN

HELICOPTER - First of all, why can't we just build the helicopter to go a lot faster than current models? The fundamental reason is the dissymetry in flow over the "advancing" and "retreating" sides of the rotor disk in forward flight. Because of the reduction in air velocities relative to the rotor blades on the retreating side, angles of attack must be increased to increase lift coefficients, through cyclic pitch or blade flapping motions, to maintain roll balance with the advancing blades. However, increasing blade angles of attack on the retreating side to maintain lift can only go so far. As forward speed continues to increase, the velocity encountered by the retreating blade decreases, and blade angles of attack must go higher and higher. The limit is when the blade section stalls. A small localized area of stall is not harmful, but as the rotor is "pushed" to more difficult conditions, large regions are stalled, power is increased, control loads increase dramatically, vibration becomes severe, and the pilot discovers that the rotor is not very responsive to control inputs.

Thus the rotor is totally unlike the wing of an airplane in its aerodynamic characteristics. The wing produces no lift at zero forward speed, but has a great deal of lift capability at high speeds. The rotor, by contrast, has a thrust capability which is maximum at zero flight speed and which decreases as speed is increased. Figure 4 illustrates the decrease of the lift and propulsive force operating envelope for a typical rotor as flight speed is increased. A line from the origin to any point on the chart represents the rotor resultant force vector for that point. Each forward speed has two limits shown: one for retreating blade stall and another for autorotation (zero shaft power). Operation much above the stall line is not feasible, and operation to the right of the autorotation line is not possible because this corresponds to negative power (rotor feeds power to the shaft rather than vice-versa). Windmills are designed for such operation; helicopters, with free-wheeling clutches and no way to dissipate energy fed into the shaft, are not.

Note that as flight speed is increased from 100 to 200 knots, the lift capability is typically reduced by one half. The drop in propulsive force capability is typically reduced by a factor of five or more, whereas the requirement, to overcome airframe drag, is four times higher than at 100 knots. At some speed above 200 knots the propulsive force capability vanishes altogether. Note also that lift capability drops substantially at a given forward speed as propulsive requirements are increased. The slope of the stall line is steeper than shown in the figure; the horizontal scale was doubled relative to the vertical scale for clarity.

Retreating blade stall is thus the reason that a 200-knot helicopter is a very rare bird. The world's speed record for pure helicopters is only 216 knots (400 km/hr), set by a modified Westland Lynx helicopter in 1986. The record is not likely to be pushed much higher, because there are more attractive ways of achieving higher speeds than with a pure helicopter.

COMPOUND HELICOPTER - The compound helicopter is the first alternate concept to consider. It is derived by adding wings and some form of auxiliary propulsion to a helicopter. A properly sized wing augments rotor lift in a nearly ideal manner, as shown in Figure 5. The wing lift potential increases with the square of the forward speed, and the combined lift capability is quite flat up to 200 knots, beyond which it increases. Thus the retreating blade stall problem is eliminated, and the compound helicopter is no longer restricted to normal helicopter speeds. Many experimental aircraft of this type have been built and flown, and two have reached the production prototype stage. A research compound helicopter, the NH-3A (S-61F), is shown in Figure 6. It was based on the Sikorsky S-61 but incorporated a wing, two turbojets for auxiliary propulsion, and airplane-type control surfaces. It was flown at speeds up to 230 knots and provided valuable data which confirmed the capabilities of the compound concept. The fastest experimental compound helicopter was a derivative of the Bell UH-1 (Figure 7). A high ratio of installed jet thrust to weight allowed flight speeds up to approximately 275 knots.

One aircraft in the compound helicopter category that was planned for production in the past was the Fairey Rotodyne, Figure 8. This aircraft used a pressure jet rotor with tip burning. Another production prototype was the Lockheed AH-56 Cheyenne (Figure 9), which used a pusher propeller at the tail. Neither of these aircraft actually reached the production stage.

The compound helicopter is a very feasible aircraft configuration with low technical risk, but there is a risk of economic viability. The speed potential is limited to about 250 knots primarily because drag of the exposed rotor head makes it too inefficient at higher speeds. Blade flapping response to vertical gusts also become a problem above about 250 knots. In addition, the drive train complications caused by the need for an RPM reduction at high flight speeds, to avoid excessive Mach numbers on the advancing blade, also contribute to it being less attractive beyond 250 knots. The weight of a wing and auxiliary thrust system reduces the payload; the added drive train components of the thrust system impacts reliability and maintainability. Weight is the chief concern; does the increased speed make up for the loss of payload? The answer in the past has always been: not quite. In the future, the answer might well be yes. The compound has one large advantage over the other types, which is that nearly any existing helicopter can be compounded. It should be considerably more rapid and less expensive to develop a compound derivative of a production helicopter than to design an entirely new aircraft from the ground up, as required for the other types discussed.

ABC - A unique rotorcraft configuration that is sometimes classified as a compound is the Sikorsky Advancing Blade Concept or ABC. Two rigid, counter-rotating, coaxial rotors are utilized for lift rather than a single main rotor plus wing. The lift potential of the advancing blade may be realized because of the strength and stiffness of the blades and the counterbalancing of the two rotors (Figure 10). Lift capability of the ABC increases with speed, unlike that of a conventional helicopter rotor. The propulsive capability, however, is not enhanced to the same extent as the lift. The concept has been proven by the XH-59A research aircraft shown in Figure 11. Two turbojet engines were employed for propulsion. This aircraft reached 240 knots in level flight and exceeded 260 knots in descent. The ABC provides a particularly compact and maneuverable vehicle that should be well suited to nap-of-the-earth operations or to an air-to-air combat role. Hub drag probably limits practical speeds to values similar to that of the compound helicopter.

TILTROTOR - The next rotorcraft configuration to be discussed is the tiltrotor. By having two lifting rotors mounted on pods at the tips of a wing, and providing a mechanism to tilt the rotor shafts forward 90 degrees, a distinctly different type of VTOL aircraft is obtained. Figure 12 shows an early experimental tiltrotor aircraft. Earlier it was stated that a helicopter rotor could not produce forward propulsive force at speeds much above 200 knots. This is true if the rotor stays in a more-or-less horizontal orientation, but it is not true if the rotor is tilted forward so that the tip path plane is essentially vertical. Figure 13 shows a typical envelope of lift and propulsive force through the entire tilt range at a moderate flight speed (~125 knots). At full tilt (propeller mode), the lift drops to zero but the thrust capability becomes very high. Thus the two rotors supply all of the propulsive force at high speed and the wing provides 100 percent of the lift. Figure 14 shows a more recent tiltrotor research aircraft, the Bell XV-15, built for NASA (National Aeronautics and Space Administration). It has achieved flight speeds as high as 300 knots. Figure 15 shows the Bell/Boeing V-22 Osprey, now in flight development status. If it goes into production, it will be the first rotorcraft other than the helicopter to do so.

The tiltrotor is unquestionably one of the most promising rotorcraft configurations and is reasonably certain to see service in the future. It should provide efficient operation for relatively long range missions. Because the rotors are in axial flight in cruise, hub drag can be greatly reduced with axisymmetric fairings. Low drag combined with good wing lift-drag ratio provides for efficient cruise. Relative to the helicopter, the tiltrotor must pay an empty weight penalty because of the wings required. However, the rotors provide all of the propulsive force in all flight modes, so that an auxiliary propulsion system or convertible engines are not required. This is a major advantage that the tiltrotor aircraft has over many of the other configurations. The maximum speed potential, however, is limited by the relatively thick wing required to provide adequate stiffness to support and stabilize the rotors. The probable speed regime for reasonably economic operation is about 250 to 350 knots. The disk loading of the tiltrotor is on the order of 50 to 100 percent higher than for a comparably-sized helicopter, so that some of the desirable helicopter attributes are compromised. The tiltrotor has other shortcomings that will be discussed in a subsequent section.

TILT WING - The next VTOL configuration to be considered is the tilt-wing/propeller aircraft. This is conceptually similar to the tiltrotor, except that the entire wing and propeller combination tilts rather than just the rotors. Figures 16 and 17 show, respectively, a twin engine experimental aircraft and a four-engine prototype transport, both of which were flown many years ago. The Ishida TW68 tilt-wing aircraft now under development is similar in many respects to the Figure 16 aircraft.

In hover the wing of a tilt-wing/propeller aircraft is in a vertical plane, minimizing download from the propeller slipstream. In conversion to forward flight, the propeller disk loading must be high enough to substantially divert the free stream to be more or less aligned with the plane of the wing - otherwise the wing would be badly stalled and cause excessive drag and turbulent flow. In hover, pitch control for aircraft flown to date has been obtained by a horizontal rotor at the tail of the aircraft. Roll control is obtained by differential collective pitch, and yaw control is obtained by the use of ailerons to deflect the propeller slipstream differentially fore and aft on the two sides of the aircraft. Cyclic pitch has not been used, simplifying blade pitch control relative to most rotorcraft. Control characteristics of aircraft built to date have not been as good as desired in hover and at low speeds, especially in turbulent conditions. Once converted, conventional airplane controls provide adequate characteristics.

Because the tilt-wing must operate at substantially higher disk loadings than the helicopter, it must install much higher power per unit lift. The high power thus makes it an inherently high speed aircraft in cruise. Design speeds above 400 knots should be achievable. This concept, however, has diverted substantially from the objective of this paper, i.e., finding a high speed configuration that has the low-speed attributes of the helicopter, with the virtues that low disk loading provides.

LIFT FAN - An even further departure is the lift-fan aircraft, in which one or more ducted fans provide all needed lift in hover. Figure 18 shows an early fan-in-wing aircraft, in which three tip-turbine driven fixed pitch fans provided lift plus pitch and roll control. Yaw control was provided by vanes in the outlet flow. Fan disk loading was very high - on the order of 250 pounds per square foot. In cruise flight the engine exhaust was directed straight aft for propulsion; the fans were stopped and covered over to provide reasonably smooth aerodynamic surfaces. A more recent study of a fan-in-wing aircraft is shown in Figure 19. A single, central fan was assumed in an attempt to minimize disk loading; however the disk loading was still on the order of 100 psf, i.e., an order of magnitude above that of the helicopter. The central fan causes many practical problems (e.g. where is the convenient location for payload and fuel?) and structural weight is also a serious problem. This configuration might have military fighter applications but not transport or civil uses.

DISK LOADING TRENDS

The aircraft described up to this point, plus the Harrier direct-lift turbofan fighter, can be plotted on cruise speed/disk loading coordinates to more accurately define the qualitative trend discussed at the beginning of the paper. This plot, Figure 20, uses a linear speed scale and a logarithmic scale for relative disk loading, i.e., the ratio of disk loading of the configuration in question to the disk loading of a comparably-sized helicopter. Because of the infinite number of design possibilities, there is no attempt to show the precise limits of any concept. Instead, both the cruise speed and disk loading parameters are divided into approximate bands as shown, resulting in "blocks" in which the various configurations tend to fit most naturally. To increase cruise speed one block to the right, it appears that disk loading must also go up one or more blocks. It should be noted that the potential speeds shown for tiltrotors, tilt-wings, and lift fans are greater than has been demonstrated in flight to date. These speeds are believed to be achievable with current technology, however.

The "relative" disk loading scale is used in Figure 20 because actual disk loading can vary considerably for any particular configuration. In particular there is a significant correlation between gross weight and disk loading, as shown in Figure 21 for three categories of VTOL aircraft: helicopters, tiltrotors, and tilt-wings. Any given aircraft appears as a straight line segment, with disk loading directly proportional to weight as the weight is varied; a series of aircraft of a given type forms a trend. The heavier aircraft have higher disk loading rotors or propellers to minimize weight growth associated with increasing dimensions. Although the database for tiltrotors and tilt-wing aircraft are much smaller than for helicopters, it seems evident that tiltrotor aircraft have disk loadings on the order of one and one-half to two times greater than typical values for helicopter for any given gross weight, and tilt-wing/propeller designs have disk loadings four to five times higher.

The disk loading of a rotor or propeller determines the mean velocity of the slipstream below the device in hover. For any given air density, the mean velocity is directly proportional to the square root of the disk loading. A disk loading of 14 pounds per square foot corresponds to a slipstream velocity of 74 miles per hour at sea level. This is, by U.S. Weather Bureau definition, the threshold of a hurricane. A wind of this magnitude is a rare event in nature, so that the flora and fauna of the earth have typically evolved under more benign conditions. The devastation that results when storms produce winds of this magnitude is the reason we have given these storms special names such as hurricane or typhoon. When a VTOL aircraft produces hover slipstreams of hurricane magnitude, the potential for problems is real, even though the high velocities are confined to a relatively small region below the aircraft. In unprepared areas the scrubbing effect of the flow along the ground will pick up sand, dirt, stones, and other debris and accelerate them to dangerous velocities. Helicopters have slipstream velocities below hurricane force for the most part, but have been known to cause considerable damage under some conditions. The recent war in the Persian Gulf area provided emphatic evidence of the problems caused by the desert sand kicked up in seconds by helicopter downwash: blade erosion, bearing wear, engine degradation, and lack of pilot visibility in the cloud of dust were all of great concern. Much higher downwash velocities could not be tolerated without prepared surfaces for both takeoff and landing operations.

LOWER DISK LOADING CONCEPTS

Configurations that break away from the trend shown in Figure 20 will be discussed next. Although none of these concepts have been demonstarted in flight, all are considered technically feasible. All candidates to be considered will utilize rotors, not propellers or fans, because only rotors achieve the relatively low disk loading values desired.

FOLDING TILTROTOR - One approach to increasing the speed potential of the tiltrotor aircraft is to stop the rotor and fold the blades aft in cruise flight, as shown in Figure 22. This aircraft type exhibits three distinct flight modes: hover and low-speed flight, with the rotors turning and the shaft in an upright position; moderate-speed cruise, with the nacelles tilted down to the propeller mode and the rotors continuing to rotate and to provide thrust; and high speed cruise, with the rotor stopped and the blades folded aft as shown. There are, of course, conversion sequences between these three flight modes. Between the first two modes the conversion is identical to that of a conventional tiltrotor aircraft. Once in the propeller mode, the second conversion is simple in concept if not in practice; the blades are simply feathered (mean pitch angle ~90°) to stop the rotation after the rotor has been uncoupled from the drive system, allowing fold actuators to be brought into play.

The wing of the folding tiltrotor does not need to be as thick as that of a conventional tiltrotor aircraft for adequate dynamic stability of the rotor/wing combination. The wing bending and torsional stiffness required and therefore wing thickness required for aeroelastic stability of the wing/ rotor system increases rapidly with flight speed. By converting to the stopped and folded mode at a low flight speed (less than 200 knots), the folding tiltrotor can utilize thinner airfoil sections or greater forward sweep angles suitable for higher cruise speeds. Cruise speeds of 450 knots and possibly 500 knots are believed to be feasible.

The folding tiltrotor pays a penalty for its higher speed capability by requiring extra propulsion system components (convertible engines and ducted fans or other propulsive devices), plus the added mechanisms for stopping, indexing, folding, and locking the blades for high speed cruise flight. The empty weight fraction will inevitably be higher than for the tiltrotor aircraft, which itself has a considerably higher empty weight fraction than does the conventional helicopter. Disk loading is also higher than for the tiltrotor.

TRAIL ROTOR - A variant of the folding tiltrotor is the trailing-rotor aircraft, Figure 23. In this concept an auxiliary propulsion system is used to provide the propulsive force while the rotor is tilted to the rear rather than to the front. The rotors are decoupled from the drive system and go into autorotation, collective pitch goes to negative values, and after the rotors are in axial flight (in the trail position), the pitch is adjusted to a value that brings rotational speed to zero. The blades "cone" upward to 90° and trail straight back. The transitions between the rotating (low coning) and non-rotating (high coning) states tend to be sudden; the intermediate conditions are apparently unstable. This configuration has not been explored to the same extent as the first-mentioned folding tiltrotor concept, but neither can claim a mature level of technology.

STOWED ROTOR - A rotorcraft concept having very high subsonic speed capability is the stowed rotor aircraft, shown in Figure 24. The idea is to fly on the rotor up to a moderate speed where the wing can sustain the aircraft, then stop rotation and fold the blades into the top of the fuselage. Once the rotor is removed from the airstream, the flight speed is limited only by the available installed power. In principle, high subsonic or even supersonic speeds should be possible since the wing design is not restricted by the requirement of supporting tip-mounted rotors, as is the tilt-fold rotor or the trailing rotor. However, the concept is not without its problems. Stopping a normal-appearing rotor blade in flight is not an easy task. Wind tunnel tests of various models have demonstrated severe difficulties. Once the centrifugal stiffening effects of rotation are lost, the rotor tends to be at the mercy of the wind; very large aeroelastic effects and blade stresses are encountered during the rotor stopping or starting sequence as well as large pitching and rolling moments to upset the aircraft. In order to make the concept workable, relatively low aspect ratio, short and stiff blades are required along with fairly low conversion speeds. This dictates a relatively high disk loading and a wing sized by the conversion requirement, i.e., oversize for cruise. The fuselage length must also be large to accommodate the blades in the stowed position.

The degree of success of these last several VTOL concepts in meeting the high speed/low disk loading objective is shown in Figure 25. Although they have broken away from the original curve, all show disk loading penalties relative to the helicopter. Only the stowed rotor is believed to have the potential for speeds above 500 knots.

LOWEST DISK LOADING CONCEPTS

X-WING - To achieve the greatest departures from the Figure 25 curve, greater innovations are required. One possible approach having a speed potential in the 400 to 500 knot range is the X-Wing concept, shown in Figure 26. This concept originated in the U.S. Navy; Sikorsky Aircraft participated in its development under NASA and DARPA sponsorship. It is similar to the stowed rotor in that it stops the rotor in flight, but it does not stow the rotor and does not utilize a wing for lift in cruise; the rotor provides the lift in all flight modes. The X-Wing utilizes a shaft-driven rotor having four extremely stiff blades to counter the aeroelastic divergence problems that more normal blades would have. The aircraft takes off like a conventional helicopter but has auxiliary propulsion or convertible fan/shaft engines that will permit it to reach moderate forward speeds with the rotor turning. At a suitable conversion speed, on the order of 200 knots, the rotor is braked to a stop and positioned with two blades swept forward 45 degrees and two swept aft 45 degrees, forming an X-shape planform wing. The blades are symmetrical fore-and-aft and utilize pneumatic control of a thin jet of pressurized air out of the leading and trailing edges of the blade, as shown in Figure 27, to provide circulation control to maintain full rotor lift in all flight regimes. Photographs of one of the experimental blades, and of the pneumatic valving system in the hub for azimuthal control of the air supply, are shown in Figures 28 and 29 respectively. The circulation control system, by means of the hub-mounted pneumatic valves, provide the equivalent of cyclic pitch as well as a limited collective pitch range, plus higher harmonic blade lift control to suppress the large moments and vibratory inputs from the rotor during the conversion between rotary wing and fixed wing flight.

The completed rotor system is shown installed on the NASA Rotor Systems Research Aircraft in Figure 30. Unfortunately, funding for the program ended prior to flight test of the rotor. Because of the complex pneumatic controls, there was still a substantial amount of work to do to qualify the air vehicle management system for flight. Wind tunnel tests of a highly sophisticated dynamically-scaled model of the X-wing were successful, however; no disqualifying defects ("fatal flaws") were discovered during the extensive tests conducted. Thus the X-Wing is a possible candidate for future application.

VARIABLE DIAMETER - Other high-speed rotorcraft concepts are available by incorporating a form of variable geometry not used by any of the other configurations considered: the variable-diameter rotor. Although more complex than a conventional rotor, it can be considerably less complex than variable-geometry features routinely incorporated in many successful transport airplanes: the multiple slotted-flap/leading edge slat/Kreuger flap system used to generate high lift for takeoffs and landings, but not for cruise. For a very high-speed rotorcraft, a large-diameter (i.e., low disk loading) rotor is desired for takeoffs and landings, but would be a handicap in cruise, just as an extended high-lift system is inappropriate in high-speed airplane flight.

Many variable-diameter concepts have been envisioned over the years; the potential benefits are quite widely recognized. Some of the configurations that have been proposed are shown in Figure 31. Sikorsky Aircraft developed one of these configurations in the late 1960's and early 1970's, labeled "TRAC" for Telescoping Rotor AirCraft. This concept was farther along the road to successful flight demonstration than any other variable-diameter scheme. The only reason the program was not continued at that time was that the U.S. Army, the customer that had been supporting it, dropped the development of all high-speed VTOL concepts to concentrate on the conventional helicopter.

The schematic arrangements of the variable-length blade and retraction mechanism are shown in Figures 32 and 33. The main lifting surface of the blade is outboard, sliding over a cambered elliptical torque tube when it telescopes in. The motion is actuated by a jackscrew inside the blade, which connects to the tip by a series of nuts and tension-torsion straps. The jackscrew, which incorporates an internal, structurally-redundant strap for fail-safety, is actuated by means of the hub mechanism. A simple differential gear set inside the hub can drive the diameter change in either direction, depending on whether the retraction brake or extension brake at the bottom of the transmission is actuated. If neither brake is actuated, the rotor maintains a constant diameter. The pilot is in full control; he can stop the conversion procedure at any point, hold the diameter at any value, or reverse the procedure at his discretion. The gears are always engaged, the blades are positively synchronized, and no auxiliary power is required. The entire system is quite simple and reliable, and positive safety systems have already been devised for all necessary functions.

VARIABLE-DIAMETER STOWED ROTOR - The Sikorsky variable diameter rotor was originally aimed at the stowed rotor configuration and a higher-than-normal-speed compound helicopter. A nine-foot diameter dynamically-scaled model of the rotor was built and successfully tested in the wind tunnel, Figures 34 and 35 (Reference 1).. Diameter changes, made at true airspeeds up to 150 knots, were easily controlled, rapid, and structurally benign. Rotor stops and starts at minimum diameter and simulated blade folds were also made at 150 knots. These were also without difficulty of any kind, firmly establishing the feasibility of the stowed-rotor configuration. The same wind tunnel test program also explored the high-speed compound helicopter mode with the rotor at minimum diameter, but continuing to rotate. True airspeeds up to 400 knots were attained. This is believed to still be the speed record for tests of a rotor in the horizontal (in-plane) mode, as opposed to axial flight (propeller mode).

In addition to the wind tunnel tests, laboratory tests were conducted on a full-scale jackscrew and nut/strap system assembly (design max rotor diameter 56 feet). Simulated centrifugal loads of over 50,000 pounds were imposed. Several hundred retract/extend cycles were demonstrated successfully (Reference 2).

A preliminary design study of the *variable-diameter stowed rotor*, made a number of years ago (Reference 3), is shown in Figure 36. The aircraft takes off with the rotor turning at full diameter, accelerates up to a suitable conversion speed, and then shrinks the diameter while at full RPM. By reducing the diameter, the problems of the stowed rotor conversion previously mentioned are greatly alleviated. Instead of gross aeroelastic effects and excessive pitching and rolling moments during conversion, the blades become short enough and stiff enough to eliminate these barriers to stopping the rotor. Stowage volume is also minimized, reducing airframe weight and drag. The wing can be optimized for cruise rather than being sized for the conversion. Because of its high cruise speed, transport productivity is high.

<u>VARIABLE DIAMETER TILTROTOR</u> - More recently, Sikorsky has been evaluating the potential of the variable-diameter rotor to benefit the tiltrotor aircraft (References 4-6). Before discussing this configuration, consider some of the deficiencies of the conventional tiltrotor aircraft. As previously stated, the tiltrotor is a very promising rotorcraft in that it significantly increases speed and range potential compared to the helicopter and does so without requiring any auxiliary propulsion system or convertible engines that most other higher-speed rotorcraft must incorporate. *That's the good news.*

The bad news is that there are a number of undesirable design compromises that must be made. The rotor must lift the gross weight plus vertical drag in hover, but is only required to overcome airframe drag in cruise, which is much less than weight. It is undersize in hover and way oversize in *cruise. Hover disk loading* is 50 to 100 percent higher than for a helicopter of similar size, so that lift per unit power is reduced, downwash velocities are excessive, and helicopter-like power-off autorotative flares become difficult or impossible. To reduce thrust over-capacity in cruise, rotor RPM is reduced, leading to reduced transmission power capacity and off-design engine operation. Gust response of the oversize propeller is excessive, vibration control with RPM a variable is difficult, and internal noise is excessive because of the close proximity of the blade tips and the fuselage in cruise flight. Useful load fraction is less than for a helicopter, so that aircraft productivity suffers on short missions despite the higher speed.

How do variable-diameter rotors change the tiltrotor design tradeoffs? Except for rotor complexity and rotor weight, which are increased, essentially all factors represent improvements. They permit larger diameters, with the rotor overlapping the fuselage to some extent in hover, and yet allow smaller, more nearly optimum sized propellers in cruise (Figure 37).

The larger rotor in hover produces more *lift per horsepower despite a small reduction* in hover Figure of Merit; lift capability increases faster than rotor weight and the useful load fraction is improved, making the aircraft more competitive. Hover disk loadings are more like those of a helicopter, as are autorotative characteristics. Hover downwash is reduced, enhancing the ability to operate in unprepared areas. Propeller efficiencies in cruise are higher and gust response is reduced. No RPM reduction is required because tip speed automatically reduces with diameter. Vibration control is easier, the engine operates in an optimum condition, and the transmission delivers more power, enhancing maximum speed capability. The reduced blade area, tip speed, and rotor kinetic energy in cruise also make avoidance of rotor/wing instability easier. This factor plus a reduced nacelle-to-nacelle spacing allows a significant reduction in wing weight and the use of thinner airfoils which will accommodate higher cruise speeds if desired. Calculated propeller cruise efficiency remains high. Figure 38 shows recent study results (Reference 5), indicating potential propulsive efficiency as a function of flight Mach number. Level flight speeds approaching 500 knots do not appear to be out of reach. Other benefits also are available, including better Category A fly-away capabilities, reduced external *noise footprints through the use of steeper* allowable approach and departure paths and reduced design hover tip speeds, and reduced internal noise because of considerably lower cruise tip speeds and increased clearance between blade tips and the fuselage.

The previous wind tunnel tests of the Sikorsky variable diameter rotor were not designed to evaluate its application to the tiltrotor configuration. The blade planform and twist distribution requirements are different as are the operating conditions. To validate the variable diameter tiltrotor (VDTR) concept, Sikorsky Aircraft has developed a semi-span aeroelastically-scaled model of the VDTR. Wind tunnel tests are planned for the second half of 1992. This test should serve to confirm many of the benefits envisioned.

Adding these last three rotorcraft configurations to the disk loading-speed chart, Figure 39, we see that they have the potential for achieving what is being sought: high subsonic speeds with disk loadings close to those of the conventional helicopter. It should again be noted that Figure 39 represents feasible design speeds. Most configurations could also be designed to operate efficiently at lower speeds than those indicated.

THE QUESTION OF USEFUL LOAD

All of these conjectured lower disk loading rotorcraft can probably be made to fly, but do they have any payload or range? A good question to which it is difficult to provide quantitative answers for at least some, and perhaps most, of the aircraft discussed. No one has attempted quantitative comparisons of all of the concepts at the same level of technology, and there are still certain issues of feasibility for some of them, making the task virtually impossible because solutions to technical problems usually involve weight. This question, therefore, will be answered in a qualitative manner. Most new aircraft concepts, when first introduced, have a high ratio of empty weight to gross weight, i.e., not very much payload. As time goes on, stronger and lighter structural materials are developed, powerplants become more powerful but lighter weight, and mission equipment including avionics becomes more capable but lighter in weight. Aircraft configurations that start out uncompetitive because of poor payload fraction can improve their standing with time because of the continuous march of technology improvement that allows a reduction in empty weight.

A simple example will be used to illustrate this point. Assume we have two aircraft; a helicopter and a high-speed rotorcraft capable of twice the speed. Assume the helicopter has an empty weight fraction of 60 percent and the high speed rotorcraft has an empty weight fraction of 75 percent with comparable levels of technology. In typical missions, each aircraft might use a fuel load of 15 percent of gross weight. This leaves 25 percent of the gross weight as payload for the helicopter, but only 10% of the gross weight as payload for the high speed rotorcraft. For equal gross weights, the high speed aircraft carries only 40 percent of the payload of the helicopter, or for equal payloads, the gross weight of the high speed aircraft is 2 1/2 times higher than that of the helicopter. The high speed aircraft is not economically competitive with the helicopter in a transport mission.

What happens, however, if both aircraft are subject to technology improvements affecting weight? The high speed aircraft, starting at a higher empty weight fraction, has more to gain by any given percentage reduction in empty weight. This is shown in Figure 40, in the form of gross weight to payload ratio as a function of the percentage reduction in empty weight. A 25% reduction in empty weight fraction benefits the helicopter significantly, reducing gross weight from 4.0 to 2.5 times the payload, a 37.5 percent reduction. The benefit to the high speed aircraft, however, is much more dramatic; the gross weight to payload ratio is reduced from 10 to 3.48, a 65.2 percent reduction. The helicopter still has a payload advantage, but no longer enough of an advantage to make up for the speed difference.

The productivity comparisons for the two aircraft are shown in Figure 41. For any transport mission delivering people or cargo, an important measure of effectiveness is productivity, defined as payload times block speed, which determines the amount of payload delivered over a given distance per unit time. Because large aircraft can carry more payload than small ones, it is necessary to divide productivity by aircraft weight to determine the relative transport efficiency of the aircraft. The cost of an aircraft tends to be proportional to empty weight; a simple but reasonably accurate representation of transport cost efficiency is payload times block speed divided by empty weight. This productivity parameter is plotted in Figure 41 as a function of the percent reduction in empty weight fraction. The curves shown represent a helicopter with a block speed of 160 knots and a high speed rotorcraft with twice the block speed: 320 knots (These block speeds correspond to cruise speeds of 200 knots and 400 knots, respectively, with "unproductive" time of 20 percent of total time). For the baseline weights assumed (zero percent reduction in empty weight), the productivity parameter of the helicopter is more than 50 percent higher than for the high speed aircraft. Although the payload fraction of the higher speed aircraft never catches up with that of the helicopter as empty weights are reduced, the speed advantage compensates. At a 15% reduction in empty weight fraction, the productivity curves cross; with greater reductions, the productivity of the faster machine is higher, i.e., the aircraft that couldn't compete with the helicopter at the baseline technology level is now superior.

Recent history suggests that aircraft empty weight fractions are being reduced at the rate of about six percent per decade; this general trend is expected to continue for some time, although not necessarily at the same rate. The message that might be drawn is that, if we are willing to wait long enough, the highest speed concepts will eventually become the most economically viable, even if they don't appear attractive now. At short ranges, where high speed is not important because the "unproductive" time will dominate, the helicopter will always be the VTOL configuration of choice, but at longer ranges (beyond one or two hundred miles), the high speed VTOL concepts will be viable. Conventional airplanes, of course, will have greater productivity whenever runways are available where needed. There will always be a price for VTOL capability.

Not all of the high speed VTOL aircraft have equal merit, and not all will be developed. The ones having the lowest empty weight fraction in any speed regime are the ones apt to be developed first, in any case. The appeal of the tiltrotor aircraft is quite logical from this perspective: it has reasonably low disk loading and is simpler than most of the higher speed concepts. In particular, the avoidance of a second propulsion system or convertible fan/shaft engine means that its empty weight fraction is lower than the higher speed concepts that require those systems.

What about the six concepts shown in Figure 39 to the right of the present trend curve? With one exception, they all require an auxiliary propulsion system or convertible fan/shaft engine. The one exception is the variable diameter tiltrotor, suggesting that this concept has a relatively favorable empty weight fraction and so has a better chance at economic viability in the near future. It also has the lowest disk loading and the helicopter virtues that derive therefrom.

The variable-diameter tiltrotor has much to commend it. Payload/range characteristics are enhanced, Figure 42. The speed/altitude capability envelope is enlarged, Figure 43. Category A one-engine-inoperative performance is improved, of vital importance to civil operations, Figure 44. Also highly significant for civil use is the potential reduction of the acoustic footprint, Figure 45. The internal noise levels will also be reduced. Ride comfort is also improved; response to longitudinal gusts is excessive for the conventional tiltrotor but is greatly reduced by variable diameter; Figure 46.

Further in the future, the variable-diameter stowed rotor appears to offer the "ultimate" high speed rotorcraft; disk loading of the helicopter and speed of the Harrier, or possibly faster if desired. Prior design studies have already suggested that it can be economically viable; time and technology will surely make it more attractive in the future.

CONCLUDING REMARKS

There appears to be a well established trend of increasing disk loading of VTOL aircraft as design speed is increased. No aircraft that departs from this trend has yet appeared in flight, but one or more will surely do so in the future. The helicopter virtues that derive from low disk loading are real and substantial; the motivation to make a high speed, low disk loading VTOL aircraft will endure.

A variable-diameter rotor is an important key to achieving these objectives (Figure 47). It adds 100 knots or more to the speed potential of the tiltrotor aircraft, while providing a desirable decrease in disk loading. For the "ultimate" VTOL, a stowed rotor concept offers the highest speeds. The variable-diameter rotor makes it feasible.

Increasing levels of complexity with time have strong historical precedents in most fields of technology and certainly for flying machines (Figure 48). Variable geometry in particular appears to be a key for better aircraft performance. Safety and reliability need not be adversely impacted with proper development. The variable geometry features of tilting rotors and variable-diameter rotors are fundamentally sound concepts and surely will be successfully incorporated in some categories of future high-performance rotorcraft.

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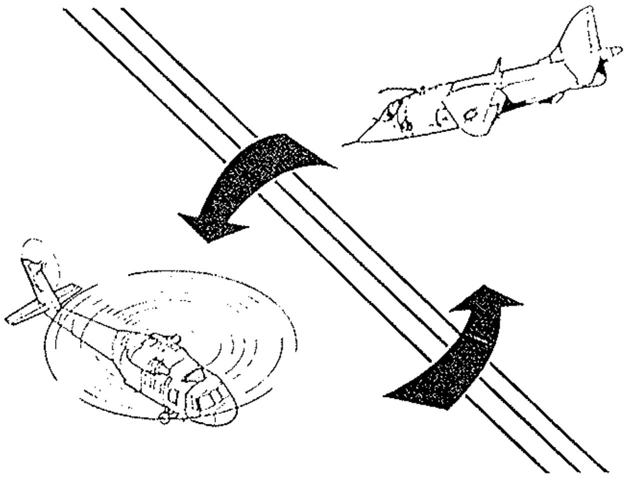

Figure 1 - Merging Two Ends of the V/STOL Spectrum

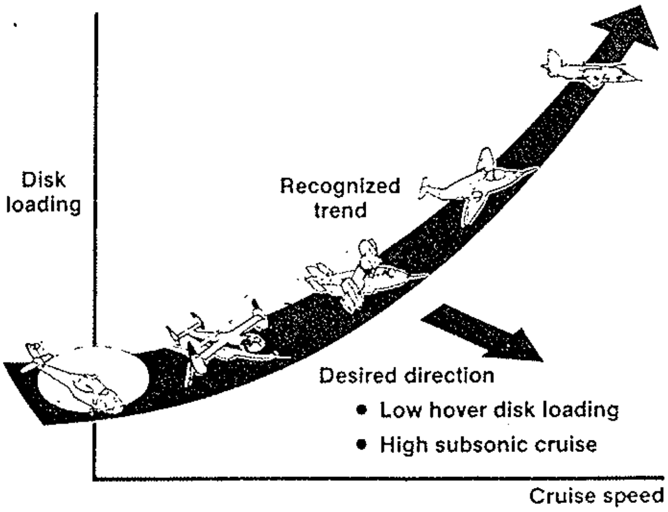

Figure 2 - Disk Loading-Cruise Speed Trends

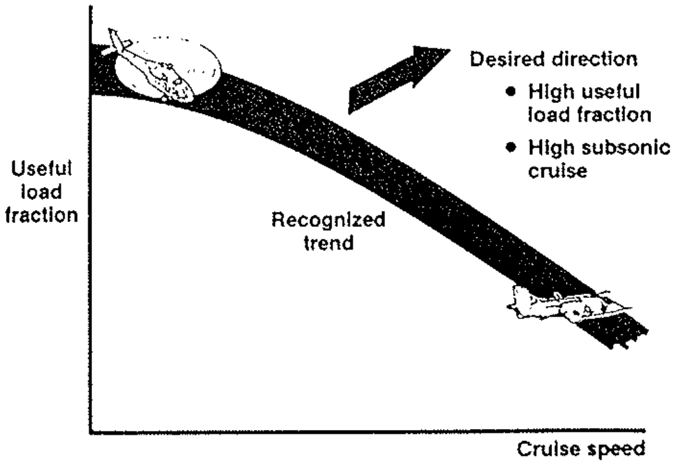

Figure 3 - VTOL Useful Load Trend

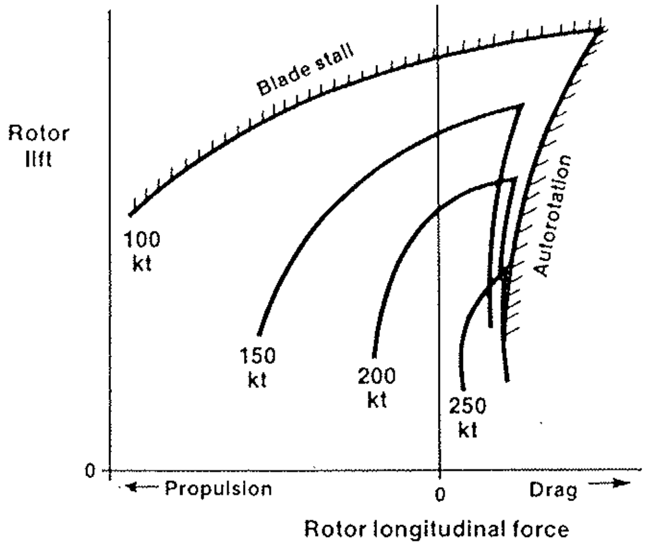

Figure 4 - Effect of Speed on Rotor Force Capabilities

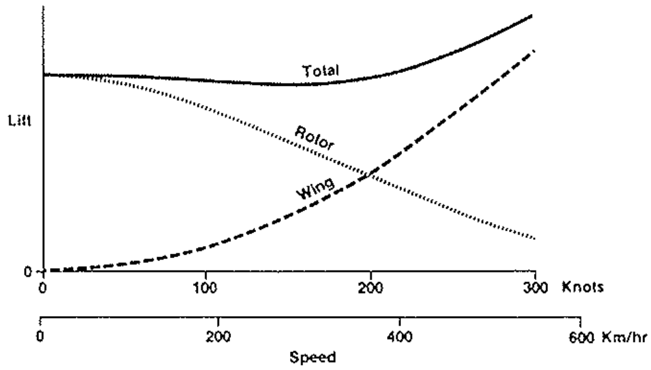

Figure 5 - Combined Lift of Rotor and Wing

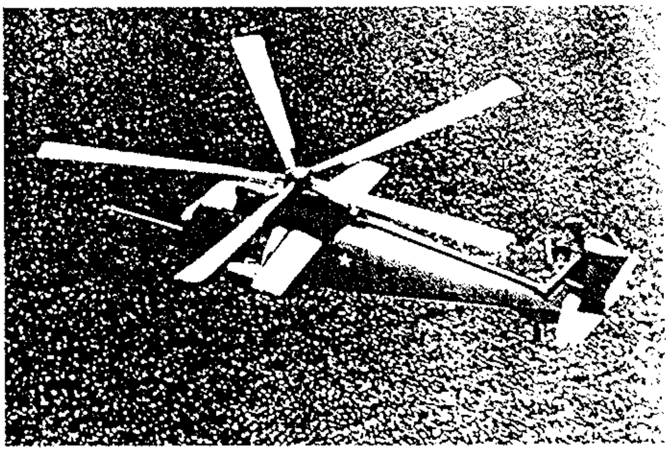

Figure 6 - Sikorsky S-61F Research Compound Helicopter

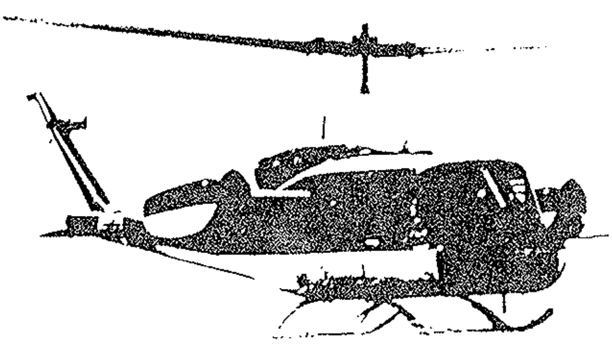

Figure 7 - Bell UH-1 Compound

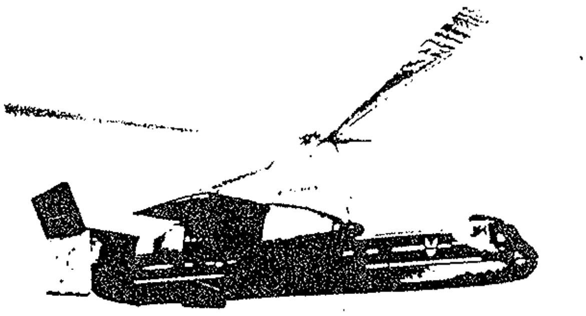

Figure 8 - Fairey Rotodyne

Figure 9 - Lockheed AH-56 Cheyenne

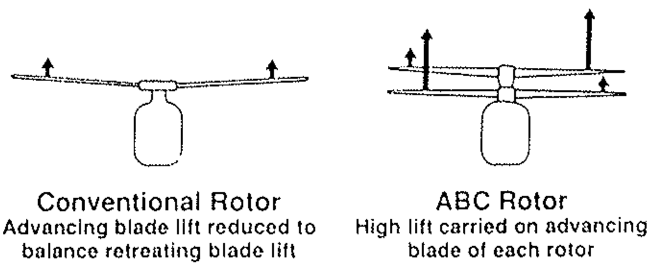

Figure 10 - Basic Principle of Advancing Blade Concept

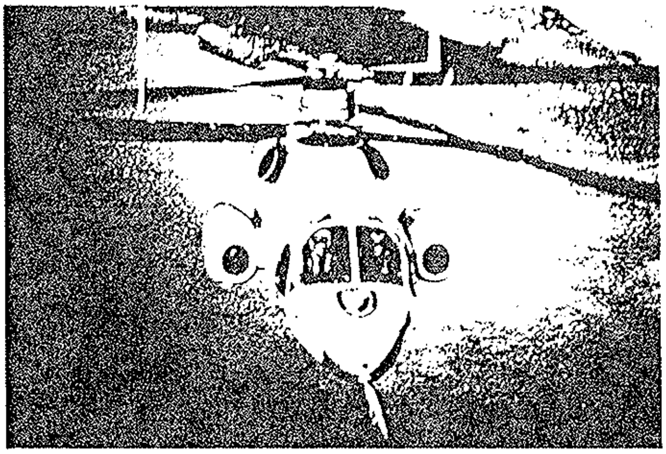

Figure 11 - XH-59A Demonstration Aircraft

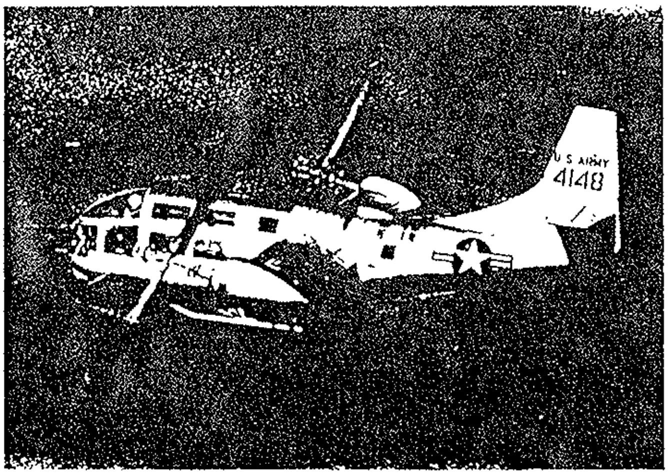

Figure 12 - Bell XV-3 Tilt-Rotor

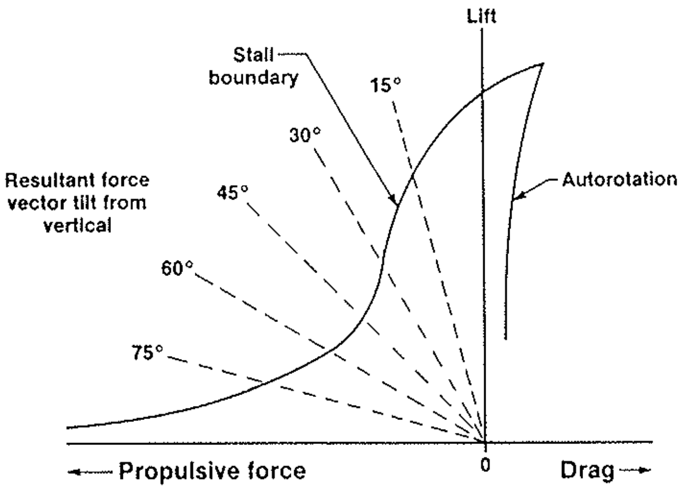

Figure 13 - Typical Rotor Aerodynamic Envelope Limits Over Full Tilt Range

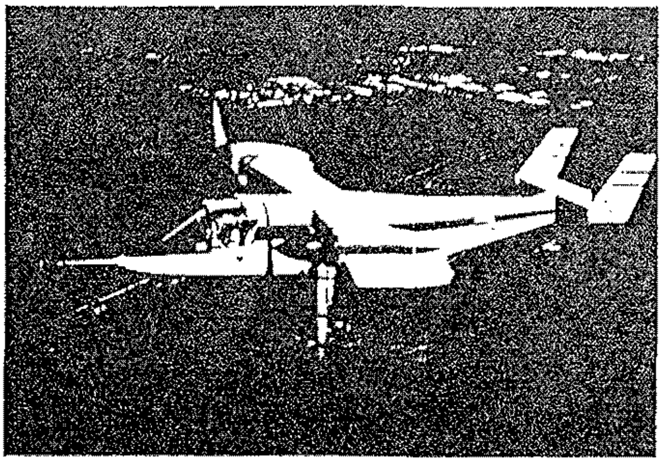

Figure 14 - Bell XV-15

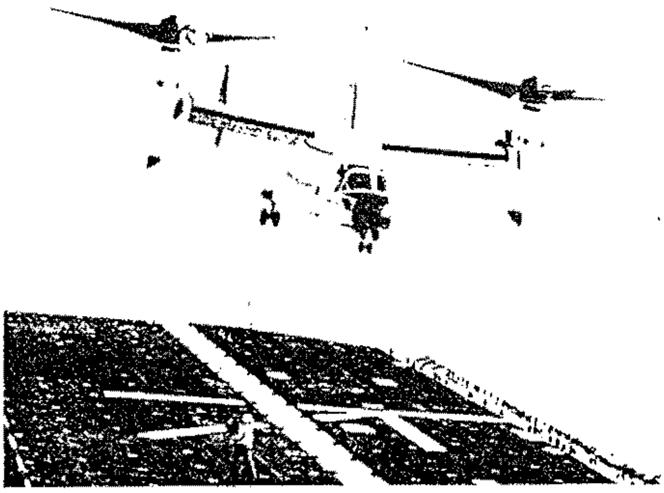

Figure 15 - Bell/Boeing V-22 Osprey

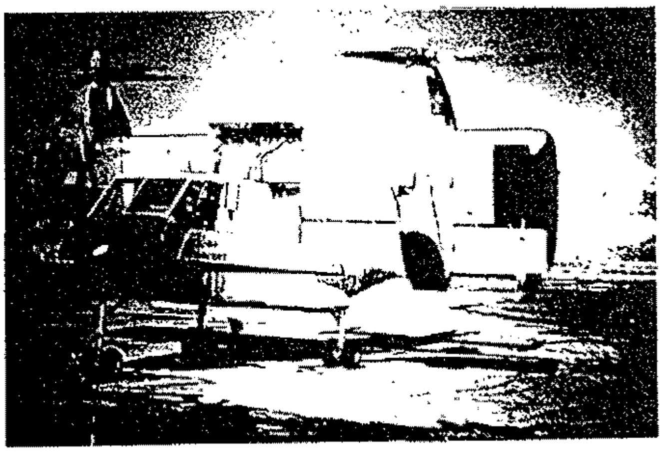

Figure 16 - Canadair CL-84 Tilt Wing/ Propeller Aircraft

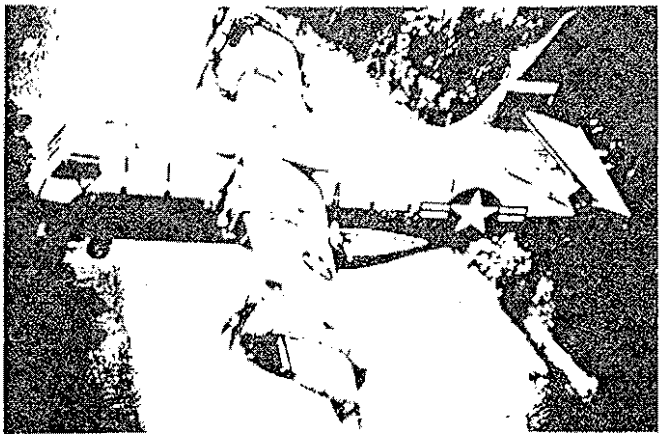

Figure 17 - LTV XC-142 Tilt Wing/ Propeller Prototype Transport

Figure 18 - Ryan XV-5 Fan-In-Wing Aircraft

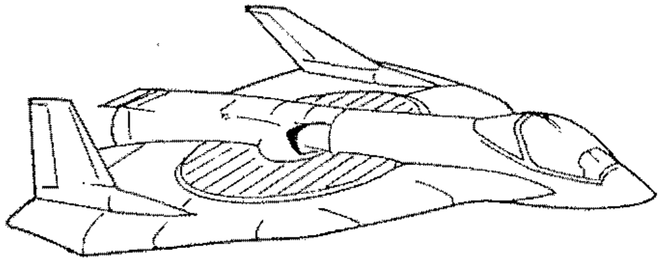

Figure 19 - Central Lift Fan

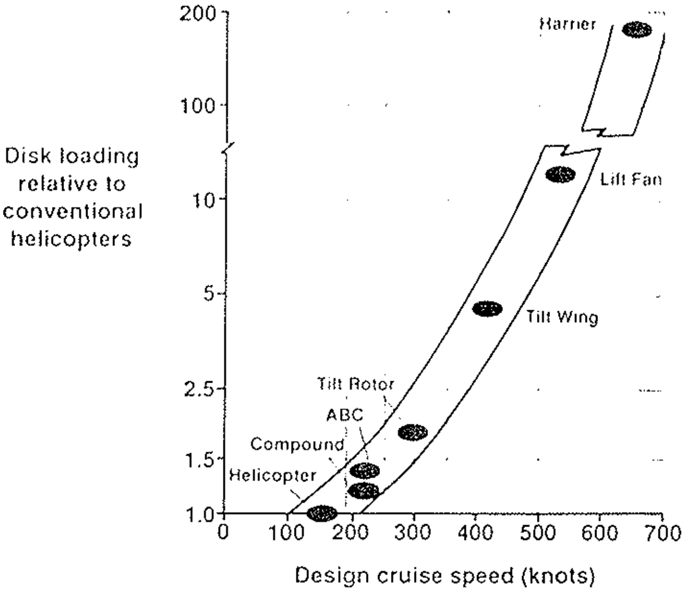

Figure 20 - VTOL Disk Loading/Speed Trend-Present

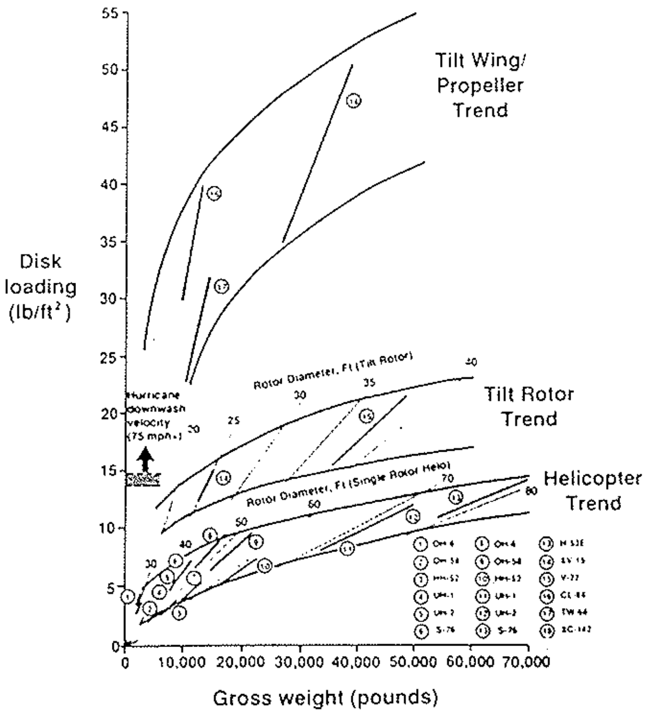

Figure 21 - Disk Loading/Weight Trends

Figure 22 - Folding Tilt-Rotor Design

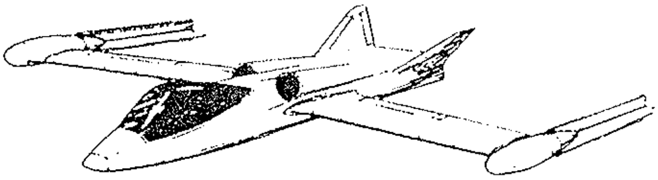

Figure 23 - Trailing Rotor Concept

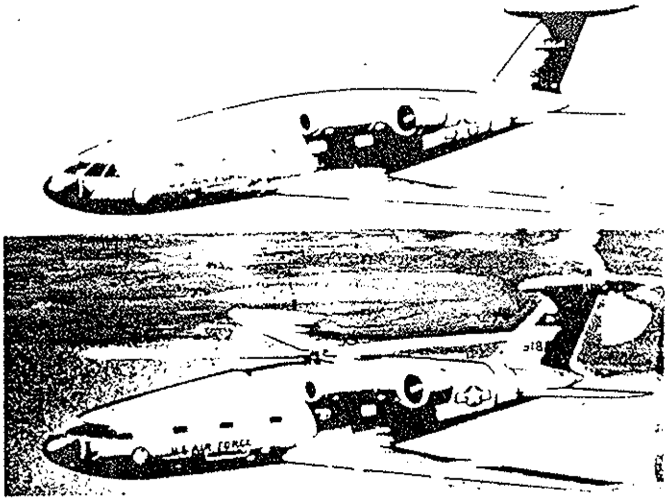

Figure 24 - Single Stowed Rotor Concept

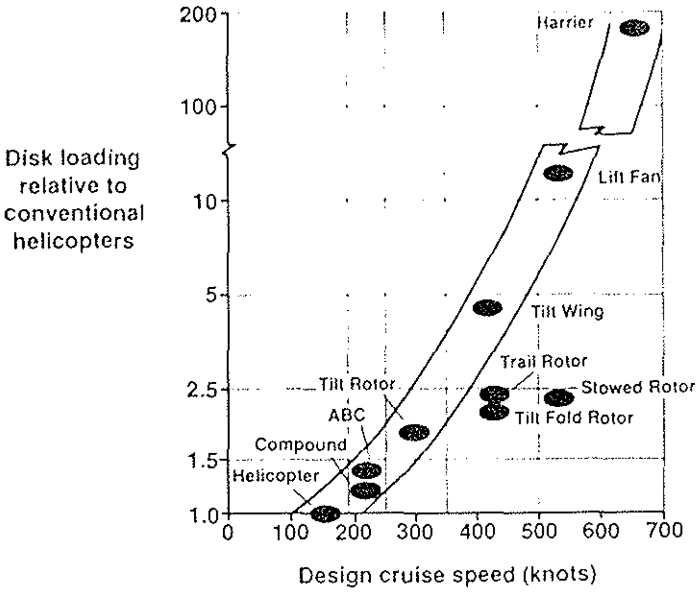

Figure 25 - Disk Loading/Speed Improvements

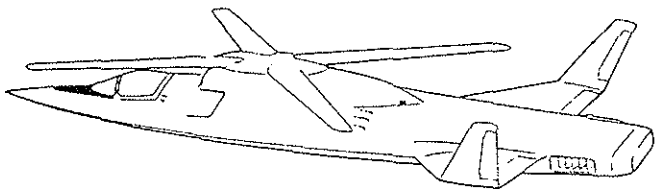

Figure 26 - X-Wing Concept

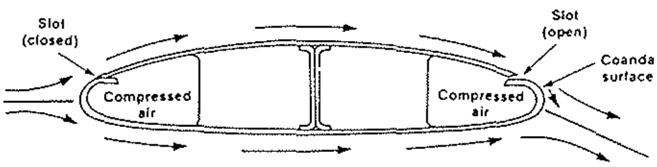

Figure 27 - X-Wing Airfoil with Circulation Control

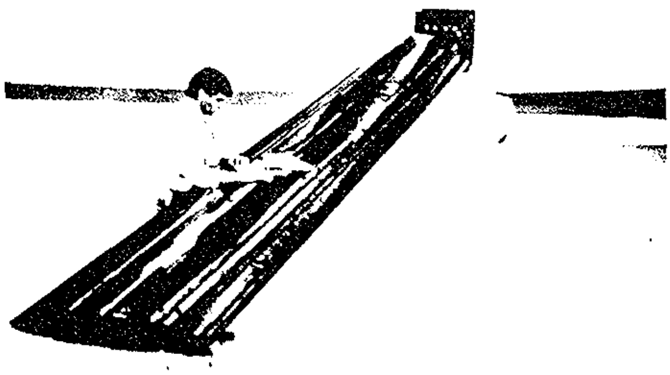

Figure 28 - X-Wing Rotor Blade

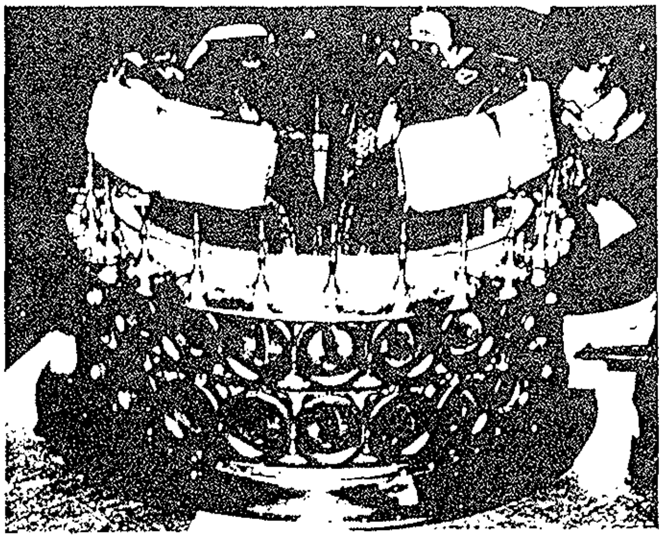

Figure 29 - X-Wing Air Supply Valves and Distribution Ducts

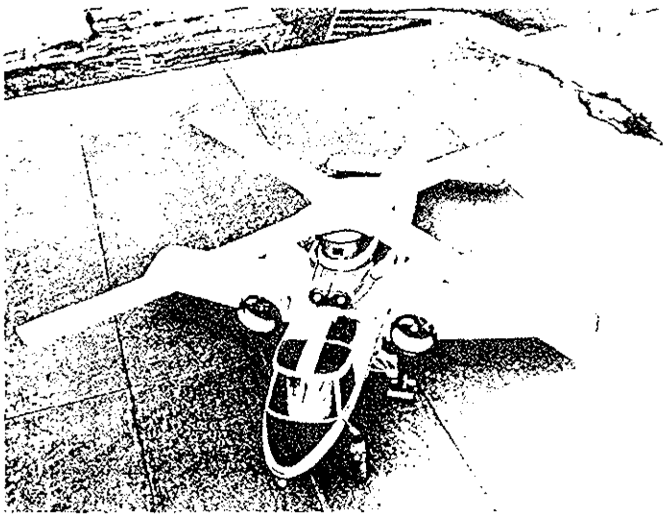

Figure 30 - X-Wing Rotor on NASA Rotor Systems Research Aircraft

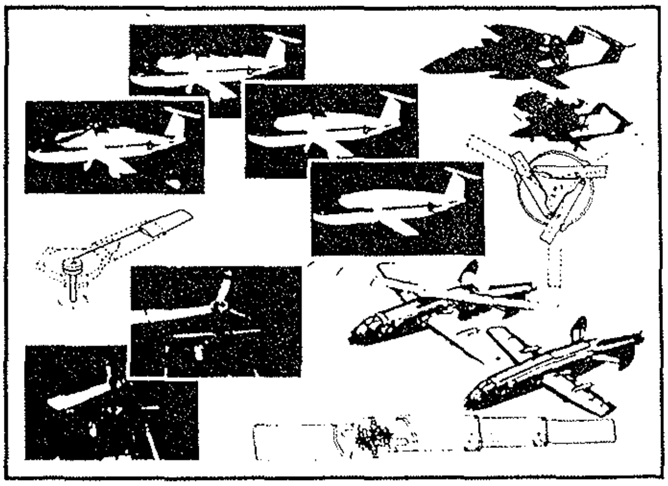

Figure 31 - A Sampling of Variable-Diameter Rotor Concepts

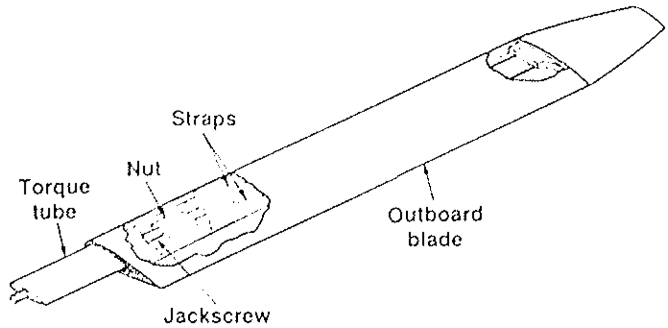

Figure 32 - Telescoping Rotor Blade Schematic

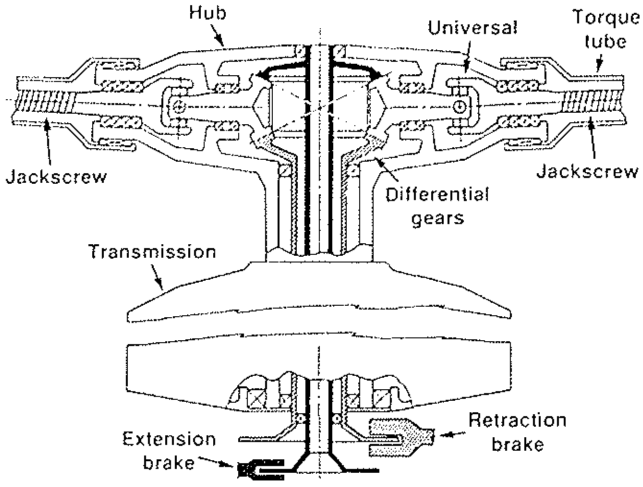

Figure 33 - Retraction Mechanism Schematic Arrangement

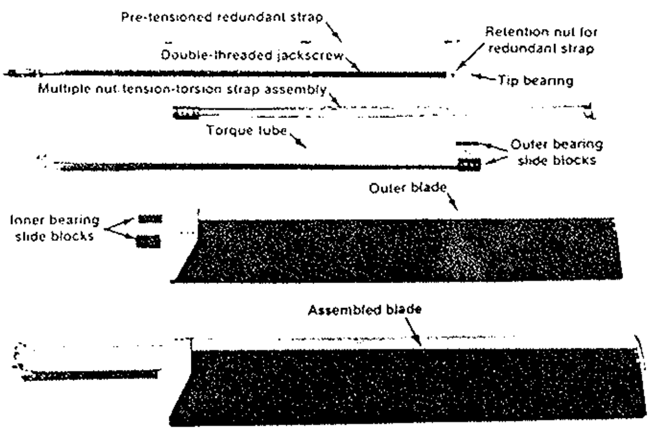

Figure 34 - Wind Tunnel Model Blade Components

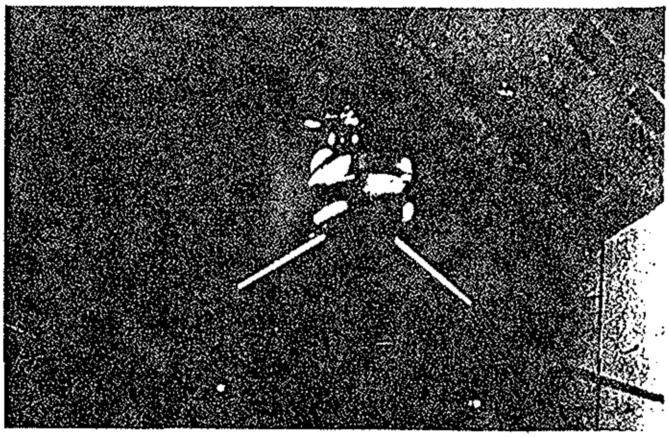

Figure 35 - Variable-Diameter Rotor Wind Tunnel Test

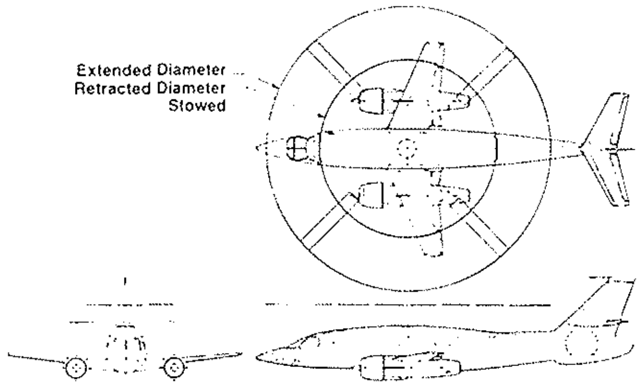

Figure 36 - Variable-Diameter Stowed Rotor Aircraft

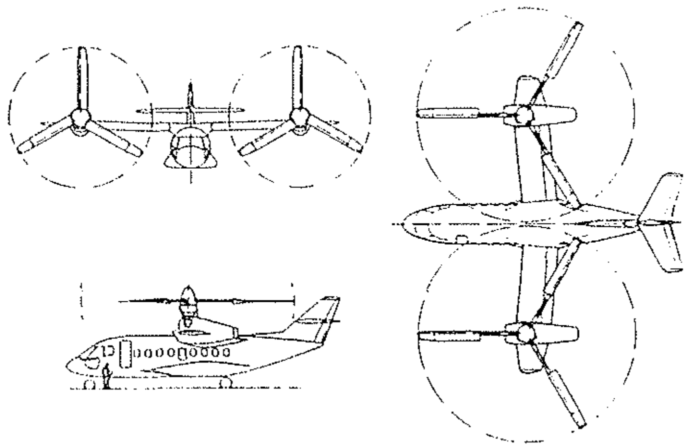

Figure 37 - Variable-Diameter Tilt-Rotor Aircraft

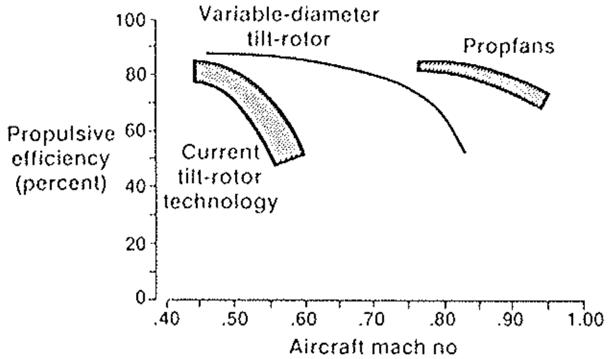

Figure 38 - Maximum Propulsive Efficiency vs. Flight Mach No.

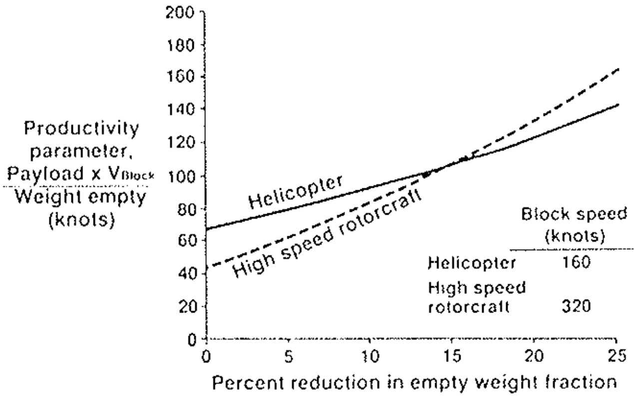

Figure 41 - Effect of Empty Weight Reduction on Productivity

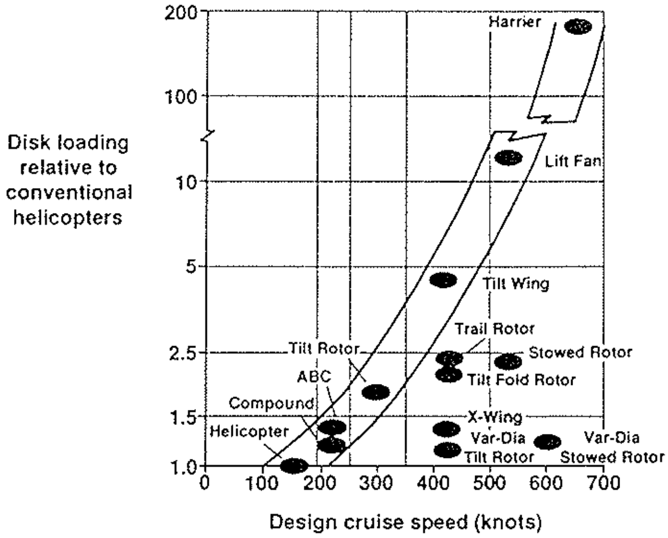

Figure 39 - Ideal Disk Loading/Speed Combinations are Available

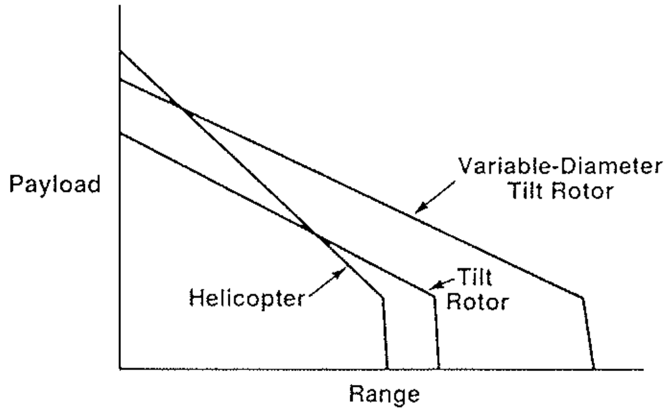

Figure 42 - Variable Diameter Improves Tilt-Rotor Payload/Range Characteristics

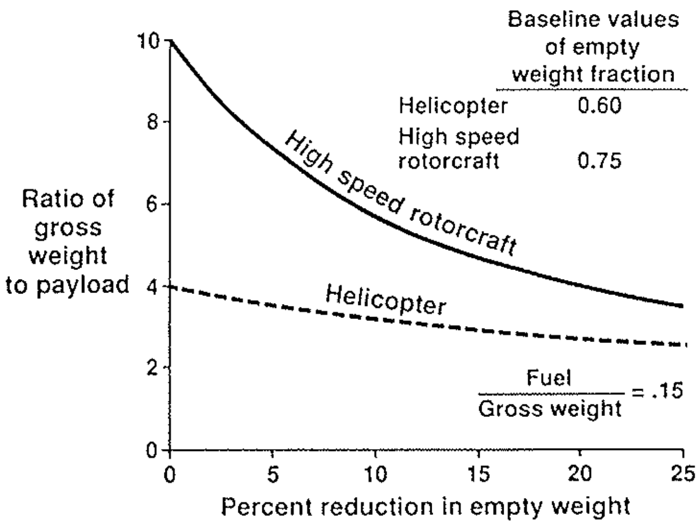

Figure 40 - Effect of Empty Weight Reduction or Gross Weight

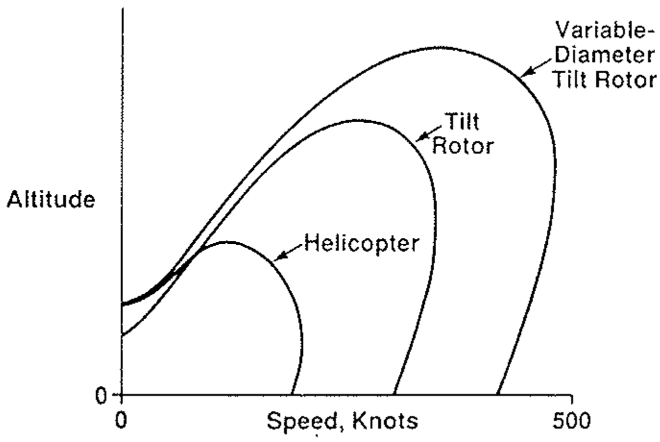

Figure 43 - Variable Diameter Expands Potential Tilt-Rotor Flight Envelope

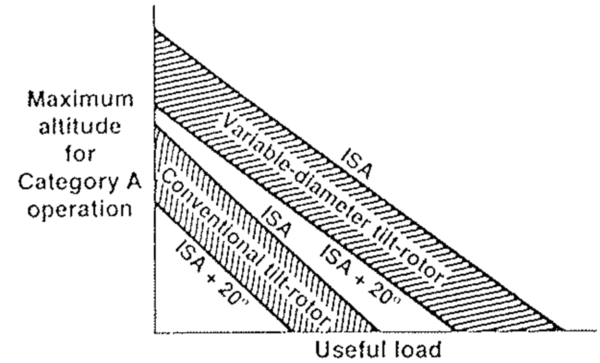

Figure 44 - Variable Diameter Enhances Category A Performance and Expands Operational Flexibility

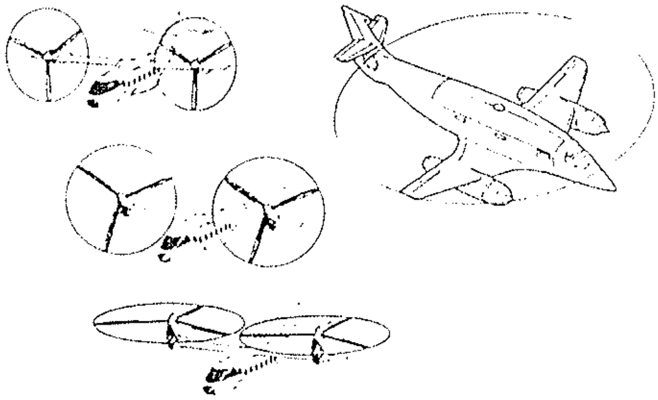

Figure 47 - Variable Diameter Provides A Key to Ideal High Speed Rotorcraft

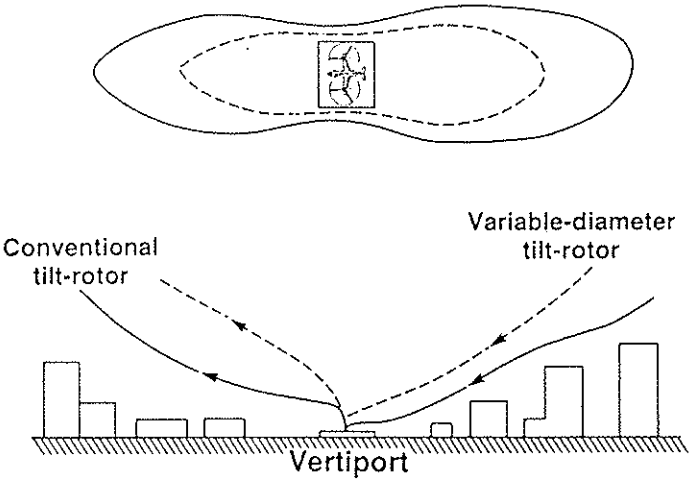

Figure 45 - Variable Diameter Will Reduce Acoustic Footprint

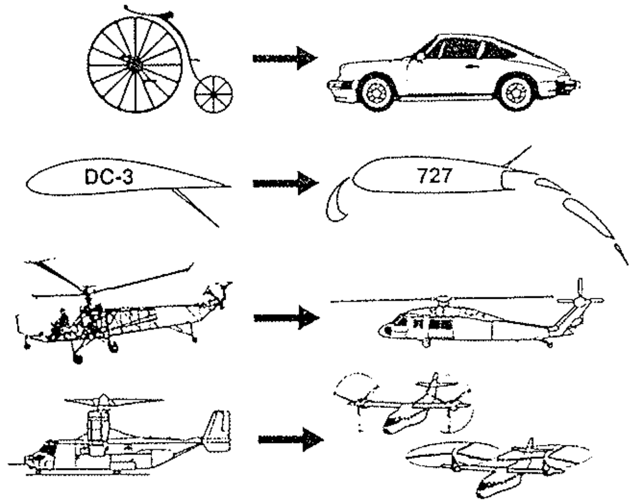

Figure 48 - Complexity Allows Improved Performance

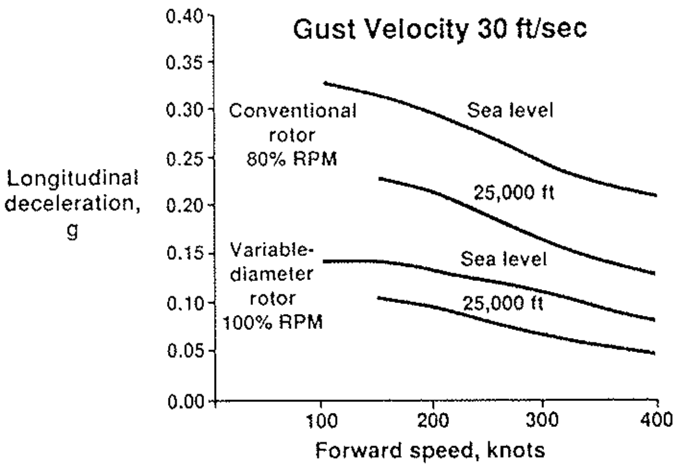

Figure 46 - Variable Diameter Reduces Response To Head-On Gust